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Name : Kubilay
Surname : Şahinler
E-Mail : Kubilay.sahinler@metu.edu.tr
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MODELLING AN ARCHITECTURAL DESIGN PROCESS

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY



BY
KUBİLAY ŞAHİNLER

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FOR
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MODELLING AN ARCHITECTURAL DESIGN PROCESS

submitted by **KUBİLAY ŞAHİNLER** in partial fulfillment of the requirements for the degree of **Master of Science in Building Science in Architecture, Middle East Technical University** by,

Prof. Dr. Halil Kalıpçılar
Director, Graduate School of **Natural and Applied Sciences** _____

Prof. Dr. Fatma Cana Bilsel
Head of the Department, **Architecture** _____

Prof. Dr. Arzu Gönenç Sorguç
Supervisor, **Architecture, METU** _____

Examining Committee Members:

Assist. Prof. Dr. Mehmet Koray Pekerliçli
Architecture, METU _____

Prof. Dr. Arzu Gönenç Sorguç
Architecture, METU _____

Prof. Dr. Meryem Birgöl Çolakoğlu
Architecture, ITU _____

Date: 02.02.2022



I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Kubilay Şahinler

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ABSTRACT

MODELLING AN ARCHITECTURAL DESIGN PROCESS

Şahinler, Kubilay
Master of Science, Building Science in Architecture
Supervisor : Prof. Dr. Arzu Gönenç Sorguç

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Architecture is influenced by developing technologies as well as by political, social, and economic practices. In this context, the scope of architectural service also evolves. Accordingly, different studies are carried out on the execution of the design process with different methodologies. In the building design process, various models are proposed and discussed, in which the role of the architect is questioned.

In this context, this research includes a series of model suggestions aimed at making the architectural design process more efficient by redefining the role of the architect. The primary motivation in the research process, is that the role of an architect can be described as not a final artefact designer, but rather as an actor who designs different stages within a specific system, defines the design boundaries, their potentials, and designs the system that will create a limited design set. Accordingly, in the research context, a series of exploration and discourses on today's changing architectural practice will be presented, and explanations will be given on how expectations from architectural design have changed. Subsequently, different models developed in this study will be presented, tested and evaluated for the design process. The first model is based on parameterizing a structure with all its elements and defining its

constraints. The second model is a system developed with generative algorithms aiming to produce generic solutions regarding the feedback coming from the first model. Discussions on the design and solution sets are carried out on this model. On the other hand, the last model is a system built upon the experience of the first two models. Design limits and expectations are defined within the system with stored building components, and with operational research methodologies, it is tried to make the design process more efficient.

In conclusion, the proposed models will be compared, and their potentials will be discussed. The effects of the proposed models on the design process to make the building design process more efficient will be examined, and ideas on how the architectural practice can be shaped in the future will be discussed.

Keywords: Architectural Design Process, Automation, Optimization, Process Design Writing,

ÖZ

MİMARİ TASARIM SÜRECİNİN MODELLENMESİ

Şahinler, Kubilay
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Tez Yöneticisi: Prof. Dr. Arzu Gönenç Sorguç

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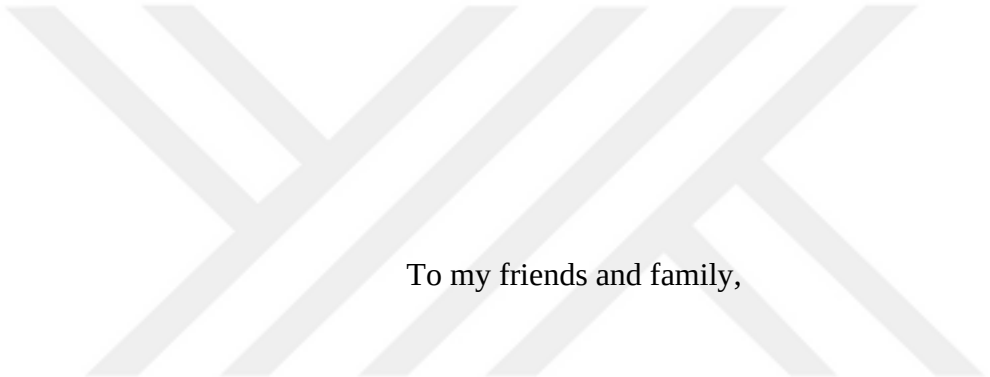
Mimarlık, gelişen teknolojilerden olduğu kadar, politik, sosyal, ekonomik pratiklerinden de etkilenmektedir. Bu bağlamda, mimarlık hizmetinin kapsamı da farklılaşmaktadır. Bu doğrultuda, tasarım sürecinin farklı metodolojiler ile yürütülmesi üzerine farklı çalışmalar yapılmaktadır. Yapı tasarım sürecinde, mimarın rolünün sorgulandığı, tasarımın belirli kriterler ve kısıtlar doğrultusunda makineler ile yapılabildiği, geçmiş örnekler üzerinden öğrenen sistemlerin tasarım yaptığı farklı modeller önerilmekte ve tartışılmaktadır.

Bu bağlamda, bu araştırma, tasarım sürecinde tasarımcının rolünün yeniden tanımlanarak mimari tasarım sürecini daha verimli kılmayı amaçlayan bir dizi model önerisi içermektedir. Araştırma sürecindeki temel motivasyon, mimarın, son ürün tasarımcısı olmasından ziyade, belirli sistem içerisindeki farklı aşamaları tasarlayan, tasarım sınırlarını çizen, potansiyellerini tanımlayan ve sınırlandırılmış bir tasarım kümesi oluşturacak sistemi geliştiren bir aktör olarak değişmesi üzerinedir. Buna göre, araştırma içeriğinde, ilk olarak günümüzde değişen mimarlık pratiği üzerine bir dizi araştırma ve söylem üretilecek ve mimari tasarımdan beklentinin nasıl değiştiği üzerine açıklamalarda bulunulacaktır. Akabinde ise, tasarım sürecine yönelik, farklı modeller önerilecek ve test edilecektir. İlk model, tüm elemanları ile,

bir yapının parametrize edilmesi, tüm kısıtlarıyla birlikte tanımlanması üzerine şekillenecektir. İkinci model ise, ilk model eleştirilerinden doğacak şekilde kapsamlı (generic) çözümler üretmeyi amaçlayan üretken algoritmalar ile geliştirilmiş bir sistem olacaktır. Tasarım kümesi ve çözüm kümesi üzerine tartışmalar bu model üzerinden ilerleyecektir. Son model ise, ilk iki modelin eleştirileri üzerinden inşa edilmiş, tasarımcılar tarafından, tasarım sınırları ve beklentileri sistem içerisinde tanımlanmış, tasarlanmış elemanların oluşturduğu bir kütüphane içerisinde yön eylem metotları doğrultusunda optimizasyon sistemleri ile yapı tasarım sürecini daha verimli kılmayı amaçlayan bir sistemdir.

Araştırma sonucunda ise, önerilen modellerin kıyasları yapılacak ve potansiyelleri tartışılacaktır. Yapı tasarım sürecinin daha verimli kılınması amacıyla önerilecek modellerin tasarım süreci üzerine etkileri tartışılacak ve mimarlık pratiğinin gelecekte nasıl şekillenebileceği üzerine düşünceler sunulacaktır.

Anahtar Kelimeler: Mimari Tasarım Süreci, Otomasyon, Optimizasyon, Süreç Tasarımı



To my friends and family,

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CHAPTER 1

INTRODUCTION

Like all other disciplines, architecture is changing with the developing technologies together with the new social and market dynamics brought by these technologies. Today, one of the fundamental changes effecting architecture is directly linked with contemporary design problems. The fact that a design problem defined by more quantitative data makes the process more data-driven than in the past, narrows down the designer's role. Second, the architect has to share his /her role in the entire building design process with other stakeholders due to the increasing need for expertise spanning over different disciplines, resulting in new specialties within the whole design and construction sector. Third, evolving design tools suggest a standardized design process rather than liberating the designer for design explorations. Finally, beyond the tools offered to the designer, mechanisms that automate specific design process steps optimize and accelerate certain processes are developing.

On the other hand, this changing context does not seem to change much the design process and the way architects design. When CAD emerged, it was just a paper and pen for architects, 3D modeling tools were used as test mockups, while BIM systems were perceived as documentation tools. (Svetel et al., 2018) This perception can lead to inefficiencies in use of them in the architectural design process. Since the design process as a defined flow is not accepted, control mechanisms could not be established, and design errors were not detected. Conventional understanding prevented even the use of several new systems. (Grobman et al., 2010)

The design's well-defined quantitative constraints/objectives, pressure exerted by the market conditions, and limited time allowed to the designer, force architectural design which in essence is individual and subjective, to be standardized.

Today, most of the buildings that make up the general face of our cities are or will be created by such standardized processes. It can be argued that the majority of the architectural designs around the world differ only in specifically defined parameters, and they can be considered as instances of the same system.

However, this research is not a critique of architectural practice, which will be discussed in more detail in the literature survey. The aim is to propose a novel method to build an architectural design system suitable for today's changing world conditions.

1.1 Motivation

Today, the building design process is subject to change with various factors. One of the fundamental problems is incorporating developing technologies into the praxis of architecture. The author's primary motivation is to discuss the ways of improving the efficiency of the design process, re-evaluating the architect's role in the building design process, and cultivating methodologies to contribute more effective systems in the light of these evaluations.

1.2 Research Statement

The design process does not seem to change much despite continuously developing technologies. One of the reasons for this discrepancy is that design as a process is quite conservative and traditional, regardless of the changing context. The designer's quest to find different values of the same parameters, starting from the very beginning each time, by treating each architectural problem as a particular case, cannot meet the dynamic needs of today. (Zeiler, 2019) Even in 1999, Tzortzopoulos and Formoso stated that in the architectural design process, the lack of

communication, the inability to manage the documentation process, the lack of interdisciplinary coordination, and erratic decision mechanisms made the practice of architecture more inefficient than other sectors. (Tzortzopoulos & Formoso, 1999)

Literature shows several successful solutions/approaches for specific stages of the design process. Yet, for the architectural design process, which is a relatively complex system, the studies conducted are far from holistic, rather than focusing only on specific points of the overall process.

1.3 Aim and Objectives

In light of the mentioned problems and motivation, this research proposes different models by approaching the building design process in a more holistic way. Beyond automating or optimizing only a certain point of the process, It is aimed to approach the building design process as a whole, including regulations and material limitations. Hence proposed models intend to generate building designs that may be confined to specific typologies yet precise and optimized according to given criteria. It is also attempted to show that there can be limitless models that can be constructed.

Shortly, the main objective of the research is to show that, in a system where the tasks of the different designers are specified and limited in mathematical models, the architectural design process can be more efficient.

1.4 Hypothesis

In the light of the problem mentioned above, definitions, and purpose, this research suggests that proposing different models and design methodologies that depend on the quantitative definition of the architectural design process can be an alternative way to architectural design practice that is more efficient is possible.

CHAPTER 2

LITERATURE REVIEW

According to the disposition towards the problem defined before, the literature survey has been conducted. Firstly, the chronological approaches toward architectural design are investigated. Design methods and models that several researchers propose are studied, and their rationality in today's practice is discussed. Secondly, the automation systems offered are presented. Their methodologies and aims are examined, and possible reasons why those systems cannot fully integrate into the architectural design practice are investigated. Then, according to the models presented, the importance of the definition of design problems is investigated, and the aspects of the architectural design problem in practice today are explored. The complexity of the architectural design problems and expectations of the client from an architectural service is questioned. Finally, the overall picture is evaluated according to the changes in practice, and the problems in the design process are investigated.

2.1 Design Cognition and Design Methods

The design itself is always a topic discussed and questioned by different actors. One of the endorsed ideas is that the paradigm shift in architectural design occurs due to the development and changes in society. Social, political, and economic turns affect not only the outcomes of architectural design but also the process of design itself. (Levy R. , 1981)

According to the dominant paradigms in the last century, it seems like there have always been two different approaches to the architectural design process. One of them considers the design as a black box, which says that design is individual and

cannot be described or formalized. According to traditional theorists, the design is subjective and personal. This approach toward design lets architects be free and authoritative. In that view, the design is nothing but a following in the heart. It is the individual expression of designers, and it is a holistic activity with no beginning and no end. (Terzidis, *Algorithmic Architecture*, 2006)

The other leading approach to design is taking design as a glass box where all the processes can be observed and formally described. (Bridges, 1986) It is a rational view that design follows defined steps and rules that are logical. Therefore, algorithms can be created to describe the process in that view. For instance, Terzidis states, “In design, and particular architectural design, the problem that a designer is called upon to solve can be regarded as a problem of permutations; that is a rearrangement of design elements within a set of discrete positions.” (Terzidis, *Permutation Design*, 2014)

Terzidis investigates whether the mental processes of design can be modeled with quantitative methods. He replies that as “one attitude is that design is based on the selection of finite elements” (Terzidis, *Algorithmic Architecture*, 2006). Even though those views represent the opposite and radical points, it is valid that throughout the history of design methodology, the primary paradigm had shifted between these two radical approaches.

There are other approaches exploring the design process as a cognition process. The design itself had been classified into three; routine, innovative, and creative design. (Rosenman & Gero, 1992) In that view, the main focus is on the design problem itself. In a well-defined design problem, we apply the algorithm that we already know to get what we want, and this activity can be classified as a routine design. However, in most cases, the design is ill-defined. Because new vocabulary elements can be introduced, and the desired criteria from the design are not predetermined. This ill definition of the design causes the ambiguity of the set of solutions since it cannot be separated from the description of the problem. (Mitchell, 1993) Therefore,

in most cases, architectural design is considered as a creative process that cannot be easily modeled and processed by algorithms.

It can be seen that the methodology and treatment of the architectural design processes have changed over the years. Even though there are models describing and defining the architectural design process, any of them is fully accepted and applied to the practice by most architects. On the other hand, the design is not entirely individual and subjective today. To criticize and understand today's practice within the insight of those approaches towards design, the automation systems that several researchers develop will be investigated. The methodologies and input-output relationships will be analyzed, and the possible problems why most of those systems could not be integrated with the architectural design practice are investigated.

2.2 Automation Systems in Architecture

From the early times of computerization, several researchers offered systems that attempted to generate solutions for different stages of architectural design problems. Although they are considerably different approaches, it is still possible to categorize them according to the methodology that they followed. (Grobman et al., 2010). These approaches can be outlined as follows:

- Complete enumeration is a permutation base solution that generates all possible solutions within a predefined set. (Grobman et al., 2010)
- Space allocation is the computational process that determines the position and size of different spaces in a two-dimensional layout according to the user's requirements and topological and geometrical constraints. (Shekhawat, 2015)
- Cellular automata is a system that generates cellular spaces based on defined states of the cells in a limited grid order within defined neighborhood rules. (Hoekstra, Sloot, & Kroc, 2010)

- Expert systems are knowledge-based systems. They can be categorized as a subset of artificial intelligence. They acquire the knowledge, and they have the potentials to be used in specific domains of architectural design (Karandikar, 1989)
- Case-based reasoning systems depend on finding a solution according to the cases that had been solved before. In the field of architectural design, it is aimed to take plan configurations as cases and develop a library. Therefore, previous experiences are employed to create new ones. (Dave B., 1994)
- Shape grammar, according to George Stiny, is “a set of transformation rules applied recursively to an initial form, generating new forms.” (Stiny, 1980) The system is based on a deconstruction of the shapes in pieces and discovers the syntax of the shapes to bring them together.
- Evolutionary Design is attempting to develop a theoretical basis for architecture using analogies with nature's processes of evolution and morphogenesis. (Frazer, 1995)
- Machine Learning is a type of artificial intelligence in which computers use massive amounts of data to learn how to do tasks rather than being programmed to do them. The number of research is increasing in architecture since AI is becoming a popular topic. For instance, in Stanislas Chaillou’s study, an AI was developed to learn architectural styles and generate floor plans accordingly. (Chaillou, 2020)

As it is seen, even though there are many types of research conducted for decoding/clarifying the design process and even new models for automation of the tasks, it is disappointing to see that most of those researches had been forgotten without drawing attention in the market. (Svetel et al., 2018) Most of the proposed methods seem to focus on a specific part of the design process with details, or they are focusing on the conceptual phase and do not draw lines on how the design can go further. (Austin et al., 2000)

After 40 years of work done in parametrizing the architectural design process with procedural methods, most models deal with only limited parameters in the design

process. Since all the parameters are dependent on each other and exponentially increase the number of possibilities, it isn't easy to connect those models to fully automated design relations. (Andia, 2014)

On the other hand, it is seen that each of the proposed systems focuses on a different phase of architectural design. Their required input types are different, and it is ambiguous to understand in an overall design process, for which a complete integration is vital. Each of these approaches offers excellent opportunities for designers. However, they don't describe how they can be implemented in the overall design process.

As it is mentioned, automation of the design process, even if it is in a partial stage, requires acknowledging the design process for which objectives and constraints are well-defined, either numerically or quantitatively. All systems have a level of simplification of the architectural design process. Since they all have partially or fully modeled the design process, they presume that architectural design becomes a glass box. However, despite all the works done, there is a lack of a complete model to bring them together by constructing a model that defines design stages with input-output relations and supervision systems.

“Designers use the computer only as a tool to realize that they already designed by hand and sketching. The main difficulties of defining the design process and making it accepted by the architectural society can be due to this technophobia (Mitchell, 1993)”

2.3 Changes in Definition of the Design Problem

In parallel with the advances and changes in each sector, the definition of the design tasks and demands from the client to architects are changing as well. Design tasks become more tangible and computational each day. (Terzidis, Permutation Design, 2014) The needs of a client are getting more intelligible due to the analysis methods and the amount of data available. Moreover, the tools and technologies that architects

use are developing each day. Each upgrade to those shortens the time required to prepare a proposal and automate some repetitive works. Each problem that should be tackled becomes more concrete and tangible in the architectural design process.

One of the best examples is Building Information Modelling (BIM) systems. As a result of BIM development, the design has been considered a rational and systematic process more than ever. The architectural design product has been divided into pre-defined elements, and those elements parameters, variables, and constraints are determined.

Most of the time, architectural design is performed within a limited time and budget. Therefore architects cannot evaluate the alternative designs appropriately by traditional methods. (Grobman et al., 2010) However, BIM and similar new approaches also shorten the time required to prepare a proposal for an architectural design problem and give some chance to explore more design options.

The client's definition of the design problem assigned to the architect is changing as well. The design requirements are prepared by professionals who get data from users, which weakens the architect's role in design. For instance, some firms use people's habits to order foods and analyze them to propose kitchen requirements. Moreover, social media data is used to create a profile, and the living habits of such a profile can be estimated and analyzed. Therefore, an architectural program leaves no space for the architect to consider people more.

Additionally, the primary forms can be simulated, and most profitable solutions for a mass where most of the flats have a view, for instance, can be calculated by real estate reports. Furthermore, due to the increased data from the post-occupancy evaluations, the user demands can be determined accordingly. In such a definition of the design problem, what is the role of the architect?

It can be claimed that architecture has lost power. Once, architects were seen as professionals close to god since they designed people's lives. However, it is evident that today, people demand what they desire directly from an architect, leaving no

space to argue about the design since the data can express what people desire. In 2009, a conference at Harvard University was titled “Who Cares?”. It is stated that who is the designer today, and how important are one's ideas versus the techniques provided in an increasingly digitally dominated world? (Who Cares?, 2009)

Additionally, there is research about applying lean principles to the architectural design process. The main concern of this approach is to decline the number of unnecessary works done and increase efficiency. According to this view, one of the main principles is reducing wasted cycles in design and focusing on value generation. It aims to reduce unnecessary tasks that do not provide the client value. (Freire & Alarcón, 2002). This approach has a position that failure is in the nature of the design process. Design is a process that should be managed with the same principle as manufacturers.

In consideration of those aspects, today, the design problem can be described as a well-defined process rather than an ill-defined problem. When an architectural design problem becomes well-defined, it is possible to model it and divide it into sub-phases that have determined inputs and outputs.

2.4 Critical Review of the Literature

Throughout the history of architectural design methodologies, it is mentioned that there were different attempts. However, despite all the developments both in the theory of design methods and tools that architects use, it seems like the traditional design methods are still used by most architects. CAD systems are still used as pen and paper, 3d modeling tools are developed, they are used just as mock-up models. BIM systems have emerged; they are used for documentation. So it would be reasonable to say that there are a few changes in the architectural design process. (Svetel et al., 2018)

However, as it was pointed out, the design problems have been changing. When the design problem is defined clearly and quantitatively, it can be modeled, and it can be

divided into sub-phases. Automating the overall design process from the analysis phase to construction design becomes more possible.

Architects are skeptical of new tools and technologies. The idea of design tools capable of generating buildings without an architect makes them afraid. However, the tools can only be the results of the changing paradigm. The overall design is begun to be defined with data, and the tools are developing accordingly. It seems like we are at the gate of another shift in the paradigm. T. S. Kuhn states that a paradigm shift occurs when two paradigms co-exist simultaneously. (Kuhn, 1962) Today, most architects stick with traditional methods. However, the number of research conducted about the automation of architectural design practice is increasing as well. Once again, as a result of the alteration of the definition of the design problem, a rational view towards design activity will gain power.

CHAPTER 3

MATERIALS AND METHODS

This chapter explains the methods followed in constructing the models are presented. Since different approaches have been proposed throughout the research process, general definitions in developing these models, common elements in the models, and models themselves are explained.

3.1 Research Materials

In the research process, different materials were used to develop different architectural design methodologies and thus to construct different models accordingly. First of all, architectural design is admitted as an identifiable process composed of stages, not as a subjective and indeterminate black box as stated in a part of literature, to enable the construction of novel models. Following this decision, architectural design, engineering design tools, and methods have incorporated with their potentials. (Pahl, Beitz, Feldhusen, & Grote, 2007) Accordingly, stages, tasks, and flow charts have been defined and associated.

On the basis of research, different system and tools have been used in model construction, automation, and optimization processes. Rhino Grasshopper is used for basic geometric parameterization processes. In the process of obtaining the geometric data with the Building Information Modeling system, Revit and Dynamo were used. Autodesk Forge was used to compute BIM Models and automatically create the models. Speckle and Rhino Inside were used in data flow processes. Whimsical was used in flow designs. While Galapagos is used in Grasshopper in optimization processes, Excel Solver and Google OR Tools are used in operation tools studies. For price information in models, construction unit prices tables of the year 2020 published by the Ministry of Environment and Urbanization Higher

Science Affairs Department of the Turkish Republic are taken as reference. (T.C. & Başkanlığı, 2020) As constraints in the models, typical development codes of Turkey are used. (T.C. & Başkanlığı, 2020)

3.2 Research Methods

This part of the study aims to contribute to developing a novel approach in design praxis as a response to discussions related to contemporary methods discussed in the previous chapters, which are summarized below

- Designer may disregard the individuality of the design requirements.
- Repetitive jobs are defined and done with algorithms.
- In design problems where the solution set is predictable, algorithms can generate the final product of the design by defining the boundary conditions.
- Designer is not active throughout the entire process. At certain stages, s/he is not responsible for the design itself, but the designing the system or the element within the developed system.
- In line with the user's demands, the architect defines the design boundaries, and thus optimum solutions can be searched with algorithms within the solution set defined by those boundaries,
- Inspection and control mechanisms can be made before the final product since the process takes place in a well-defined flow

3.2.1 Assumptions

Although each model follows different methods within the scope of the study, there are common decisions in model-building processes. These decisions are as follows;

- Each model might be considered as a parametrization of a single design. However, as the parametrization of geometry and spaces increases, the number of designs that

can be achieved from that model is also increased. For instance, in the figure below, you see Seagram Building in New York designed by Mies Van Der Rohe in 1958 and Villa Foscari in Venice by Andrea Palladio from 1560. Even though they are different buildings, they can be considered a geometric manipulation of a single cube on an abstract level. A cube is modified to shape the boundaries of the buildings, different division lines are defined in the plan, they meet with the proper materials, and façade elements are added as external elements. Even it is an exaggerated example, most abstractly, this approach towards architectural design is the core of each model.

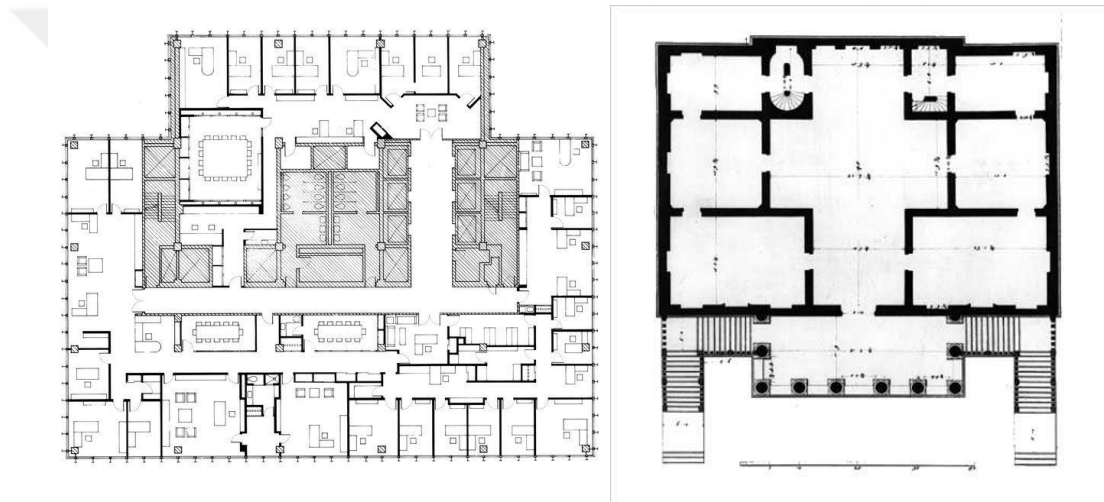


Figure 3.1. Plans of Seagram Building and Villa Foscari

- Each model follows atomic design principles. Although these systems are not specific to architectural design, they have essential and applicable suggestions for breaking up a design process. (Frost, 2013) The design process has been divided into minor parts to determine the required parameters, and the dependent and independent variables between them have been searched.
- Each model works as a microsystem. Models with defined stages contain different modules responsible for specific functions. The inputs to be received by each module, the output types, and the formats to be produced are defined. The whole

system consists of the continuity of these modules. All modules automatically generate their output as long as the input data standards are met.

- Each model is customized for building groups serving a specific purpose. Due to their content, models are developed to address the defined problems of particular functions, such as dwelling complexes or office buildings.

3.2.2 Meta Design

Meta-design can simply be described as designing the design. The Greek word “meta” in that sense refers to passing beyond what is implied. Therefore, meta-design is a process that redesigns the design. The idea of meta-design acknowledges that future uses and problems cannot be completely anticipated at design time. To achieve the models that were described, a meta-design process should be structured. Gerhard Fischer and Eric Scharff, in their paper named “Meta-Design: Design for Designers” explained the process and constructed several roles. These definitions are influenced while determining the roles in the architectural design models. (Fischer & Scharff, 2000)

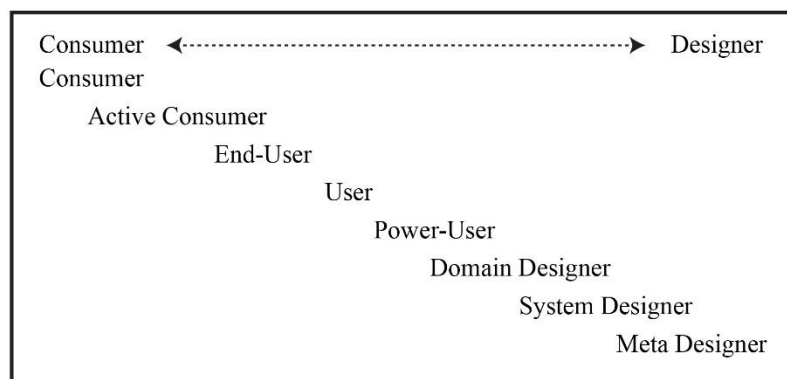


Figure 3.2. Multiple roles in the consumer/designer spectrum, Source: (Fischer & Scharff, 2000)

Accordingly, in all the models, the roles are specified. Moreover, the types of flow of information in any part of the models are categorized. Finally, after determining

the roles and flows, the elements of the model and hierarchies are constructed in the meta-design process.

3.2.2.1 Roles in the Models

As mentioned, the models will serve to different designer profiles. There will be different roles in the construction and use of models to insinuate the fragmentation and reconstruction of the design process within a specific system and the integration of automation and optimization systems in this editing process. These roles are explained below.

- Designer 1: S/he is the one who designs the system. Within the scope of the research, instead of proposing a fixed model, the potentials of designing “any” model are investigated. Accordingly, a designer identity will create this model, define the parameters, determine the model's boundaries, decide the set that the system can produce, and develop the tools of this model.
- Designer 2: S/he is the one who designs the elements in the system. All models contain fixed design elements of different scales, whether from the product class of only some manufacturers or the design of an entire flat. This role of designer fulfills the task of designing, modeling, and making the elements used by the models.
- Designer 3: S/he is the end product designer. It is the end-user of the models developed. S/he is not taking a role in the development of the models. S/he is the one who uses the model. S/he searches for the optimum solutions to the problem within the model by using the system in line with certain design stages.

Therefore, by referring to Gerhard Fischer and Eric Scharff's paper, the roles are re-categorized as visualized in the figure below. While explaining each model, these definitions will be used, with already described role definitions.

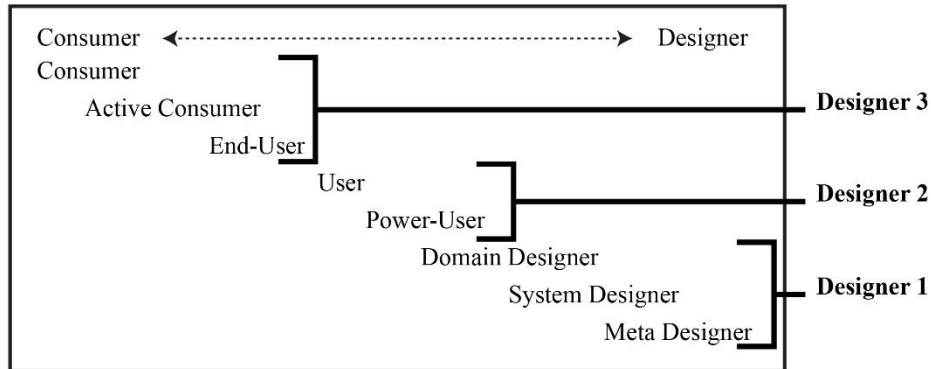


Figure 3.3. Recategorize the multiple roles in the consumer/designer spectrum,
Source: (Fischer & Scharff, 2000)

3.2.2.2 Element Hierarchies in the Models

Classification of the building components has always been a topic of interest in various fields. Different methodologies are proposed to categorize and handle the complex structure of building design. In most cases, a tree structure that classifies the components and constructs a hierarchy among them is the primary method.

For instance, ASTM Unifomat II Classification for Building Elements (Charette & Marshall, 1999) defines three hierarchy levels. Level 1 is major group elements such as shells or interiors. Level 2 is group elements under major group categories such as stairs or roofing. The final categorization is the level 3 group which is individual elements. For instance, stair finishes or roof coverings belong to that category.

One other example is from “A Conceptual Framework for Classification of Construction Work.” (Ekholm, 1996) The main aim is to develop ISO Technical Report 14177 further so that it can be included socio-technical aspects and technical parties.

One more example is the classification of the building components for BIM. (Ekholm & Häggström, 2011) The main aim of that paper is to develop ISO 12006-2 standards further to include building management via BIM.

As it can be seen, the categorization of the building parts is purpose-oriented. The classification aims not to develop an ideal categorization rather a classification created under the aim of the research. In the scope of this research, to construct a model described, categorization of building components and putting them in a hierarchy is essential. Accordingly, main categories are defined according to the complexity and number of elements or types of any group. Accordingly, from lowest level to higher ones;

- **Product:** a single product designed, modeled, and parametrized. For instance, with its material's specific dimensions and other related information, a single wall is a product in all the models.
- **Element:** a group of products that defines a single "space." For instance, a single room is defined by-products. A room with all its products, dimensions, and other documentation information is classified as an element.
- **Element Group:** a group of spaces that defines a specific building function. For instance, a flat or group of offices that represents a single function together can be described as an element group.
- **Organism:** a group of spaces that is a combination of different building functions in a way to define a specific boundary for the overall building design. For example, a storey of housing with all of its flats, circulation units, etc., defines an organism that can merge with other organisms in a specific way.
- **Structure:** a functional building that is a complete structure with a defined relationship with other structures. For instance, a housing block that is complete, however, can be duplicated, it can have common spaces in the basement, or it can be reoriented in the site defines a structure.

3.2.3 Universal Set, Design Set, and Purpose Set in Models

Fitting the design process to a model means reducing an infinitely converging set of problem solutions to a large but limited number that varies according to the model. There are a limited number of alternatives that each model can produce according to the values that all parameters can take. This set defines the universal set for that model. Within the universal set, there is a smaller set of solutions that can meet the numerically defined constraints of the design problem. This set will be called the design set. This set contains all the universal set elements that do not meet all requirements but fall between specific threshold values in line with any design problem. Finally, a set containing quasi-optimal solutions is defined as a purpose set in the models.

These cluster definitions will play an essential role in the processing system of all models because the fundamental success criteria of the models will be the relationships between these clusters.

3.2.4 Model Evaluation Criteria

It is essential to point out that models proposed here are not defined at the beginning of the research and constructed afterward. Models have been developed and evaluated sequentially, and then each model has been obtained in line with the evaluations of previous models.

3.2.5 Summary of the Models

Before explaining each model, the brief methodologies they follow are described in the figure below. The different roles, element hierarchy, and sets of the models are shown there. After, each model's methodology is explained in detail in the following chapter.

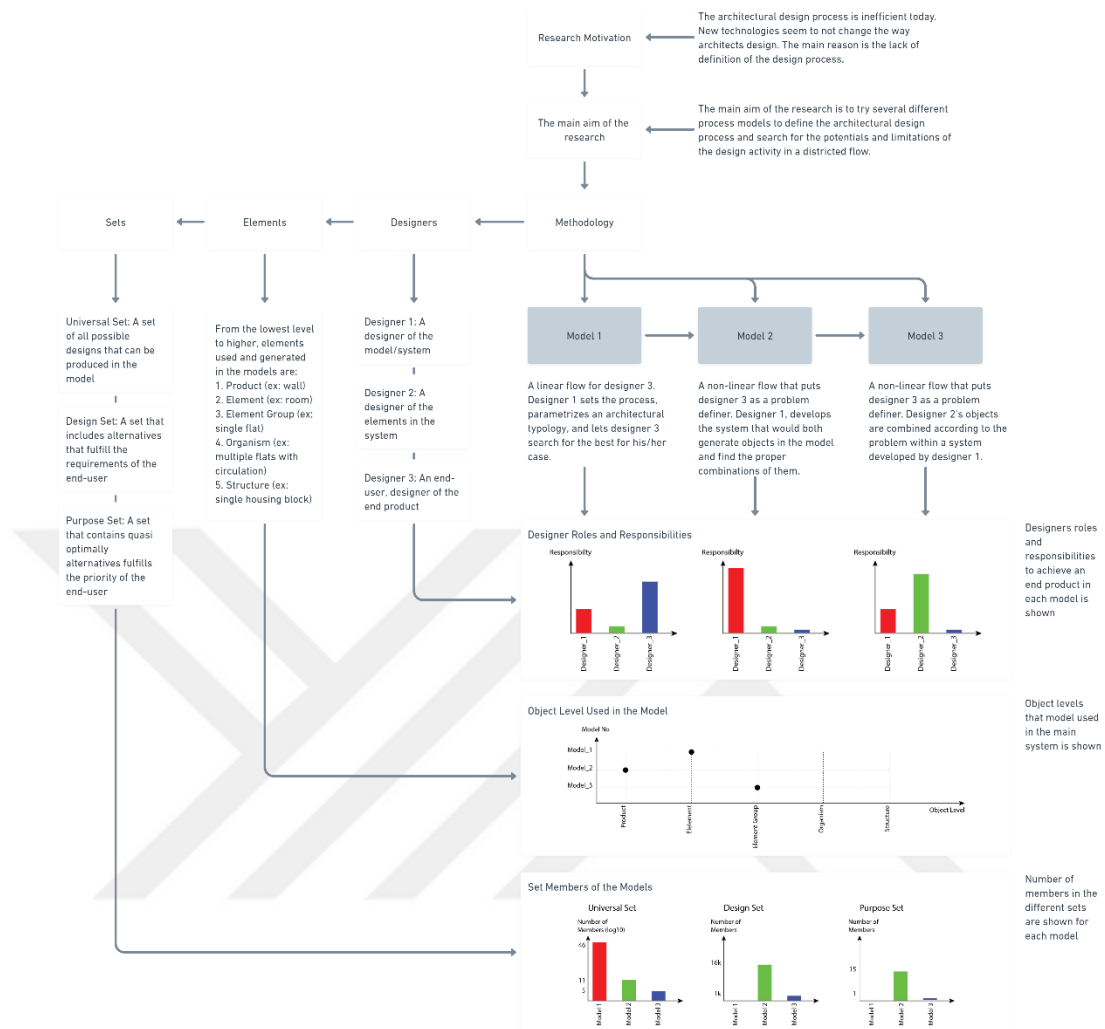


Figure 3.4. Model comparison and their methods

CHAPTER 4

PROPOSED MODELS

4.1 Model 1

Model 1 defines a design process in which a building design is fully parameterized, and alternative structures can be produced within the given parameter limits. The system is broken down into the design stages. When this fragmentation is followed linearly, a method is formed to generate an architectural design in line with the problem definition. Within this model, algorithms respond according to designer 3's parameter selections. Algorithms do not set the parameters. It is designer 3 who determines the design. Accordingly, designer 3 has to use the model as a design tool.

The following steps are applied in the model description. First, the construction process of the model is narrated, and the definition of meta-design for model 1 is clarified. The role definitions and control mechanisms for that model are confirmed. Afterward, the production dynamics are explained according to the hierarchical status of the elements in the model. Finally, instead of explaining the model theoretically, it is concretized over an example scenario developed. Tests will be made in line with that scenario, and lastly, results will be evaluated. The potentials and disadvantages of the model are discussed.

4.1.1 Methodology

The model begins with designer 1's general non-case-specific architectural problem description. This description can be a linear office block or a residential block with a courtyard scheme. At this stage, designer 1 defines the model boundaries. Within the methodology of model 1, the design process is fragmented. This fragmentation is designer 1's subjective approach. Accordingly, specific, independent process

models can be defined. Following this definition, designer 1 describes designer 3's data to control.

After defining the relationships between those parameters, the system is created by the parameters specified. Designer 1 decides on the model elements that will be produced instantaneously in the system, which will be formed according to the designer's 3 inputs. Subsequently, together with the data of designer 3 and the library elements created by designer 2, algorithms are developed to transform the system to generate geometric outputs during the defined process. The simplified approach of the model is shown in the figures below.

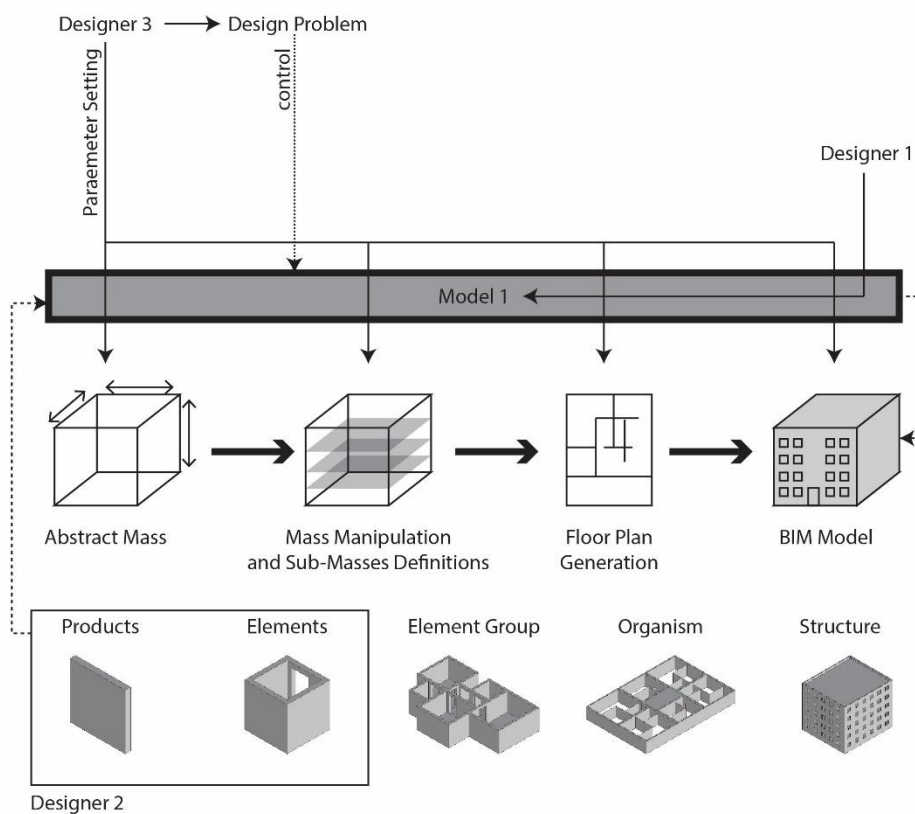


Figure 4.1. Process diagram of the Model 1

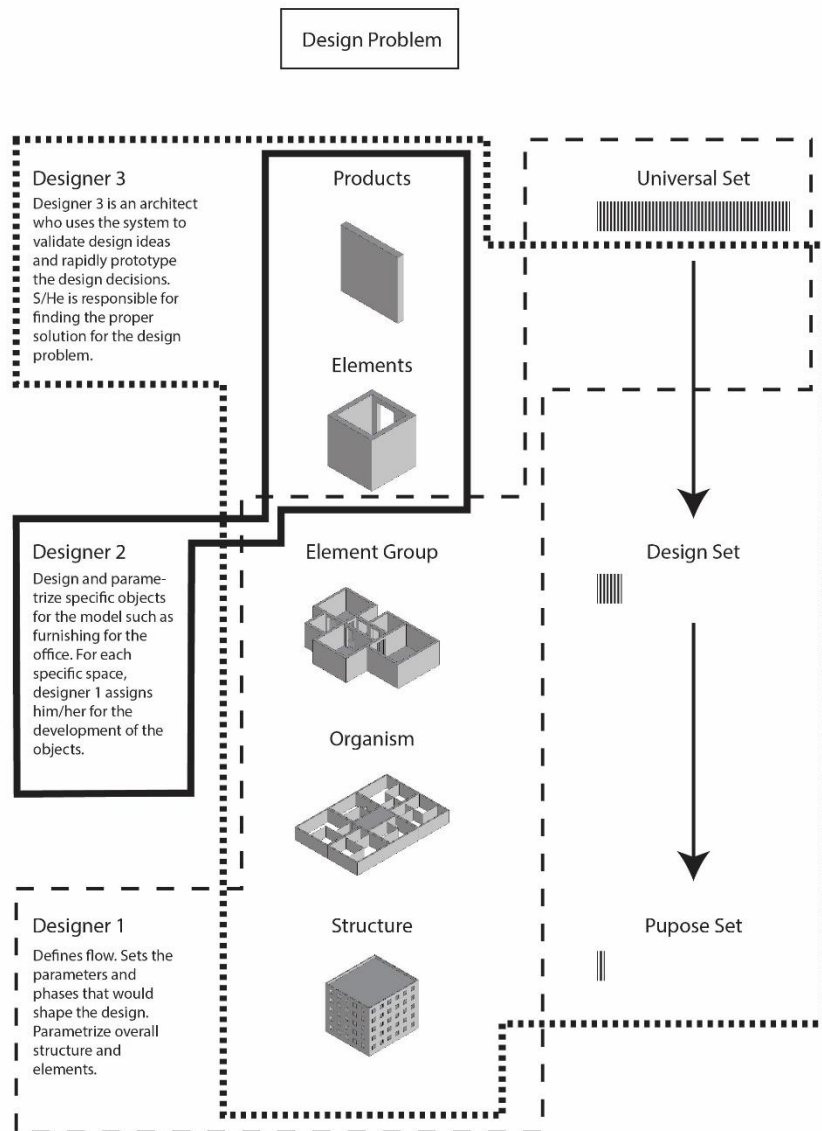


Figure 4.2. Model diagram of Model 1

As understood in the figures above, designer 1 develops the model where the designer 3 sets parameters to design. S/he develops the system in which the universal set is defined as well. The reduction of the universal set to the design set in relation with the purpose, is designer 3's responsible. By following the linear process and setting different parameters in the models, from a single abstract geometry, designer 3 reaches the completed BIM model with elements designed by designer 2.

Here a case model exemplifying the methodology mentioned above has been developed to produce a linear office block using the proposed systematic. Model 1 will be explained over this case.

4.1.1.1 Process Definition

The proposed model fragments the design process as shown in the figure below. Stages include land analysis and program definition, mass formation and placement, circulation setup, mass articulation, structural design, regional definitions, room definitions, furnishing, and facade design. Each of these is explained in detail with its parameters, variables, and constants. The detailed version of the flow diagram can be found in the appendixes.

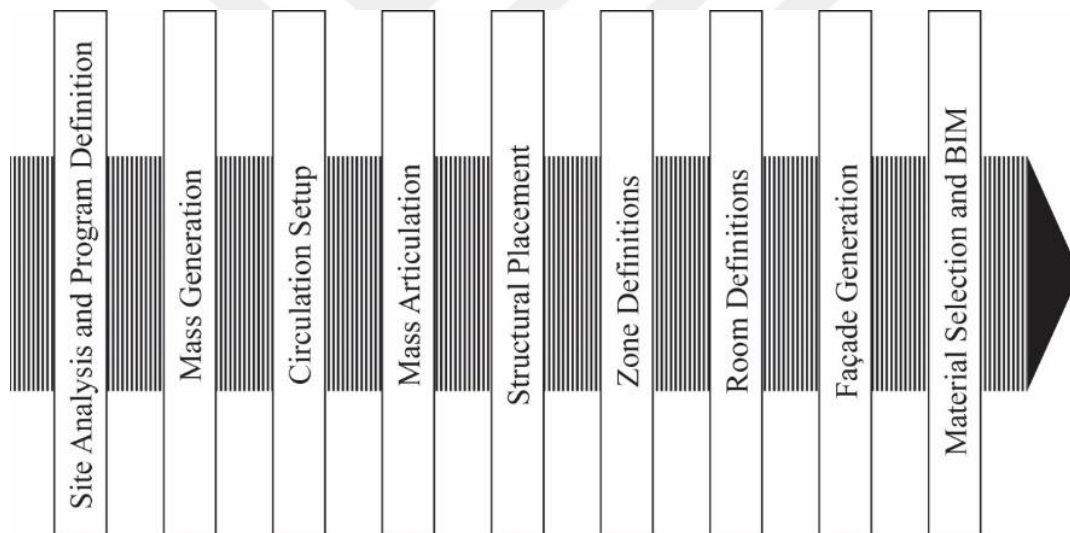


Figure 4.3. Linear process definition of the Model 1

- **Site Analysis and Program Definition:** The user (Designer 3) defines the problem. It represents the numerical constraints of the land, such as the dimensions and the distance of pull. Subsequently, the total construction area is specified. Related calculations about the potentials and limitations of the site are shown to the user. Then, the system calculates the mass alternatives

that can provide the specified area under the land constraints following a grid structure. Designer 3 selects masses that converge to the specified site.

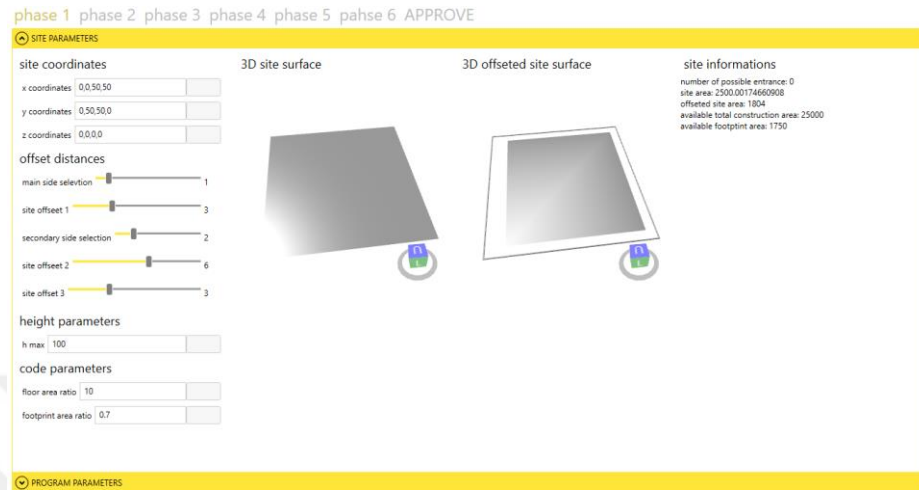


Figure 4.4. User Interface, A designer enter the inputs about the site, and the algorithm calculates and shows the results

- Mass Generation:** Masses are generated after the user determines the total construction area according to the site boundaries and desired floor area. The user (Designer 3) selects one. After the user chooses the specific building, requirements, and dimensions such as typical floor height, staircase type, or mechanical system for ventilation, the system analyses the proposed mass accordingly. The basic information about the building is calculated and shown in Figure 4.4. Afterward, the user revises the mass according to the information about the structure shown in real-time, as given in Figure 4.5. In the calculation process, the requirement of the several spaces, Planned Areas Zoning Regulations by Environment and Urban Ministry of Turkish Republic is used. (2017)

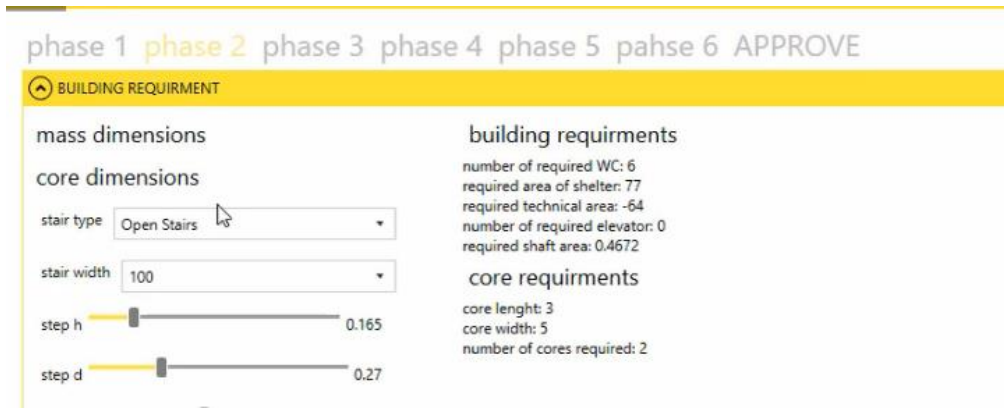


Figure 4.5. User Interface, A designer specifies several aspects of the building, and the system calculates related information

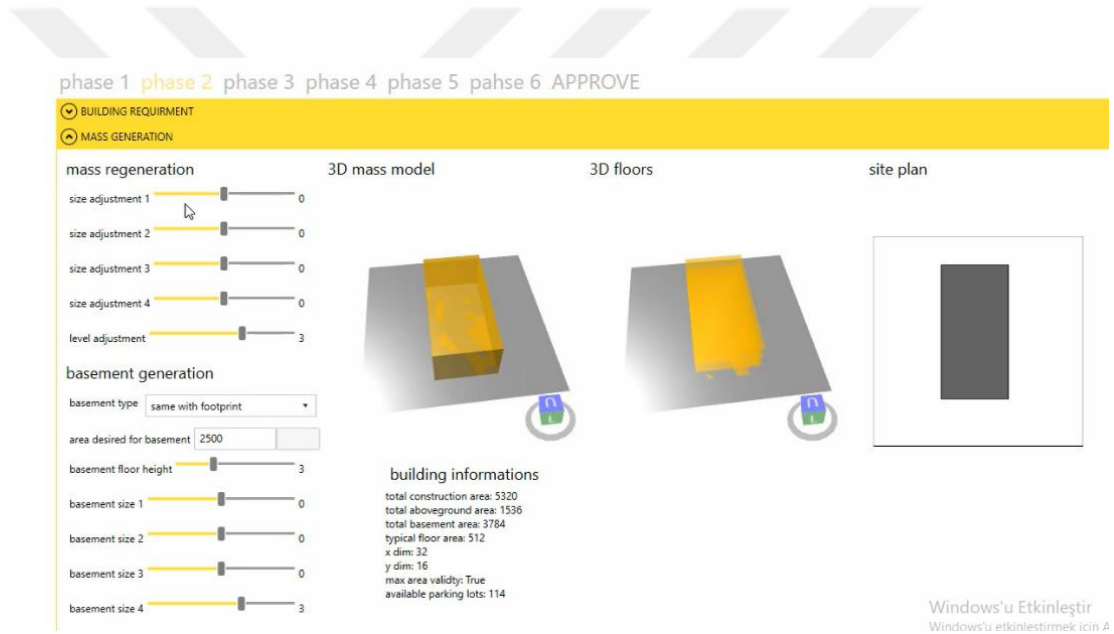


Figure 4.6. User Interface, A designer, determines the mass dimensions and sees the results accordingly

- **Circulation Setup:** In the next step, designer 3 defines the circulation elements and setup. It describes the location of the cores in the mass, the load of the corridor, and the circulation routes. The algorithm places the circulation elements in line with the definitions. The corridor areas are defined, and the spaces other than the corridor area are listed separately as

functional spaces. In this process, related regulations about fire escape codes are considered.

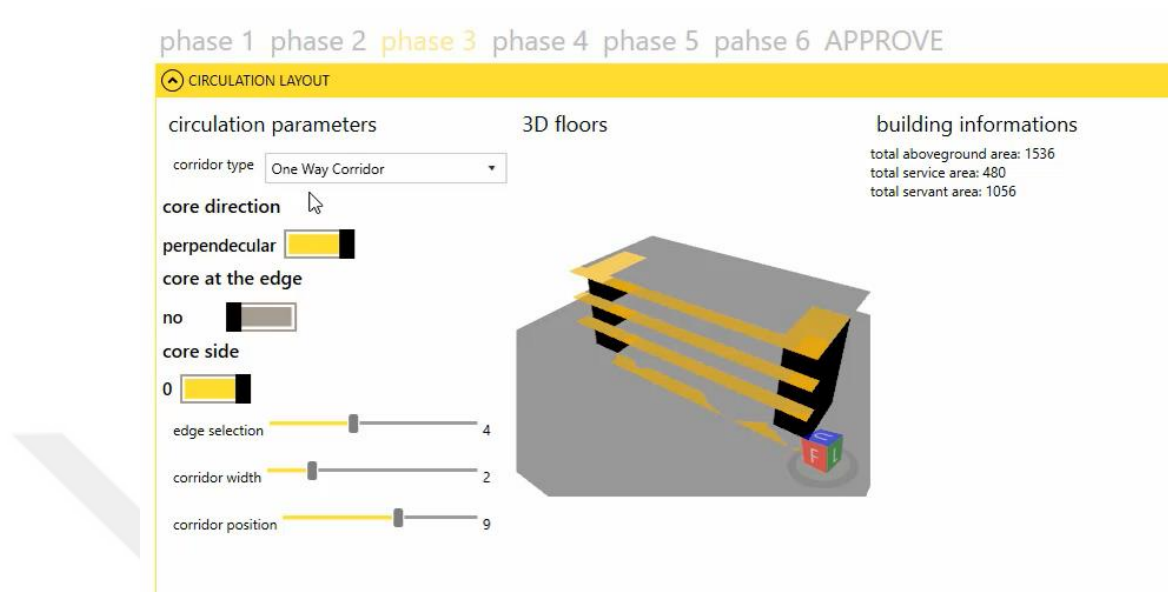


Figure 4.7. User Interface, Designer, determines the circulation types and observes the outcome areas of the decisions

- Mass Articulation:** After the circulation, set up within the general mass, is finalized in terms of content and quantity, designer 3 can articulate the mass in a list of functional spaces. S/he does this by adding or subtracting mass forms to the overall assembly. In this process, designer 3 only decides on the dimensions and position of the mass. As shown in the figure below, the system checks the spatial, regulatory, and technical conditions that will change with the specified process.

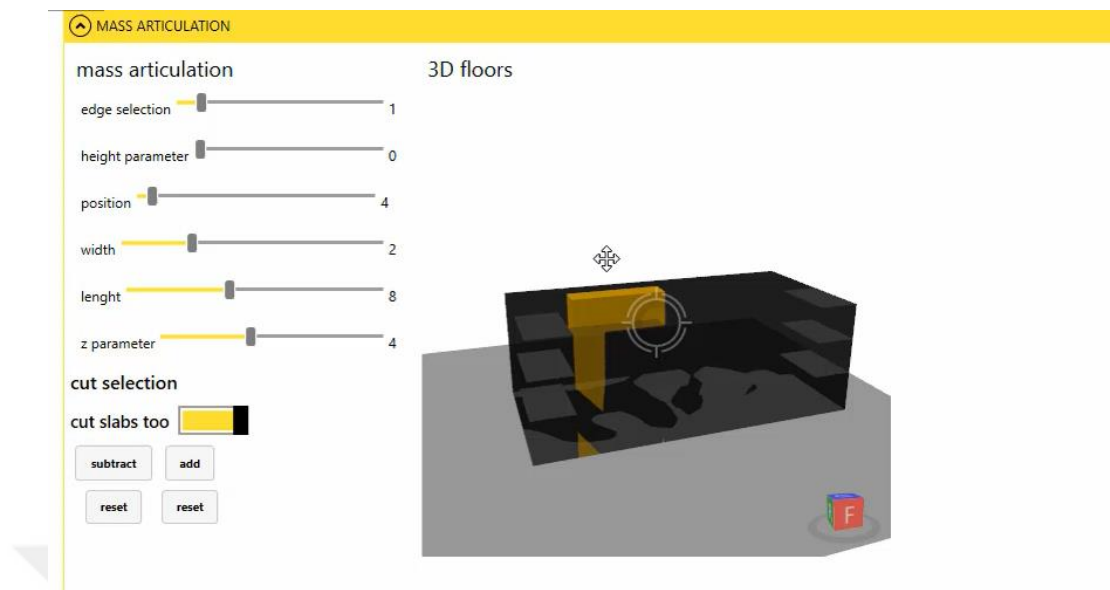


Figure 4.8. User Interface, Designer, add or subtract a mass in selected dimensions and positions

- Structural Placement:** The structural placement phase begins after the mass is finalized and the circulation elements are defined. At this point, the user specifies the maximum range within the design that structural axes can span. The system will have the least number of axes within the specified range in line with several experiments made by starting from an arbitrary root, following the initially defined grid system, according to the conditions where the axis is defined on at least one side of the core elements. In this way, a layout is created in which the core circumferences correspond to the shear wall and the column diagrams of the intersecting axes. Subsequently, the thickness and properties of the structural elements calculated according to basic methods that are used for pre-calculation of the concrete structure described by Souza are defined. (2020, Souza)

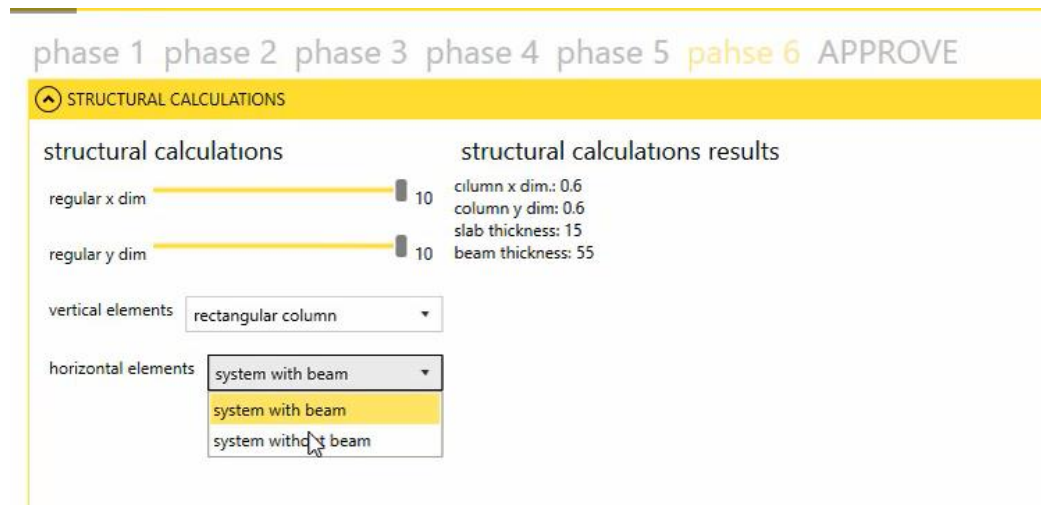


Figure 4.9. User interface, Designer 3 determines the properties of the structural elements and sees the results.

- Zone Definitions:** At the next stage, the sub-spaces are defined within the spaces leftover areas from the circulation layout. At this point, wet areas are decided first. Designer 3 defines the point of access to the wet spaces through the corridor. Subsequently, the system calculates the wet volume areas that should be present on the floors accordingly. The wet areas are generated automatically by algorithms that are developed by Designer 2 with all its elements, together with the shafts and all the furniture.

After placing the wet areas in the remaining spaces, the user divides each zone into sub-elements by following the zones sequentially. In this division process, designer 3 determines which grid point to divide in each region. In the end, a draft model is obtained, where the boundaries of all spaces are defined for floor plans.

During all these processes, designer 3 can experience the process through the interface with specific tables, areas, etc., of the design s/he, made simultaneously.

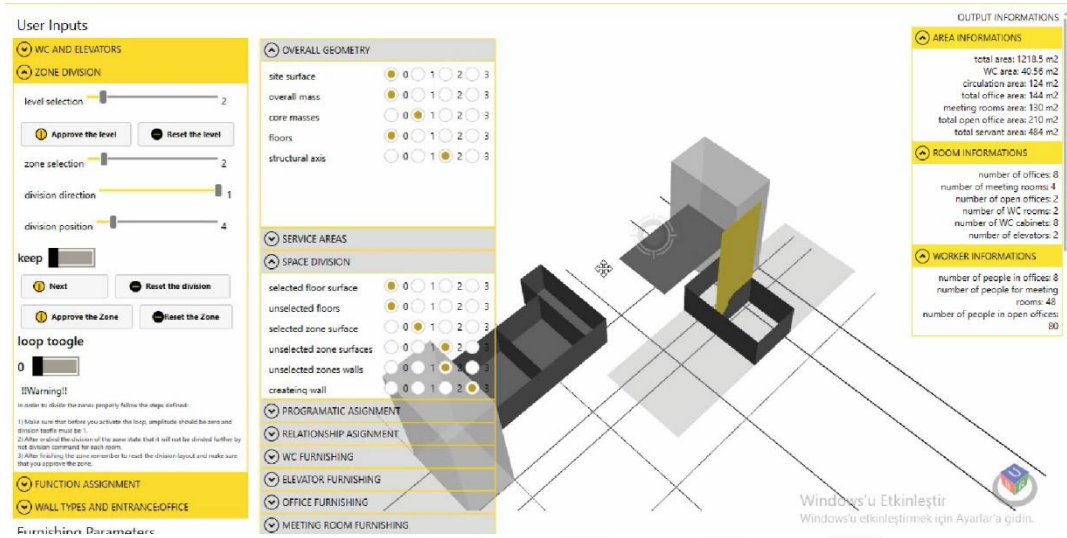


Figure 4.10. User Interface, Designer divides each zone into rooms.

Determine the function for them and observe the results in real-time

- Room Definitions:** Within defined boundaries, designer 3 chooses one of the functions for the rooms that are defined, prepared, systemized, and automated by designer 2. The suitability of this function to the specified room is tested. In case there is no problem, designer 3 chooses the edges of the space for the room to get its access. Subsequently, the algorithms defined by designer 2 place the room's furnishing and door elements. At the end of this stage, all architectural element definitions for each place in the building are made.

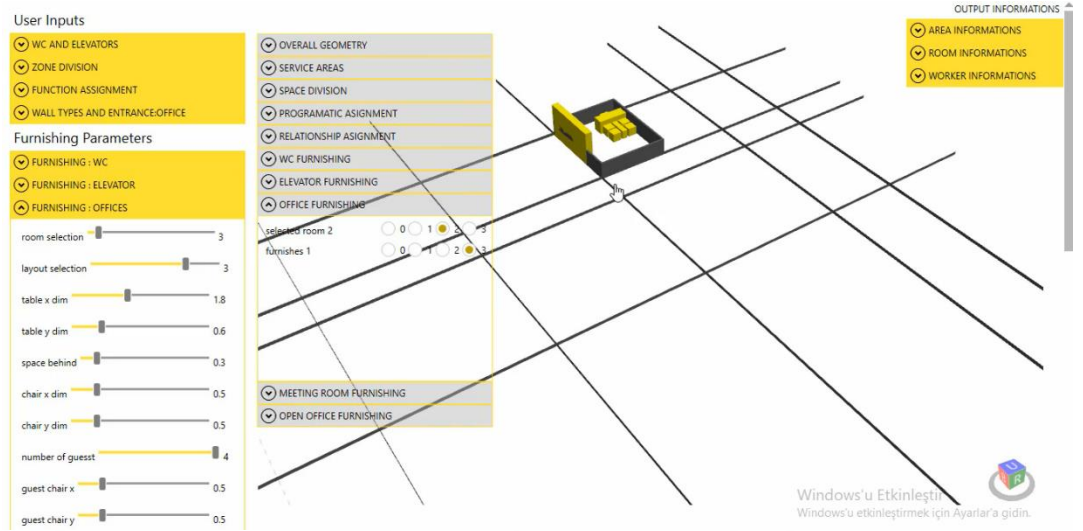


Figure 4.11. User Interface, designer select furnishes and the element according to the selected function

- Façade Generation:** After assigning the function for all the spaces, the facade surfaces of each room are categorized in separate lists. Accordingly, designer 3 organizes those lists in line with design decisions. S/he determines the functions that will have the same façade systems that are developed, designed, and parametrized by designer 2 and merge their lists. Then the system applies the façade elements to the specified lists, and designer 3 can control the parameters for different façade design methods.

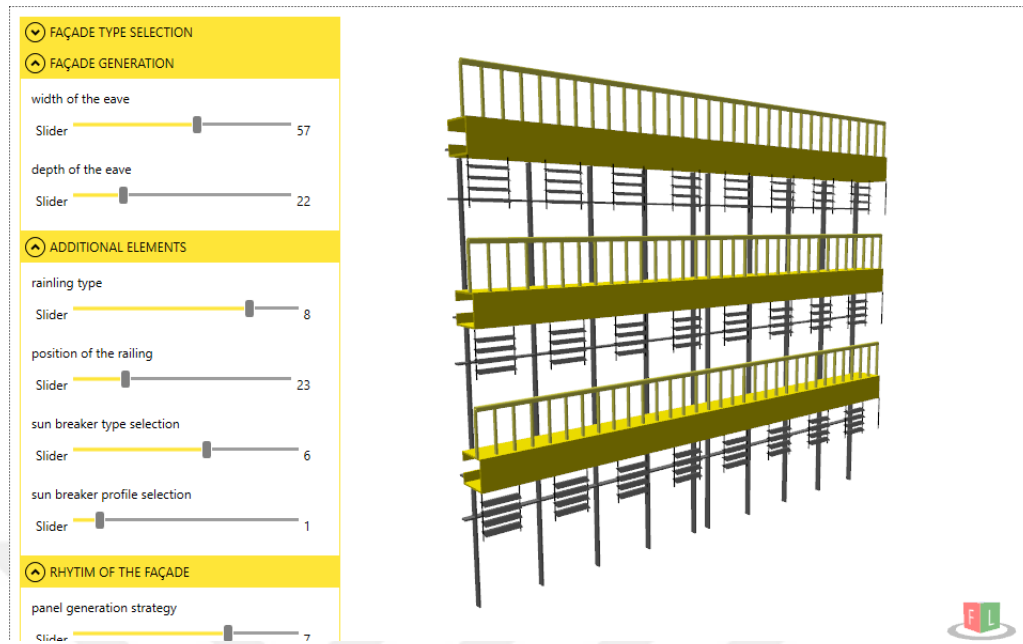


Figure 4.12. User Interface, the designer determines the available parameters for a specific type of space

- Material Selection and BIM:** After the design is made for the whole structure, designer 3 defines his selections among the product and material elements, designed and developed by designer 2. The user can compare the cost for different material selections at this stage. After selecting the materials, all the decisions and generated geometries are sent to Autodesk Revit, and they match with specific families developed by designer 2. Finally, designer 3 can achieve a BIM model for the specific design problem.

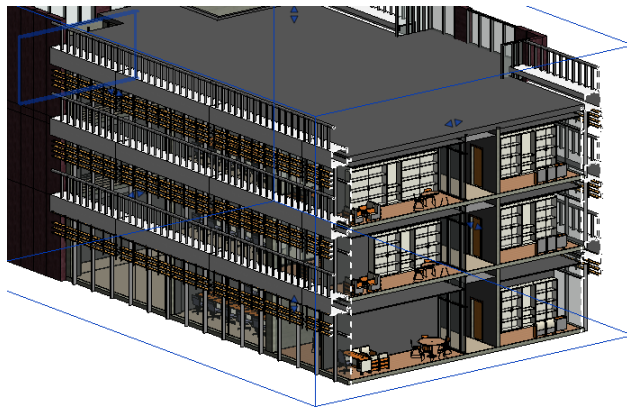


Figure 4.13. Example Revit model produced by the Model 1

4.1.1.2 Designer's Roles

In model 1, it can be observed that different designer roles have specific roles in the model. Accordingly, designer 1 is responsible for the definition of the system. S/he defines the linear design process. Afterward, s/he describes each step with its parameters and variables. The inputs and the outputs of every phase are determined by designer 1.

Moreover, a critical role of designer 1 is to assign to designer 2 what algorithms, models, and drawings should be produced for designer 3 to use. In this context, designer 2 is responsible for the assigned task by designer 1. Designer 2 does not necessarily know the overall process. S/he is accountable for developing algorithms, models, and drawings that will be used for the general model. For instance, in the example given, designer 2 is responsible for developing an algorithm that will automatically place an office layout and call the proper office furniture model according to that layout. Therefore, as long as given input type and expected output results are defined, designer 2 is interested in only a limited part of the overall building design. In contrast, designer 1 is responsible for determining what to assign and expect from designer 2.

On the other hand, in model 1, designer 3 is responsible for the overall design process of the building. The model developed by designer 1 offers a method that limits the possible solution for any design problem. However, it is designer 3's responsibility to achieve the proper design in that limited set but still quite large. Therefore, designer 3 is the one who sets the parameters, changes the variables until s/he reaches a proper/targeted solution for the design problem.

4.1.1.3 Model Hierarchies

First of all, the critical decision about model 1 is that it begins with a mass, and the method is dividing it and manipulating it in several ways. Therefore, instead of a tectonic approach where the overall design is shaped by getting elements together, the proposed approach can be considered as a stereotomy as the base method of defining the overall strategy. On the other hand, this model let the overall design emerge in two different ways. Firstly, as a starting point, it takes a mass while always considering the relationship with the spaces and the "elements" that would be merging with. For instance, while spaces are divided into rooms in the model as a specific function, an algorithm controls if the predefined elements can generate the defined space. Secondly, even the starting point is a mass, products, elements, and element groups are already modeled and defined with their constraints. Therefore, the model is finding an intermediate point from bottom to up and up to bottom. A more precise expression, model 1 is about manually finding an optimum interface with overall building mass and a bulk model with limited, defined, and constrained elements.

4.1.1.4 Tools and Technologies

In model 1, Rhino Grasshopper is used to parametrize the geometries. For generating the user interface, a grasshopper plug-in Human UI is used. For BIM integration,

Revit Dynamo and Speckle for Grasshopper and Speckle for Dynamo are implemented for the information transfer.

4.1.1.5 Flow of Information

The flow of information in model 1, as was mentioned, is a linear process. The detailed flow diagram can be found in appendix A. Here, the flow will be summarized.

As mentioned, the design process will be divided into several stages. For instance, RIBA had defined several stages for the architectural design process and flow of information. (Sinclair, 2019) Here under, the design process had been divided into phases such as mass definitions, circulation layout definitions, etc. There are definitions of stages that determine the sort of documentation or information to be delivered or required.

Moreover, in each phase, all the process components will also be divided into more sub-components to simplify the tasks and make it possible to identify all the parameters that affect all the small tasks. Therefore, the overall design process is defined as a tree structure where the parameters in the smallest branches will define the overall structure.

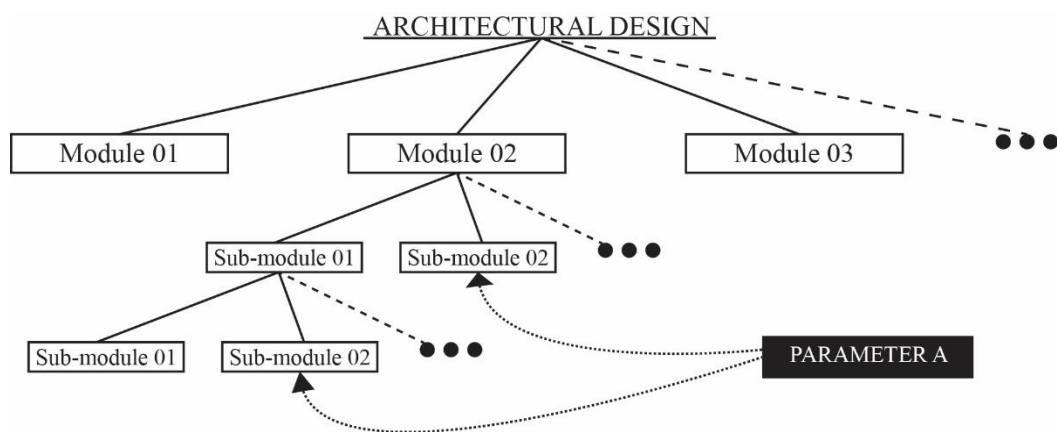


Figure 4.14. Diagram of the modular definition of the model

In order to have a continuous process in the flow of information among the modules, there are several criteria that each of the modules of the design should fulfill. First of all, all the modules are domain-specific. A module can contain several different sub-modules. However, each module has a specific task with defined and limited inputs. Types of the data that modules receive and deliver to the other modules are defined. Secondly, all of the modules generate outputs automatically. It means that results are generated without human interaction. Human interaction can exist only in the definition of the inputs or selection from the generated set of output results. For instance, if a module is responsible for the modularization of the façade, the only human interaction can be the definition of the ruleset of the division of the façade. Finally, all the modules in the model are independent. As long as they receive the data required, they can generate the output regardless of the rest of the process.

All of the modules, their sub-modules, examples of the parameters asked from the designers, and parameters defined by other modules as input are defined in the model. However, because of the complexity of the system, the list is simplified by selecting only several sub-modules and their inputs. (Table 4.1)

The larger-scale relation between the modules can be found in appendixes. On the other hand, how the modules are working in themselves as an encapsulated structure is exemplified in figure 4.15 below.

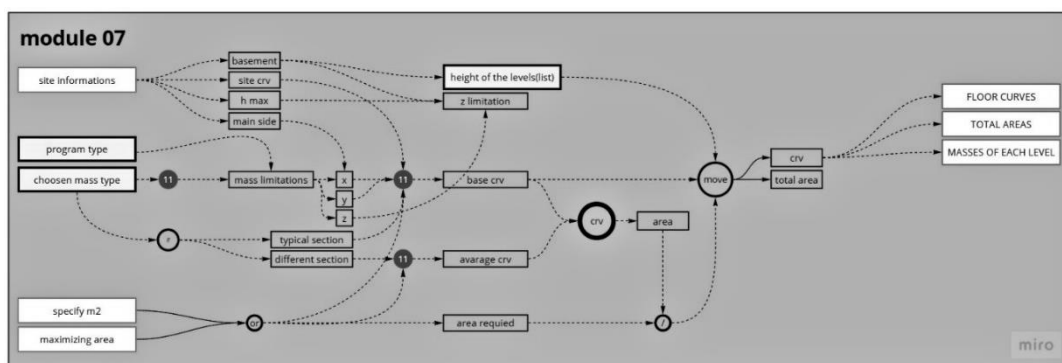


Figure 4.16. The example process of module no:07

Table 4.2 Some Modules and Their Input-Output Relations

Name of the Module	Name of the Sub-modules	Example User Input	Example Input from other modules	Example Output	Library Condition
Site Analysis	Geographical Analysis	Site Srf.		Placeable Areas	
	Code Analysis	F.A.R.	Site crv	Available Area	
Brief	Program	Number of Element	Program Type	Total Number	
	Budget	Number			
	Technical Req.	Yes/No		Technical Area	
Mass Generation	Program Categorizer	One way Corridor	Mass crv	Corridor Geometry	
	Site Placement	Ratio of open park	Site crv, Mass crv	Parking Zones	
	Scheme Selection	Scheme C	Mass crv	Zone Areas	
	Scheme Modifier	Dim X	Axis crv	New Mass Brep.	
Plan Generation	Plan Strategy	Strategy A	Boundry crv	Plan Zone crv	
	Plan Selection	Plan 53	Boundry crv	Plan crv.	
	Plan Modification	Y Dim	Axis crv	New Plan crv.	
Structure Generation	Calculations	Max. Span		Beam Thickness	
	System Selection	Concrete Frame		Column pt.	
	System Modification	Reinforcement Sel.	Calculations	Detail Drawing	
Furnishing	Content Selection	Living Room	Boundry crv	Room Crv.	
	Placement Selection	Type 3	Boundry crv	Object Base pt.	
	Object Selection	Object Selections	Dim. of Object	Object Assignment	
Electrical Project Generation	Calculations		pt. of sockets	Electrical Load	
	System Distribution		Boundry crv	Cable crv.	
Façade Generation	Strategy Selection	According to Function	mass brep	Sets of mass srf.	
	Mass Selection	Scheme 08	mass brep	Sets of façade crv.	
	Element Selection	Elemet 03,11,57	façade crv.s	Sets of Element crv	
	Distribution Selection	Randomize	furnishing placemen	Set of structured crv.	
Mechanical Project Generatino	Calculations	Insolation Selection	number from codes		
	System Selection	Air Conditioning	Calculations	Height of the storeys	
	System Distribution		Calculations	Plumbing crv.	
Landscape Design	Strategy Selection	Strategy A	Site crv.		
	Layout Selection	Layout 03	Mass crv	Layout crv.	
	Customisation	Density of Greenery	Site crv.	Pt. of Objects.	
Materialization	Material Selection	Composite Cladding		BIM Model	
	Manufacturer	XXX		BIM Model	

4.1.2 Test of the Model

As it was explained, the model method is developed for an office building. An imaginary site is generated to apply the model in the testing process, and the design stages are followed accordingly. At the end of the test, a BIM model is completed. In the testing process, the researcher act as the designer 3. He developed predesign decisions and applied them in the model's design decisions. The initial design decision can be seen in the figure below.

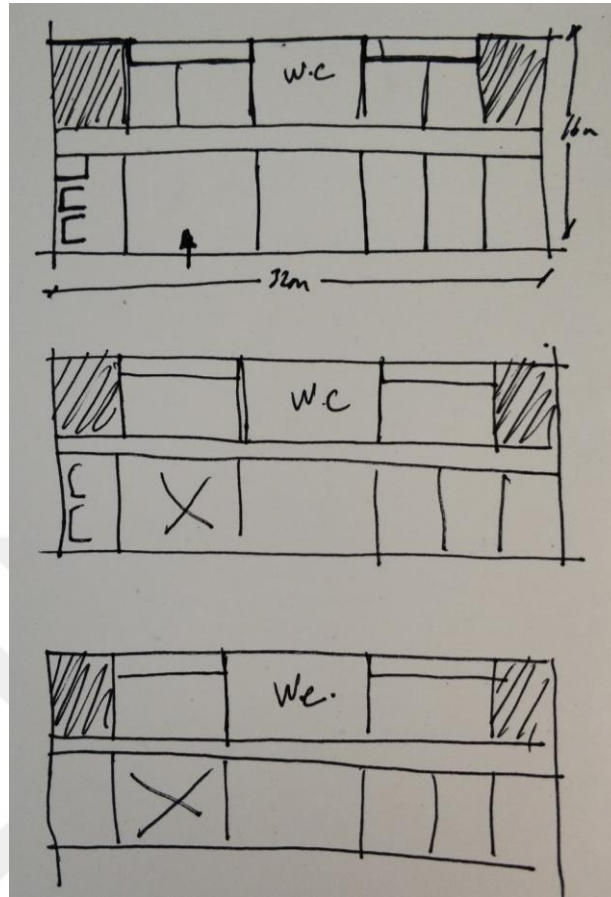


Figure 4.17. A predesign sketches to test the model

After following the defined steps, A model of the predesign building is realized by minor changes due to the development level of the design and limitations of the model. Finally, a BIM model of the design, with the required tables, drawings, and information, is prepared automatically only within 10 minutes.

4.1.3 Results and Evaluations

After testing the model, the evaluation of the model is conducted. Firstly, the potentials of the model are explained. Then, the limitations and the errors of the model are discussed. Finally, what can be done further to develop the model will be investigated.

4.1.3.1 Potentials

Model 1, as tested before, can work properly in a well-defined problem with an expected outcome. For instance, in the tested case, a sketch describes such a building even though it is still a fuzzy description. Therefore, model 1 can be understood as a tool that can test the predesign solutions within only minutes as a rapid prototyping tool. Furthermore, the model can be applied to different design problems if the design problem can be categorized in the same class. Therefore, this potential makes the model useful where the design problem is generic, and the expectation from the design is proper for the defined methodology.

4.1.3.2 Limitations

Besides the potential of the model, there are also limitations and disadvantages. The model cannot generate in a stand-alone way; it needs an operator who should be an expert. It should not be considered as a complete design tool either. Because it limits the designer in a way that the designer can only design with other tools and use the model to test predesign decisions concretely. Moreover, due to the linear structure of the model, the control mechanisms and dependencies of the parameters may result in precision and accuracy problems. Designer 3 may not fully anticipate the effects of the design decisions in the further phases.

4.2 Model 2

Studies conducted within the scope of Model 1 have shown that a methodology followed in this context has limitations and potentials. In this context, the researcher has developed another method. This model's primary motivation is to build designer 2's tasks with generative algorithms and perform designer 3 tasks with optimization tools. In this direction, it aims to expand the possible solution set considerably by

constructing a model more abstractly. Instead of dividing a mass into subspaces, subspaces are combined to generate the mass in this model.

4.2.1 Methodology

Within the model's scope, like model 1, firstly, the model's design process and process steps are to be explained and discussed more comprehensively by describing through flow charts, data exchanges, and algorithm tasks. The simplified process of the model is shown in the figures below.

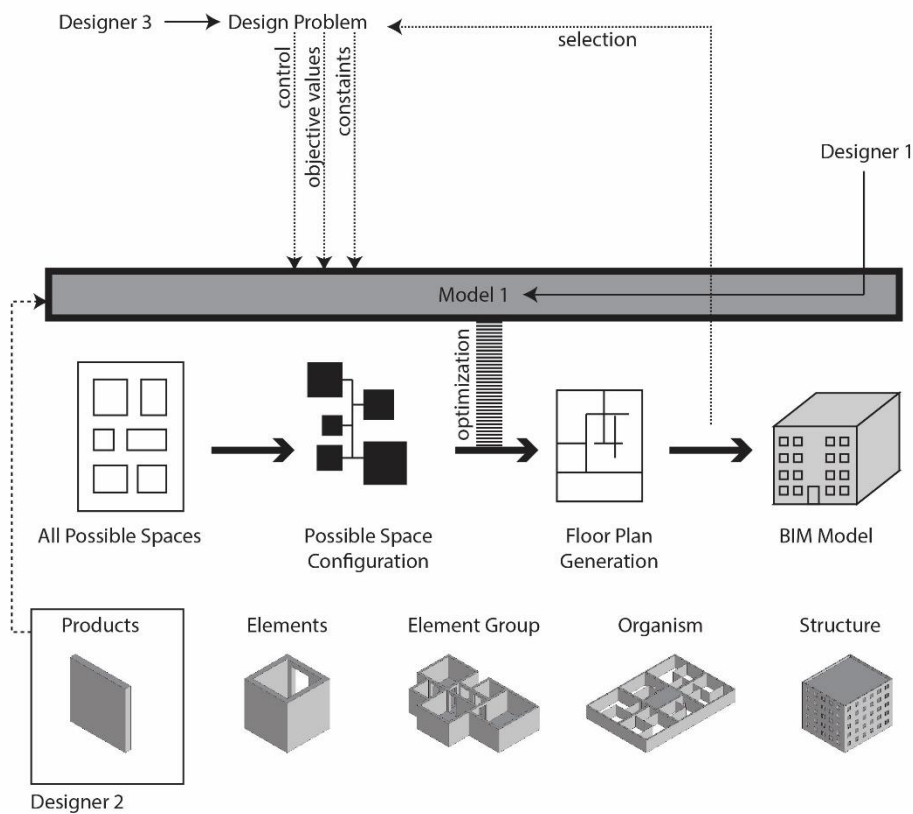


Figure 4.18. Process diagram of the Model 2

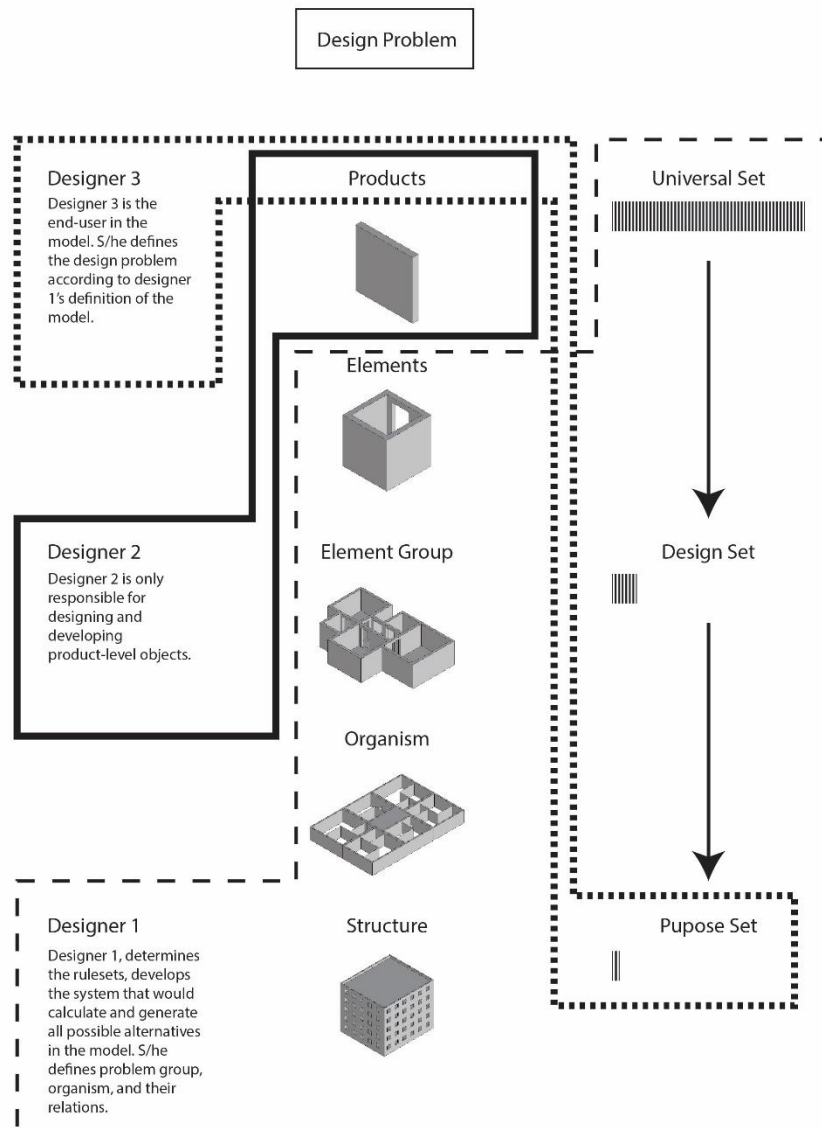


Figure 4.19. Model diagram of Model 2

4.2.1.1 Process Definition

The basic approach in this model is to propose a holistic, permutation-based model within a system defined by specific modules without constructing a hierarchy between the modules but instead breaking down the design process as in the previous model. Accordingly, the system has been designed to accommodate the spaces and

elements in a more flexible hierarchy, eliminate the potential solution clusters of the selections, and present the remaining cases to the designer 3. This setup will be explained not as the system flow but through the user (designer 3) experience and through the sequential steps that the system processes after the user decisions.

Each category limits or determines specific associated parameters. After all definitions, the universal set of the model, which can be obtained as the result of the permutation of all possible parameters, is reduced to the solution set. Then, the numerically narrowed solution set is optimized according to user criteria compliance and scored and presented to the end-user.

Since the solution set will be expanded within the proposed model, a specific problem group is selected while building the model, and the problem category is narrowed down. In this context, this model is built, tested, and evaluated on a model that would only produce a single-story house.

4.2.1.1.1 Design Problem Definition

Designer 3 is more passive in this model compared with model 1. S/he is in a position where it does not have to decide the content of the design, the location or direction of the elements, and design the final product, but defines the problem in more detail from the beginning and decides the final product from the set possible final outputs. In the case of a single-story house, the definition of the problem is shaped under the descriptions of the designer 3. These definitions are in various categories: field information, numerical information about the place, and content information about the program. At the same time, alternative building languages were developed by designer 2 and integrated into the system by designer one. These building languages classify the roof form, the library of the elements in the building, the opening ratio, and the architectural style. The user evaluates these conceptual decisions according to several fields such as cost, form, the margin of error, efficiency and makes his selection in the light of these criteria.

4.2.1.1.2 Layout Selection

The single-storey residence is systematically divided into two main categories. This distinction is made according to the privacy of the rooms. Accordingly, category A is defined with living room, kitchen, entrance hall, toilet, warehouse, parking lot, and study room, category B as having all other bedrooms, bathrooms, and other functions. The building program is defined in terms of the numbers and areas of these elements. These two categories are spatially handled within themselves and produced with definitions of how they will combine with the other category. Accordingly, the relations that each space group can establish with the spaces inside, with other space groups, and with the outer space have been defined diagrammatically by generative algorithms, with all possible connections in an orthogonal geometry. (Figure 4.20.)

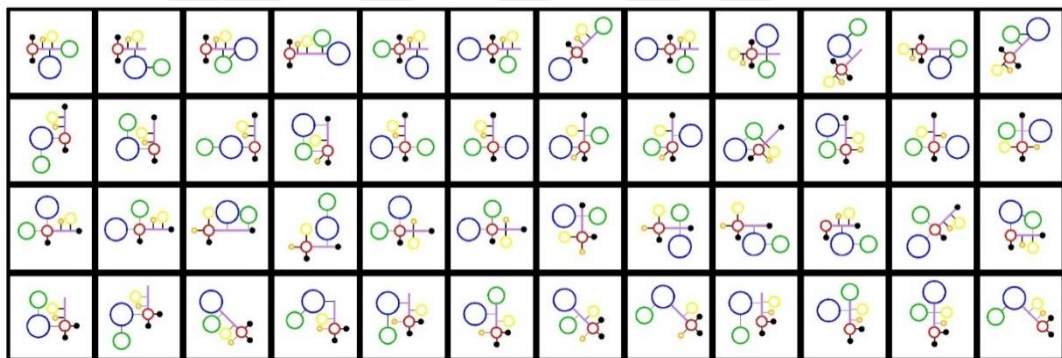


Figure 4.20. Layout alternatives that designer 3 can select

A system was established for 10 of those diagrams, which were taken randomly for both A and B groups, and the model is advanced in this direction.

Following a grid system determined for each location, a database has been created that includes all dimensions of spaces, which will adapt to the area information of the user. An example of possible room dimension is shown in the table below.

Table 4.3 Example of the Possible Room Dimension in the Specified Grid Size and User Value Comparison

	A	B	C	D	E
1	Desired Area	X dim	Y dim	Generated Area	Difference
2	3	0,8	3,6	2,88	-0,12
3	3	1,2	2,4	2,88	-0,12
4	3	1,6	2	3,2	0,2
5	3	2	1,6	3,2	0,2
6	3	2,4	1,2	2,88	-0,12
7	3	2,8	1,2	3,36	0,36
8	3	3,2	0,8	2,56	-0,44
9	4	1,2	3,2	3,84	-0,16
10	4	1,6	2,4	3,84	-0,16
11	4	2	2	4	0
12	4	2,4	1,6	3,84	-0,16
13	4	2,8	1,6	4,48	0,48
14	4	3,2	1,2	3,84	-0,16
15	4	3,6	1,2	4,32	0,32
16	5	1,2	4	4,8	-0,2
17	5	1,6	3,2	5,12	0,12
18	5	2	2,4	4,8	-0,2
19	5	2,4	2	4,8	-0,2
20	5	2,8	1,6	4,48	-0,52
21	5	3,2	1,6	5,12	0,12
22	5	3,6	1,2	4,32	-0,68

In line with the user's problem definitions, the area information required for each location is matched with these room dimensions. All measures meeting requirements and converging more than a specified ratio are included in the solution set. These solution set values are applied to A and B category alternatives, and those that cannot fit into the field are eliminated. After this screening, the building plan draft is created according to the specified room dimensions. Afterward, space, facade, and material areas are calculated based on these drafts. According to the materials in the library developed by designer 2, the instances within the budget are investigated and shown to the user. The remaining cases from this elimination continue to the following stages.

4.2.1.1.3 Structural Placement

Following the previous stage, structural layout algorithms run on the plan diagram. These algorithms place axes where all the room lines cross the sketch. Subsequently, these axes start from an arbitrary root, and the distance between them and the nearest axis will not exceed the threshold value. When this axis is lifted, the distance between the next axle remains below the threshold value, and at the same time, the axis intersection points are on the lines of the rooms. At this point, at the end of several trial periods, instances with less axis count considered optimum local value.

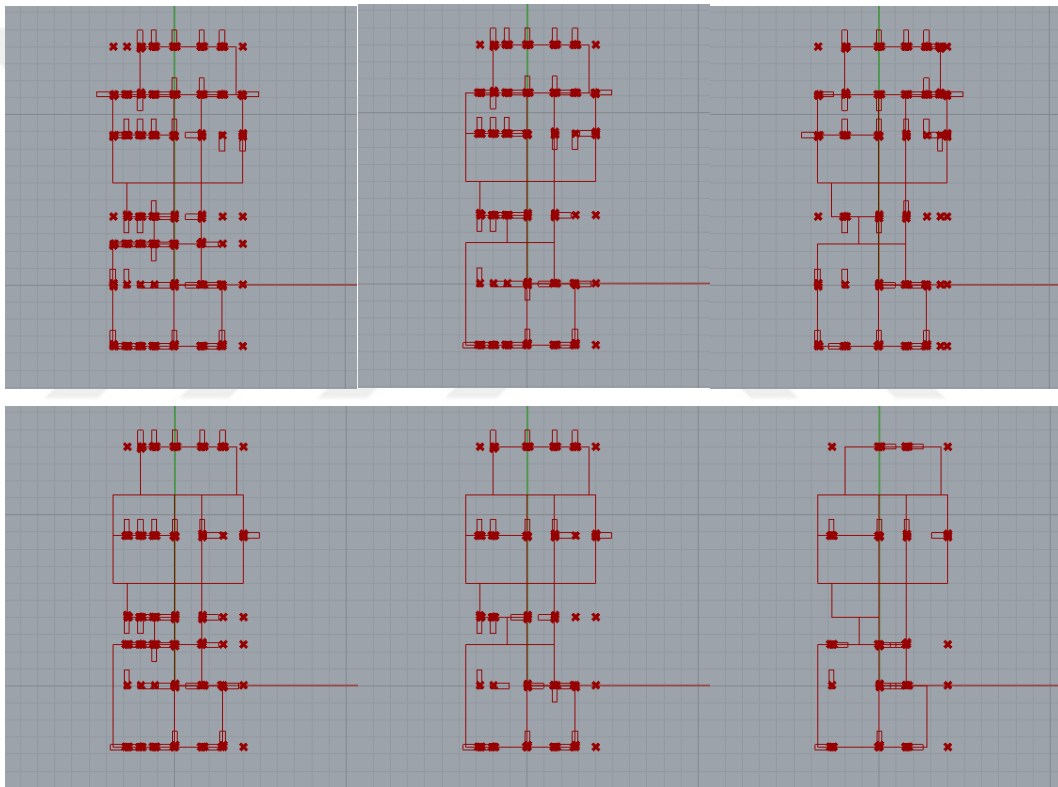


Figure 4.21. Structural Axis Determination and Column Placement Algorithm

4.2.1.1.4 Furnishing Placement

In the furnishing layout stage, the module in the first concept is used. Even though the functions are different, algorithms have been developed by designer 2 to generate

the furnishing layout of the room is similar. At the end of this process, furnishing elements such as sofa, bed, etc., are generated and matched with several BIM products.

4.2.1.1.5 Façade Generation

The facade formation stage is handled as in the first model. However, the difference is that the user does not choose those façade styles. Still, they are created automatically by placing the elements on defined façade lines according to the selected design alternative. At this point, designer 2 generates different versions of element parameters such as the opening width within the facade system s/he designed, listed, and matched. Next, the cost calculation is made for these conditions, and the cases that do not meet the initial criteria are eliminated. At the end of this stage, data for all cases that meet the user demands or cases that stay in a specific threshold remains; the rest are eliminated.

4.2.1.1.6 Optimization

Optimization is one of the main goals of this model. In this context, the basic optimization methodology calculates the possible permutations of all the elements at each step and reaches the solution set that meets the demands of designer 3 instead of proceeding on a linear follow-up in the design process. While doing this, first of all, an error threshold is defined for each user request. Solution clusters that meet these threshold values are sought. After the solution set is obtained, designer 3 favors a case from the solution set.



Figure 4.22. Different designs that have the same façade language, plan layout but different dimensions generated by model 2

4.2.1.1.7 Scoring and Selection

After the solution set is obtained by the permutations of possible parameter values, instances of the solution set is evaluated according to how close their values are to the required criteria. The total area of the house, spatial needs, and overall design cost are calculated and scored. Those three aspects have an equal impact on scoring. An example of scoring an optimization process will be shown in the case below.

Designer 3 picks designs that are scored in different categories as a result of this evaluation according to which category is more important. After this decision, the model is completed, and designer 3 gets the final product.

4.2.1.1.8 BIM Integration

The procedure for developing the design in the BIM environment is the same as Method 1. Only the selection of materials is not made by designer 3. The optimization algorithms' decision to convert the relevant reference elements into architectural objects is completed as explained in the previous step.

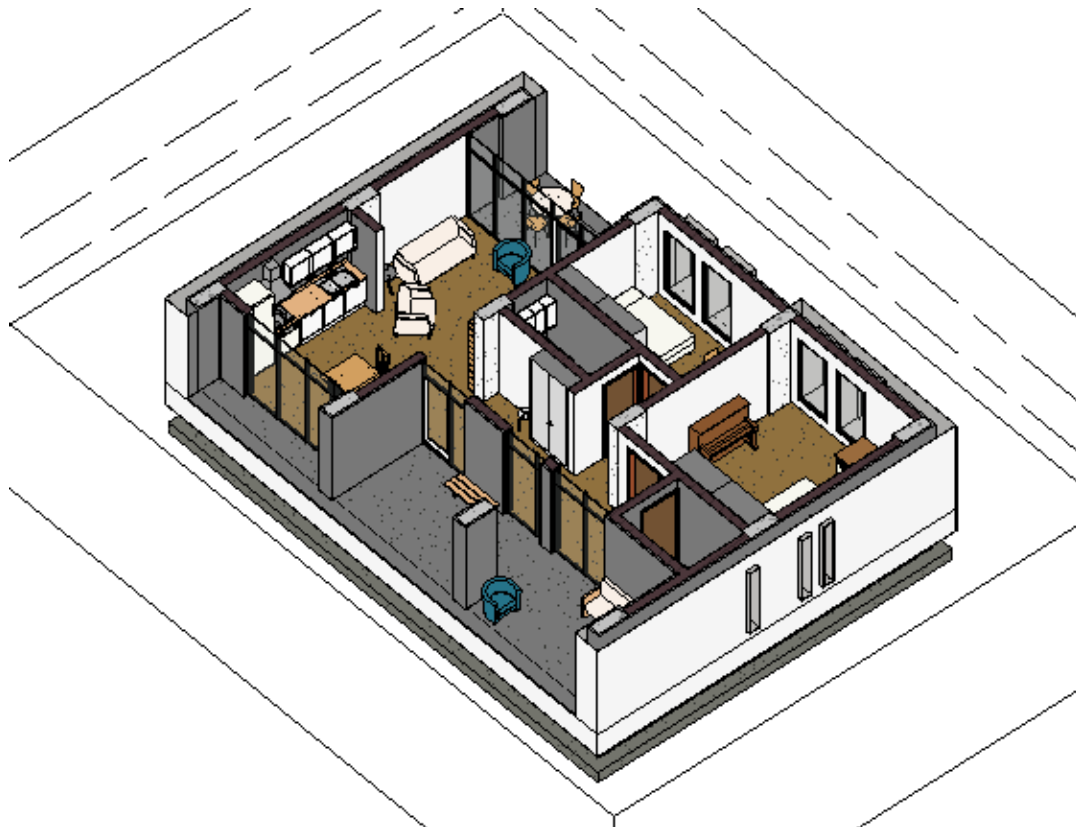


Figure 4.23. BIM Model of selected design proposals

4.2.1.2 Designer's Roles

In model 2, unlike model 1, designer 3 is relatively more passive. In this model, designer 3 is responsible for determining the design problem and selecting a quasi-optimal solution, while in model 1, it is his responsibility to design the overall structure. On the other hand, designer 1 determines all the rulesets, and s/he is responsible for the generation of all elements in any hierarchies. S/he determines the problem group, defines possible layouts, limits the dimensions of any elements, and constructs possible combination rule sets of those elements. Therefore, designer 1, in this case, has to deal with various problems in different scales which are dependent on each other. Moreover, in this model, designer 2 is responsible for only designing and modeling at the product level. All the different elements that are used in the

model according to the model hierarchy are generated according to the algorithms constructed by designer 2.

4.2.1.3 Model Hierarchies

As it was mentioned, the designer 2 design models only at the product level in the hierarchies such as furniture, wall types, or façade elements. Then, designer 1 determines all possible rooms in the building and defines the possible dimension precisely. Later, according to the programmatic layouts designed and parametrized by designer 1, model groups composed of rooms (A or B groups in tested case) are generated. Finally, façade elements are added to the model with respect to designer 2's design, and the design is completed.

4.2.1.4 Tools and Technologies

In model 2, Rhino Grasshopper is used to parametrize the geometries. For the calculation of possible combinations, an algorithm is developed in python. In finding optimal solutions, Galapagos for Grasshopper and Excel Solver is used. In excel solver, the Generalized Reduced Gradient method is used. For BIM integration, Revit Dynamo and Speckle for Grasshopper and Speckle for Dynamo are implemented for the information transfer.

4.2.1.5 Flow of Information

Unlike model 1, the process is not linear in this model. It is a process that can be started at any point, and then according to the defined input to the system, the solution set gets limited. After having several inputs, the number of solutions reduces until the needs of designer 3 are satisfied.

Firstly, all the possible results of the combination are calculated with low precision. In the beginning, room dimensions are calculated in a grid of 160 cm. Then, the

possible combinations with respect to the layouts are calculated and listed. Next, for each possible configuration in each dimension, minimum and maximum costs are calculated according to the element library. By doing this, the library developed by designer 2 is evaluated in each type of element, and the minimum and maximum cost of each construction item is calculated.

Table 4.4 Possible Room Dimensions with Different Precision in the Model

Desired Area	X dim	Y dim	Desired Area	X dim	Y dim
15	2,8	5,2	15	2,8	5,2
15	3,2	4,8	15	4,4	3,6
15	3,6	4	16	3,6	4,4
15	4	3,6	16	4	4
15	4,4	3,6	17	3,2	5,2
15	4,8	3,2	17	5,2	3,2
15	5,2	2,8	18	4	4,4
16	2,8	5,6	18	4,4	4
16	3,2	5,2	19	3,6	5,2
16	3,6	4,4	19	5,6	3,2
16	4	4	20	3,2	6,4
16	4,4	3,6	20	5,2	4
16	4,8	3,2	21	3,6	6
16	5,2	3,2	21	5,6	3,6
17	2,8	6	22	4,4	5,2
17	3,2	5,2	22	4,8	4,4
17	3,6	4,8			
17	4	4,4			

Then, according to the designer's 3 inputs, several items in the list are eliminated, and after each step, the precision is increased. This model can be described in figure 22 below.

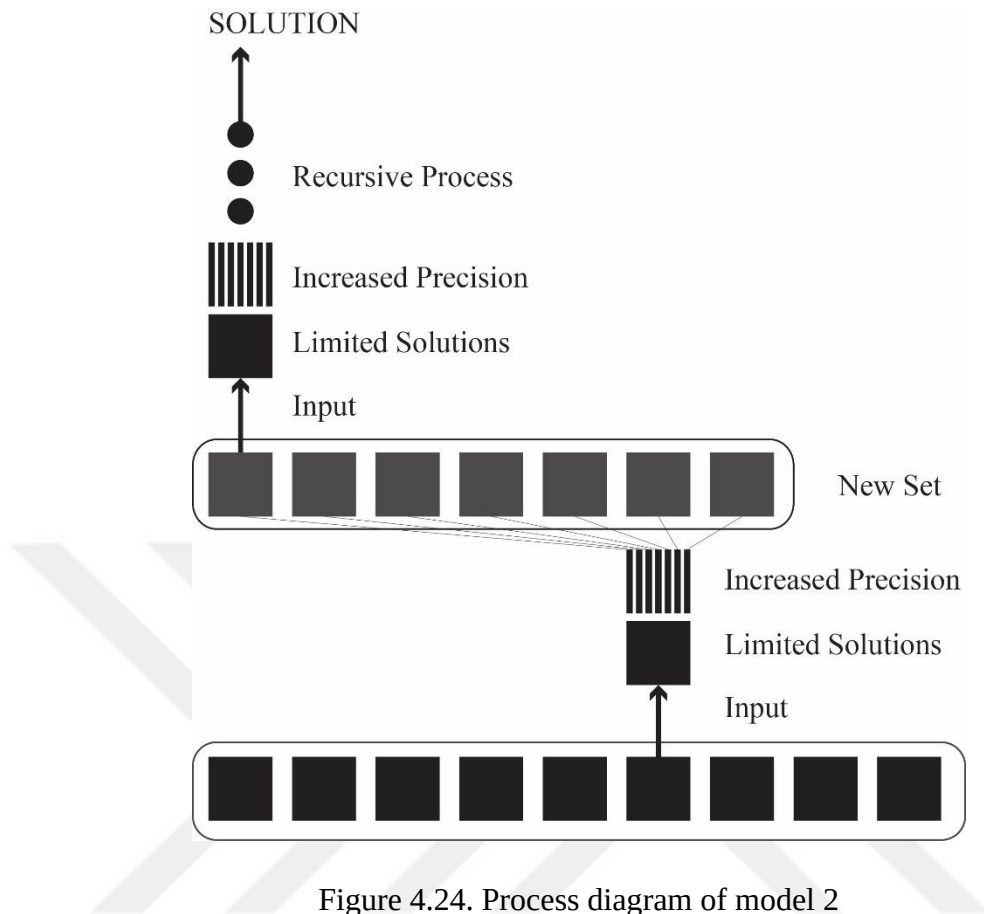


Figure 4.24. Process diagram of model 2

As seen in the figure, the model is limiting the possible solutions by increasing the precision. In each step where the user defines an input, the system increases possible solutions by increasing the accuracy of the dimensions. In the selection process, the algorithm aims to find several solutions with respect to the input types. While doing that, it measures only one parameter in the elimination process defined by the input. Finally, after each input is limited and the final solution set is clear, it scores them according to their error values in each previous step. It does not calculate an overall score. It calculates the score of each step. Therefore, the first input that the user defines effects the solution set more than all the others. Thus, designer 3, in this model, should be aware of that.

4.2.2 Test of the Model

As it was explained, the model is constructed for the design of a single-storey house. In that process, available parameters for designer 3 are two types. First input types are compulsory inputs: site boundary dimensions, desired net area, layout selection, program selection, and cost. The order of those inputs is given according to designer 3's priority. The second type of input is not compulsory. They determine the size of the spaces, such as the direct area of a living room, ratios between 2 specific rooms or the furnishing requirement of a particular room, etc.

In the testing process, to lower the computational cost, the 5 A and 5 B group is parametrized and implemented into the system. Then, the precision that determines the gridline of the model is selected as 160 cm. In that case, in the beginning, there are 76 possible dimensions for living room that their area is ranged from 15 m² to 50 m². This process is defined for all potential spaces in a house. The number of possible dimensions for each space is calculated as: for kitchens 32, master bedrooms 41, other rooms 26, for bathrooms 4, for WC 2, and depots 2. After this simplification, for a house with two rooms and one bathroom, more than 40 million possible combinations occur. Therefore, the possible results are not calculated for each program type and layout due to the increased combinatorial complexity.

The user defines obligatory inputs. S/he desires a house that has a 2-bedroom house with two bathrooms and a depot. After setting the site dimensions available footprint of a house in sizes of 12m to 12m is calculated as an available construction area. After, s/he sets the total area of a house as 110 m². Later, an algorithm calculates layouts to fit the site and fulfill the area requirements.

While an algorithm does that, it begins with the analysis of the program. First, it finds combinations of any matched results of room combinations that result in the desired area. It focuses on the areas and finds all the possible room combinations regarding the dimensions. The important thing here is that the house's circulation areas are not included. Therefore, the ratio of circulation in each layout is calculated,

and the average of those values is subtracted from the total area. One may say that, in each layout, the circulation percentage is different and this results in a lower number of possibilities to achieve the objective. First of all, designer 3 can start the process by selecting the layout, and in this way, the calculation would be more accurate. Secondly, since the dimension precision is relatively low, it will be reevaluated later.

Table 4.5 Example Table. The algorithm Tries to Find a Combination of Different Rooms with Their Areas

type	area min	area max	selected area	count	TOTAL AREA	DESIRED TOTAL AREA	value to minimize
living room	15	50		1		120	G2-F2
kitchen	10	24		1			
master bedroom	12	40		1			
room	9	24		1			
bathroom	4	9		1			
depot	2	5		1			

The algorithm found 68440 possible room areas that would match the desired area. Following this step, another algorithm checks for the relationship with the site. To do that, each room's minimum and maximum values in terms of areas and the room's minimum and maximum x/y ratios are determined. Then, it applies extreme cases to each combination of A and B layouts. (10 A and 10 B, in total 100 layouts) Then, it eliminates the layout that two extreme cases do not fit the site. In the tested case, 64 of the layouts were eliminated.

Later, s/he select a layout for the design problem in the set of eliminated layouts. In the tested case, A-4 and B-3 are selected from figure 18. It is tested if an instance would not fit the site in given conditions by trying extreme cases of the room dimensions. Regarding this process, the number of possible room areas is decreased to 16256.

Following to that, designer 3 determines the cost of the building. The library, composed of the Revit families, is used to calculate the minimum and maximum cost

of the building. To simplify the process, only façade walls and other façade elements are considered. Therefore, the number of corners that the building footprint has and the façade length becomes the main parameter for calculating the cost. For each case, cost values are calculated, and ones that do not satisfy the cost values are eliminated.

Finally, the solution set downs to 1256 instances. At that point, the precision of the room dimensions is increased. Each instance generated in a 160 cm grid regenerated with 80 cm precision. After, the solution set increased to 27648 instances. In that point, designer 3 sets the other inputs to narrow the list down. S/he determines the room areas by changing the weight of each rooms area parameter and defining room requirements such as the number of sofas in the living room or cupboard requirements for a bedroom. In the new list, the average area of each room is recalculated, and this value is considered the base number that the user will be changing.

For instance, let the possible living room areas be set A and possible kitchen areas be set B.

$$f = A_n + B_n = 42$$

$A = \{24, 26, 26, 27, 26, 25, 27, 26, 28, 26, 27, 30, 32, 31, 30\}$

$B = \{18, 16, 16, 15, 16, 17, 15, 16, 14, 16, 15, 12, 10, 11, 12\}$

In that simplified case, the average of A is 27.4 and average of B is 14.6. without changing the total values, user can select any of the specific area of any room and other room values find proper values in a way that to satisfy the total area.

After room dimensions are specified, predesigned elements are generated in BIM, and developed algorithms for furnishing the rooms are applied to the system. Finally, the BIM model will be ready to use.

4.2.3 Results and Evaluations

After testing the model, the model's potentials, limitations, and errors will be explained.

4.2.3.1 Potentials

As mentioned in this model, designer 3 can define the design problem in any state. For instance, users can start by selecting a layout, or s/he can begin the process by determining the room requirements. Therefore, this model lets the final designer be freer than model 1. Moreover, the power of permutation and combination for finding and generating optimal solutions for the design problem results in relatively accurate answers. The main potential of this model is even in a well-constrained problem; to achieve a proper solution, it tests and evaluates many alternatives and selects accordingly. In addition, it is a model that considers and evaluates the different type of objectives and decide accordingly.

4.2.3.2 Limitations

Besides the model's potential, there are limitations and errors in the system as well. First of all, precision becomes a critical problem. Because each time one tries to increase the precision, the computational cost increases enormously due to increasing the number of each set doubling the number of the combination. This leads to a high computational cost. Even in a single-family house with several rooms that are differentiated in terms of material, language, and design, the number of combinations is escalating in a way that it will not be logical even to test. Therefore, the system is hard to control because of the precision problem and the instant increase in computational cost due to the combinatorial complexity. Hence the system is not scalable. In a limited case in terms of the scale and program of the building, the system can be considered successful in fulfilling the requirements of the designer 3.

However, since the scale of the building increases the number of elements used and combined in the design process, the system might fail due to the logarithmic increase of the possibilities.

Finally, even there are errors and limitations of the model, it can be said that these problems are not impossible to solve. Due to the success of finding optimal solutions according to the user's demands, this methodology can be developed further by using different technologies in the system.

4.3 Model 3

In line with the basic inferences made after the testing of model 1 and model 2, the primary motivation in constructing a new model is limiting the role of designer 3 to obtain optimized designs; while doing this, the system has the potential to be scaled, and the solution set is relatively narrowed. In order to make it possible, optimization does not work through all possible permutations. Instead, the primary method is to increase the optimization step of the model within the parts defined in the hierarchy of model parts, to reduce the number of steps by liberating the role of designer 2, and to carry out the optimization processes in the stage of climbing up the part hierarchy. The simplified approach of the model is shown in the figure below.

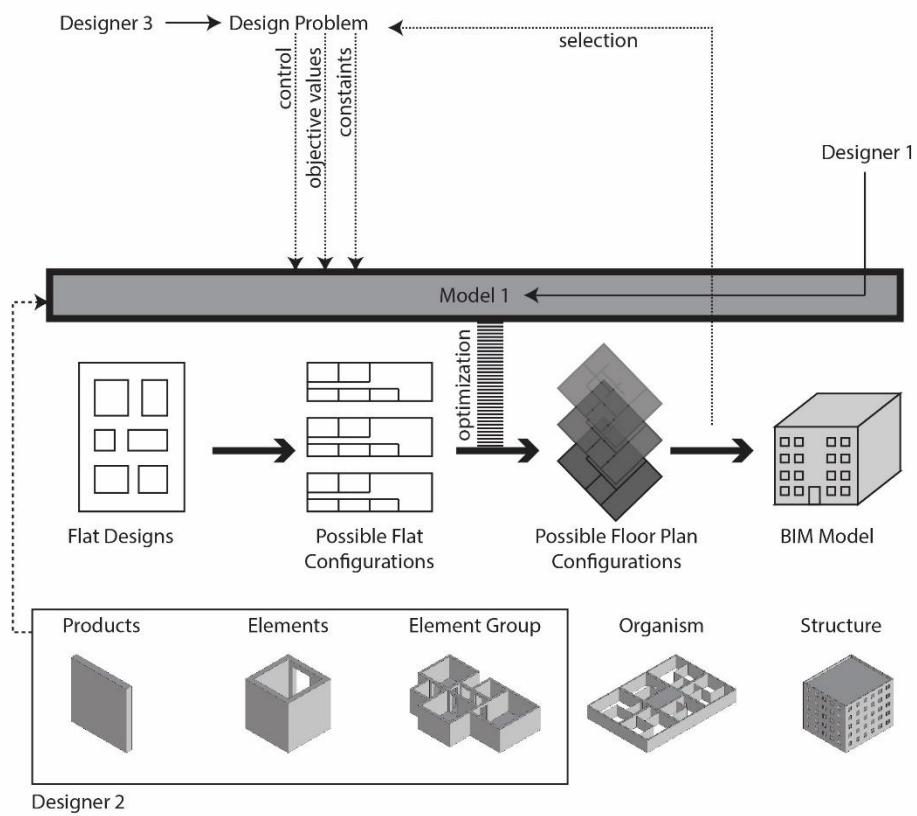


Figure 4.25. Process diagram of the Model 3

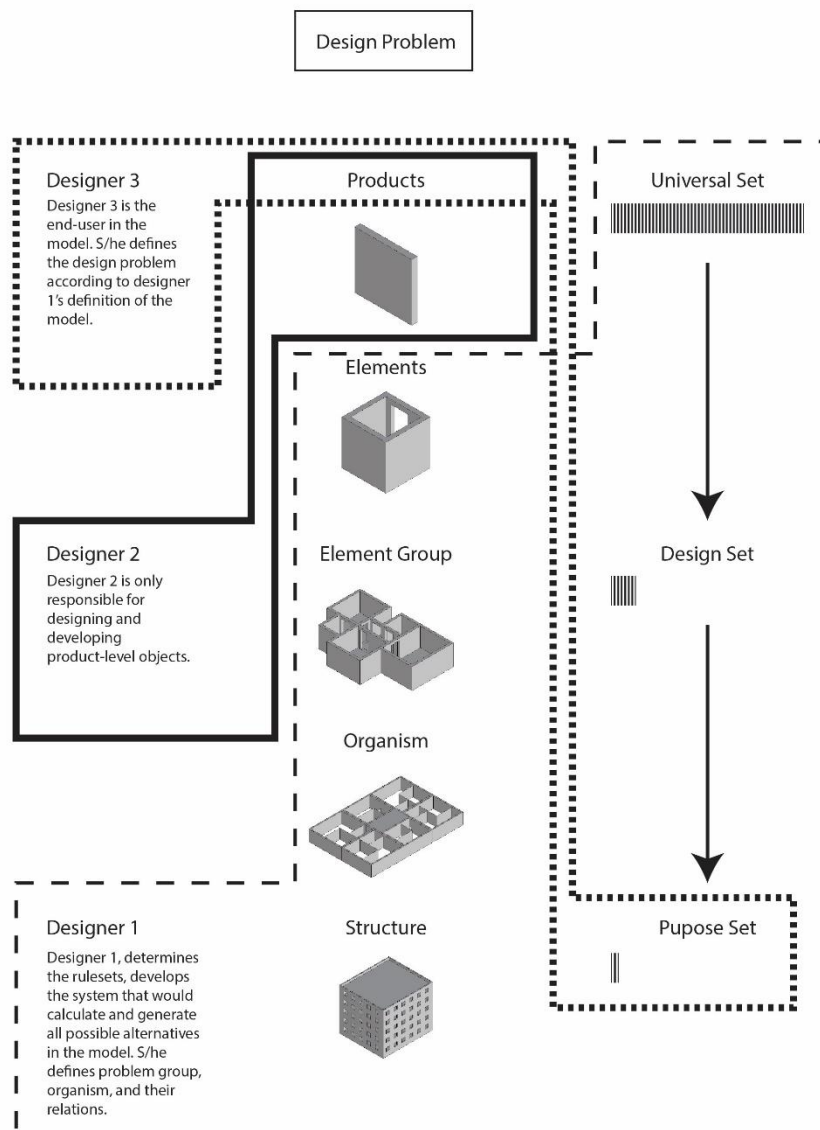


Figure 4.26. Model diagram of Model 3

4.3.1 Methodology

Within the scope of this model, like previous models, the model's design process and process steps are explained. Model hierarchies, tools used, and optimization and generation processes are presented, and the model will be tested.

4.3.1.1 Process Definition

In the light of what has been learned from models 1 and 2, this model is developed. Designer 3 is in the same role as model 2. S/he is only responsible for determining the design problem. Designer 2, on the other hand, unlike the other models, design, parametrize and generate alternative “element groups” such as a single flat itself. Designer 1’s role in the model is to combine element groups to generate “organism” (for definitions of element group and organism, see section 3.2.2.2 “Element Hierarchies in the Models”). In the process, s/he is responsible for finding the quasi-optimal instance of the combinations.

4.3.1.1.1 Design Problem Definition

Unlike model 1 and similar to model 2, the definition of the problem begins with the definition of the final design expectation and constraints beyond the input definition for defined stages. Since this model is built based on the experience from the evaluation of other models, it has been developed to respond to the complexity of the design problem by extending the scale, which seems to be problematic in previous ones. Accordingly, the definition of demand, constraints, and threshold for the design's final product varies from the beginning. The user, namely designer 3, is expected to define all the allowed properties regarding the end product of the model at the beginning.

4.3.1.1.2 System Selection

Within the scope of this model, system definition is made independent of the first and second models. Designer 1 defines a specific problem class. In this method, designer 1 systematizes not the elements (see model hierarchy) but how they should be designed by any designer 2 and how they will come together. For example,

designer 1 develops an algorithm for a core generation systematic. Accordingly, the algorithm determines the location of the structural axes.

Moreover, it determines how the other elements, such as shafts, can be produced within limits. Different designer 2 designs elements that are suitable for this system in line with these limits. The potential of these designed flats how to come together is determined by an algorithm developed by designer 1. Each element's flexible parts are parameterized, and variations of the same component are obtained. The structure defined by designer 1 and expanded by designer 2 is converted into a library, and the model will call them. Accordingly, each "system" has limited potential to solve specific design problems.

4.3.1.1.3 Element Selection

Upon system selection, each element series (with its variations) checks whether they meet the problem description. The elements in which some cases may answer the problem are listed. Later, permutations of these elements are brought into the system so that they do not form the entire structure but define the group (see Model Hierarchy). In other words, all the groups that can answer the problem are obtained and listed. All the permutations of all the elements that can meet the problem with each other are calculated and documented. These group lists will eventually be optimized to fit the problem constraints.

4.3.1.1.4 Optimization

Within the scope of this model, a mechanism is proposed in which the combination of elements is designed and parameterized in different categories within the selected system that will create a structure. Also, convergence to values defined numerically by the user (Designer 3) can be regarded as an objective function. The optimization problem at this point can be handled within the scope of operational research. At the same time, parameter values are optimized while there are several limits such as total

construction area maximum height. Accordingly, although the optimization problem varies according to the number of building blocks, it can be defined as a knapsack problem in operational research studies. Because, it can ultimately be summarized as the problem of placing more than one element with different properties (both space and material, etc.) in a system with defined boundaries minimizing the differences between user demands..

4.3.1.1.5 BIM Integration

At this stage, the BIM generation process is different from other models. Here, all system elements are found in a library. For this reason, it is a more accurate model obtained.

On the other hand, the parameterization process of system elements designed by designer 2 works similarly to previous models. However, the model is still stored in a library system, the relevant information is recorded in the system in databases.

4.3.1.2 Designer's Roles

In previous models, the main responsibility of achieving the end product of the system is on designer 3 in model 1 and designer 1 in model 2. In this model, like model 2, designer 3 is in a position that acts as the end-user of the system. S/he determines the design problem and expects the system to generate solutions. On the other hand, unlike model 2, designer 1 is not the only one who takes all the responsibility. In this model, designer 2 is way more active than the previous ones since s/he develops designs and generates models on step further in the model hierarchies mentioned. In previous models, s/he was responsible for creating the product level of elements. In contrast, in this model, it is his responsibility to generate elements and set a rule for generating the element groups (for instance, s/he is responsible for developing the flats parametrically). In this process, designer 1 is

responsible for having those rule sets, generating all possible element groups, and bringing them together to find optimal solutions for the design problem.

4.3.1.3 Model Hierarchies

In this model, product and element level models are designed by designer 2. Moreover, element groups are also designed by designer 2 in a way that s/he determines the parametrization process. After, designer 1 develops a system to generate and optimize the structure and finalize the list of element groups parameter values used.

4.3.1.4 Tools and Technologies

In model 3, for parametrization of the geometries, Rhino Grasshopper, Rhino WIP in Revit, Grasshopper in Revit are used. Autodesk Forge design automation API is used to generate possible element groups. In the process of finding optimal solutions, Google OR Tools are used. Multiple knapsack problem and constraint optimization methodologies are tested and used in this process. For BIM integration, Revit Dynamo and Speckle for Grasshopper and Speckle for Dynamo are implemented for the information transfer.

4.3.1.5 Flow of Information

Like model 2, the process is not linear either. However, it is fragmented. The methodology divides the process into several parts. First of all, designer 2 develops a series of design decisions that limit designer 1. Then, designer 2 designs and parametrizes the element groups of the design by using predefined products. Designer 1 defines the boundaries of designer 3's inputs and develops an algorithm that would find the optimal solutions for designer 3, among all possible designer 2's design within the system that s/he developed before.

4.3.2 Test of the Model

The sample scenario is considered a story that explains the tested product and shows the research process to the reader. According to this;

4.3.2.1 System Design by Designer 1

4.3.2.1.1 General Decisions

The design problem is defined as;

- One block apartment building that will follow Turkey zoning regulations,
- It will have a reinforced concrete structure, with a minimum of 3 floors, maximum of 38 floors,
- Footprint dimensions of the mass will be
 - if the height of the building is less than 21.50 m, 24.80*24.80
 - if the height of the building is between 21.50-35.50 m, 27.20-24.80 m
 - if the height of the building is between 35.50 m-51.50 m, 30.40-24.80 m
 - if the height of the building is more than 51.50 m, 33.60-24.80 m
- The site slope will be lower than %5

A housing block will be designed accordingly.

4.3.2.1.2 Design

In line with the specified constraints, the system where designer 2 will design the elements is developed by designer 1. In this case, a core plan of each possible building dimension is provided to the designer 2.

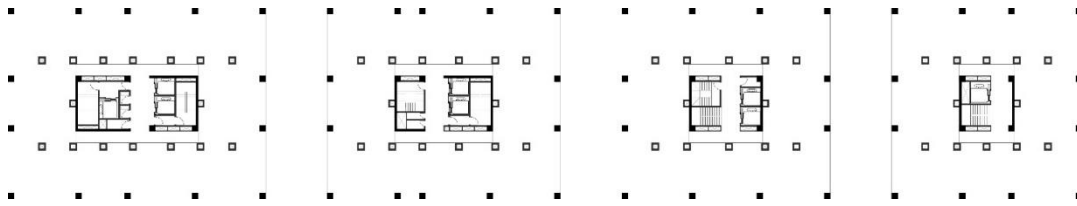


Figure 4.27. Different core designs of designer 1

4.3.2.1.3 Constraints

Designer 2 will create parametric flats within the designed core, structural system, mechanical and electrical shaft systems, and circulation setup. There is a grid scheme in 0.4 m dimensions. S/he can make four grid projections from the structure or draw the boundary in as many as two grids. The structure system is defined as well. Therefore, the design problem assigned to designer two is generating possible flats in defined core and shell.

4.3.2.1.4 Additional Decisions

Other constraints and rules regarding the specified design system are as follows:

- **Block Entry Decision:** The block is always entered from the surface perpendicular to the intra-core circulation area. In addition to apartments, lobby, concierge suite, social space, gym models are expected from designer 2, which can be parameterized in different directions.
- **Roof Decisions:** For each flat he designs, designer 2 will also model a separate variation for the flat for the top floor.
- **Mass Decisions:** The building can be massively articulated by extracting flats or groups of flats on particular floors. Accordingly, different group alternatives are developed. Different mass geometries are made possible when these combinations are used together in various quantities.

- **Basement Decisions:** The basement includes parking lots, warehouses, technical volumes, and shelter. What is expected from designer 2 is that he designs those spaces parametrically so that they can be shaped according to the needs of the building (shelter area according to the total area of the building).
- **Commercial Decisions:** On the ground floor, 1 or 2 storey commercial spaces with different areas can be demanded by the designer 3. In accordance with the fixed grid system and the structural layout, Designer 2 is responsible for modeling each possible commercial space. In contrast, designer 1 is responsible for founding proper commercial models and combining their variations.
- **Façade Decisions:** The system separates the facade according to functions and defines reference lists. The list types are different facade categories: living room, kitchen, bedrooms, structural elements, balconies, open circulation areas, blind core area, entrance lobby, and social areas. Accordingly, designer 2 designs those elements compatible with each other within the grid size and the function.

4.3.2.2 Product and Element Design by Designer 2

Designer 2 designs the products to be used in the building design. Since the model was developed within the Revit program, what is meant by the product at this point is the family definitions in Revit. Moreover, required information about the product such as cost, pose number, technical specific information is also entered to the families.

While talking about Designer 2, the following should be stated. Designer 2 is more than just specifying a subject; it is a task description. There can be many independent designers 2 in the same task group. But for each model, the designer is one unique. What is meant by the element in the sample system is flats.

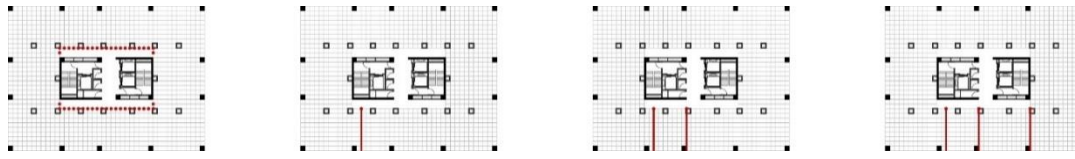


Figure 4.28. An algorithm that searches for possible flat boundaries

While designing the apartments, flats that directly connect with shafts, entrance is taken from circulation at the center, and separation walls at the full or half grid will be considered. Moreover, each flat will have a minimum of one living room, one kitchen, one-bedroom, and one bathroom. Within those limitations, flat dimensions will be parametrized. For instance, if designer 2 defines a plan layout for a flat, s/he also determines the possible parametric dimensions, such as the living room length. Moreover, it is demanded from designer 2 that the minimum area of a flat should not be less than 45 m^2 , and the maximum area of a flat should not be more than 160 m^2 .

A space divider algorithm developed by designer 1 generates possible flat division lists. (Figure 24) The algorithm is the system given as an example is as follows. First, a random point on the grid at the edge of the boundary is selected. Then, the closest perpendicular line to the circulation center is generated from that point. A flat that might have the largest and smallest area defined in limitations is generated from that line. Randomly select one of the possible flats. After, from the other edge of the flat, process continues till there is not enough space for a flat at all. This algorithm eventually generates all possible flat layouts for a floor plan.

Following the spatial divisions, an algorithm developed by designer 1 detects cases where flat boundaries, shafts, and structures are simply rotation or mirror symmetry of each other and categorize them as the same flat. Subsequently, each flat typology is assigned to designer 2. Some examples of possible flat divisions are shown in figure above. In the test phase, instead of all possible permutations, the smallest possible flats are created. The larger flats are defined by combining these flats, so that reducing the computational load and increasing the ratio of common walls between different elements. Using these definitions and previously designed products, designer 2 develops flats within the specified areas.

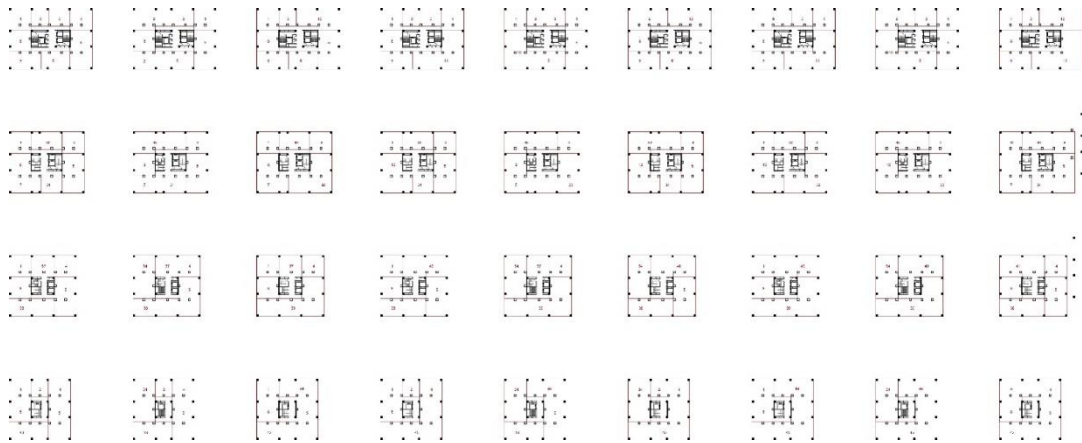


Figure 4.29. Different plan layout for a housing complex

4.3.2.3 Parametrization of the Elements

At the end of the design process, a 2D sketch drawing and a Revit family group corresponding to each drawing element are created. The element defined by designer 2 is parameterized by designer 1 within the constraints specified by designer 2. What is meant by parameterization covers two different meanings. Geometric parameterization is the ability to change the wall on any grid in line with the threshold values defined by designer 2, in accordance with the constraints within the flat definitions. List specific intent is more than one product group to which geometric references can correspond. In both cases, all permutations for a flat are calculated and recorded. Subsequently, all permutations are converted to the Revit model and saved. A sample parameterized drawing, its variations, and the final Revit model are shown in figures 4.30 and 4.31. Rhino Inside, Grasshopper, and Dynamo Revit were used to create the specified reference drawings in the Revit model.

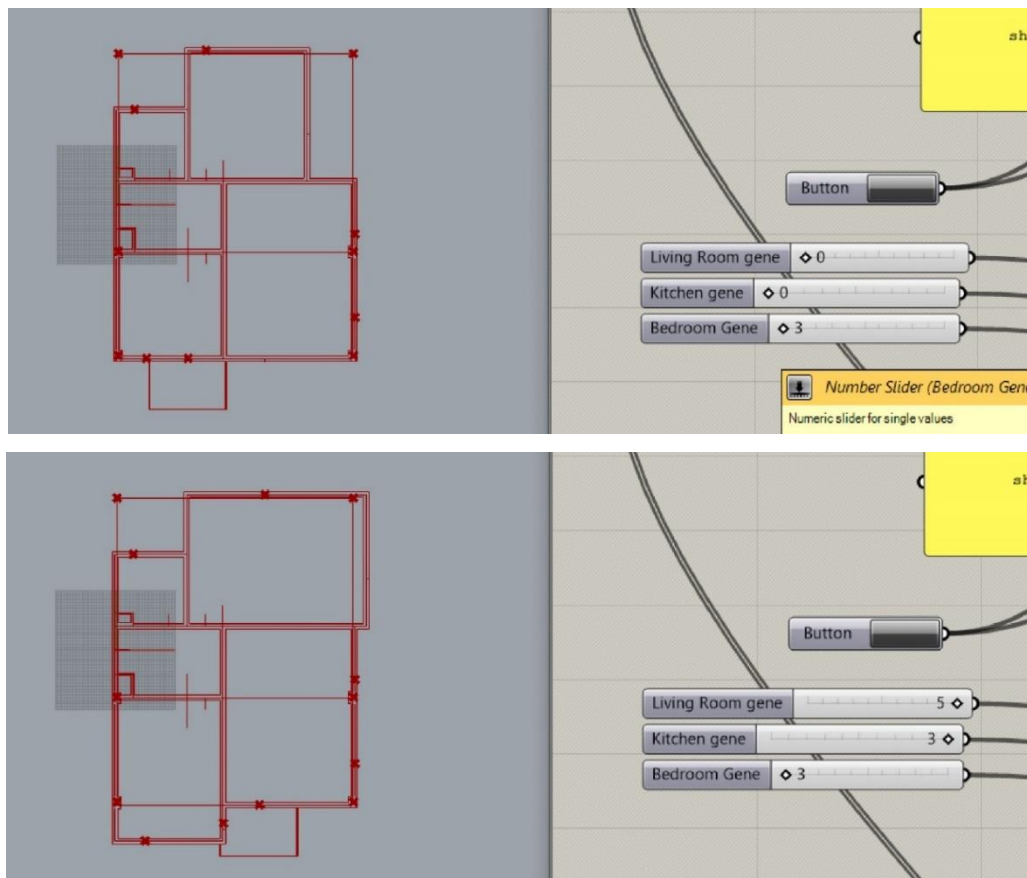


Figure 4.30. Parametrization of the flats

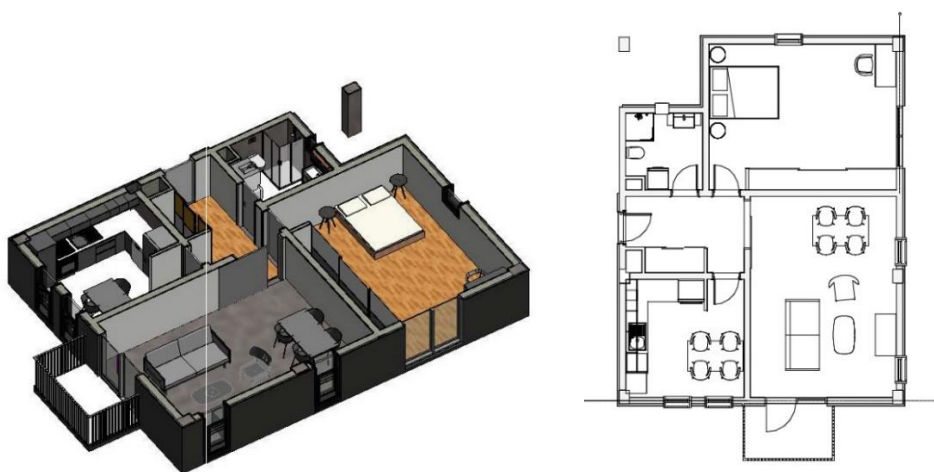


Figure 4.31. BIM model of flats

4.3.2.4 Model Group Generation

The database that includes all permutations of flat types is generated, then the cases where these flats can converge around a core are combined to create floor models. Tables containing values such as total floor area, construction area, apartment areas, apartment types, material quantities, unit costs are made for these floor models. Afterwards, with the completion of all possible floor models, a list that contains information about them with different contents that can be placed on top of each other is created. In these tables, different articulation possibilities are considered as well. Moreover, information about the entrance floors with or without commercial areas, basement models, and roof models are also generated and listed. An example floor model is shown below.

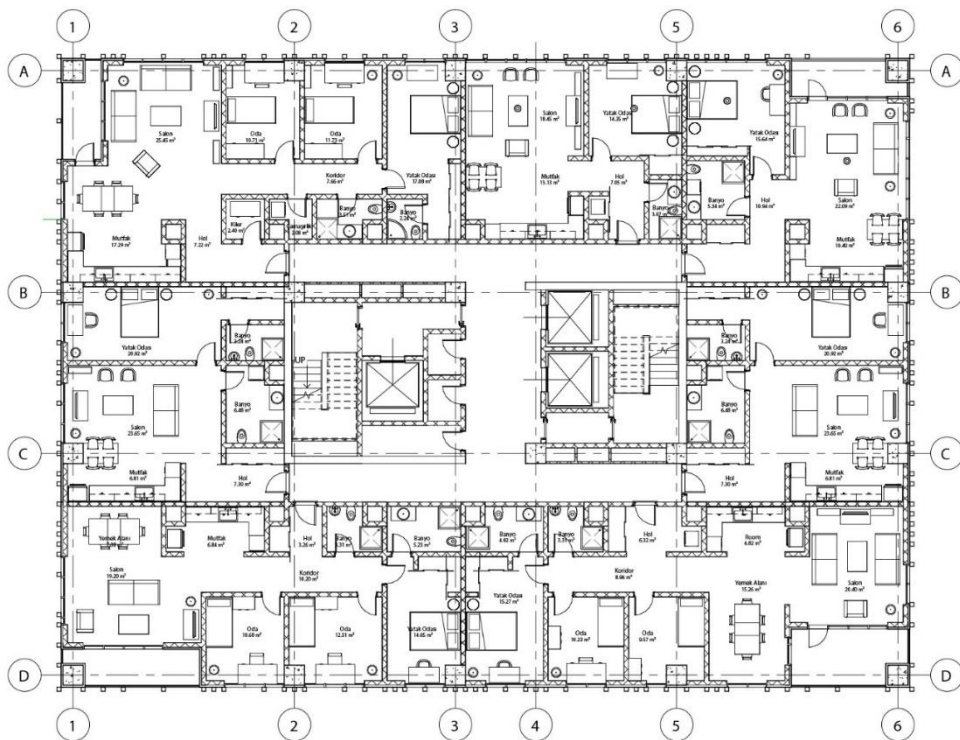


Figure 4.32. Plan of example storey

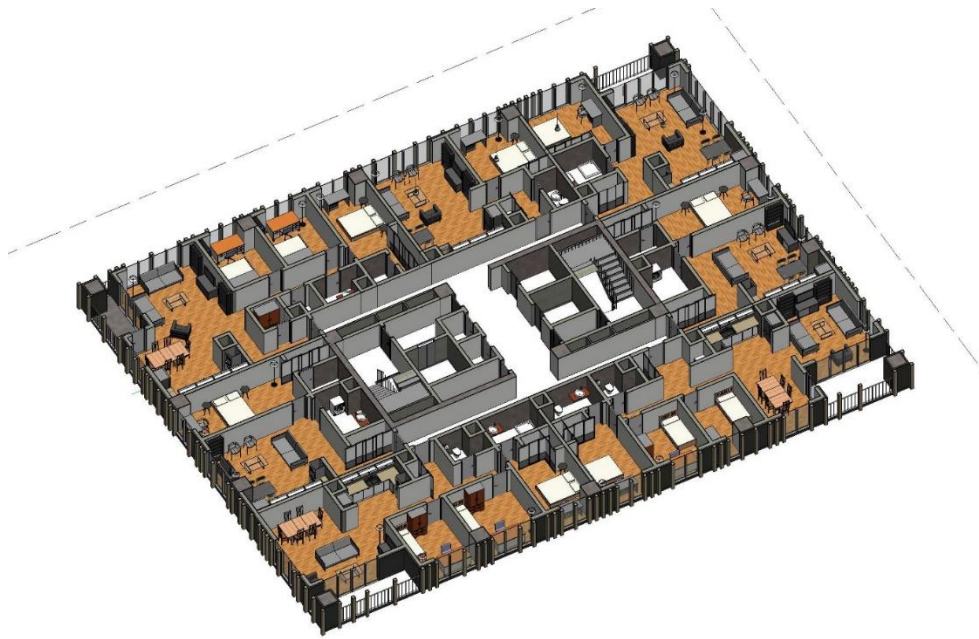


Figure 4.33. 3D of example storey

4.3.2.5 Optimization of the Design

After the model group generation process, for tested case, in total, 8463 possible floor plans are generated in different categories such as basement model, regular floor model with zero articulation. The naming procedure of the model is explained:

Model Name: a string that will be given to the model after combine the required models. Naming procedure of the models will be following the rule;

Model_Name: AA_XX_YY_ZZ

AA; =Symbolized its type of model

XX; =Level Type

YY; =Articulation Number

ZZ; =Instance Number

Model Type; ST; =Regular Storey

ST_XX_YY_ZZ

XX; =Level Type

YY; =Articulation Number

ZZ; =Instance Number

RO; =Roof Model

RO_XX_YY_ZZ

XX; =Level Type

YY; =Articulation Number

ZZ; =Upper Model Articulation Type

EN; =Entrance Model

EN_XX_YY_ZZ

XX; =Level Type

YY; =Articulation Number

ZZ; =Commercial Condition (Note that if ZZ=0, no commercial area, if it increased by the user, the amount of the commercial area in the entrance level increased as well.)

BA; =Basement Model

XX; =Level Type

YY; =Articulation Number

ZZ; =Technical Area Condition (Note that if ZZ=0, there are technical areas in the model.)

Level Type; =0; 00.00-21.50

=1; 21.50-35.50

=2; 35.50-51.50

=3; 51.50-99.99

Articulation Number; =0; no articulation

=1,2,3 level of articulation

After getting a list of all possible models with their properties, the generation process for designer 3 begins. In this step, the aim is to find quasi-optimal solutions according to designer 3's inputs. This process comprises several sub-processes; user input definition, list grouping, data normalization, and optimization.

4.3.2.5.1 User Input Definition and Actions

In this model, designer 3 determines the design problem according to the following table. The algorithm takes action specified in the table as well.

Table 4.6 User Inputs and Actions

USER QUESTIONS	MIN VALUE	MAX VALUE	USER INPUT	ACTION
Available Site Area for Construction(m2)	322	100000	X1	cull each row in "model properties" which "Bounding Area" value is smaller than X1, name new "model properties" file as "model properties_X1". If not specified, take it as "100000"
Maximum h Value(m)	12.50	100	X2	define set of possible levels as L. If $X2 < 21,50$, $L=\{0\}$; $X2 < 34,50$, $L=\{0,1\}$; $X2 < 51,50$ $L=\{0,1,2\}$; else $L=\{0,1,2,3\}$. Then cull each row in "model properties_X1" which "Level Type" value is not an element of set "L". Name new "model properties_X" file as "model properties_X2". If not specified, take it as "100"
Desired FAR Area	1265	let the max. value be named as "a". If number of elements in the set "L", $a=25000$; $a=10761$, $a=2$, $a=6336$; $a=1$.	X3	define range value for each level type accordingly. for {0}, from 1265 to 3521; for {1}, from 2356 to 6336; for {2}, from 5270 to 10761; for {3}, from 4950 to 25000. Test if "X3" value is inside of the range. If not, cull each row in "modelproperties_2" which "Level Type" values'es range does not include "X3" Name new "model properties_X2" file as "model properties_X3". If not specified, error.
Desired Level Group	min value of column "Level Type" in "model properties_X3"	max value of column "Level Type" in "model properties_X3"	X4	cull each row in "model properties_3" which "Level Type" value is not equal to "X4" value. name new "model properties_3" file as "model properties_X4". If not specified, take it as "max value"
Basement Condition	0	3	X5	if "X5"=0, cull each row in "model properties_X4" which "model type" value is "basement"; if "X5"=1, cull each row in "model properties_X4" which "model type" value is "basement" and last two digit of the "name" is equals to "01"; else do not cull. name new "model properties_4" file as "model properties_X5". If not specified, take it as "0"
Commercial Condition	0	2	X6	cull each row in "model properties_X5" that the "model type" value is "enterance" and the last digit of "name" is not equals to "X6". name new "model properties_4" file as "model properties_X5". If not specified, take it as "0"
1+1 Ratio	0	100	X7	
2+1 Ratio	0	100	X8	
3+1 Ratio	0	100	X9	
4+1 Ratio	0	100	X10	
5+1 Ratio	0	100	X11	$X7+X8+X9+X10+X11=100$
Cost	$X3 * 763,15$	$X3 * 997,19$	X12	

The table of example user data for the tested case is shown in table 4.7. below.

Table 4.7 Example User Data

USER QUESTIONS	USER INPUT		
Available Site Area for Construction(m2)	990	990	990
Maximum h Value(m)	60	60	60
Desired FAR Area	4770	4770	4770
Desired Level Group	0	0	0
Basement Condition	3	3	3
Commercial Condition	1	1	1
1+1 Ratio	30	30	30
2+1 Ratio	20	20	20
3+1 Ratio	30	30	30
4+1 Ratio	20	20	20
5+1 Ratio	0	0	0
Cost	₺ 8.000.000,00	₺ 8.500.000,00	₺ 9.000.000,00

4.3.2.5.2 List Grouping

After getting user inputs and eliminating the overall model list according to the action mentioned, the data is analyzed in their areas included in the FAR. (Figure 4.34.) Accordingly, information is grouped at the beginning to minimize the computational cost.

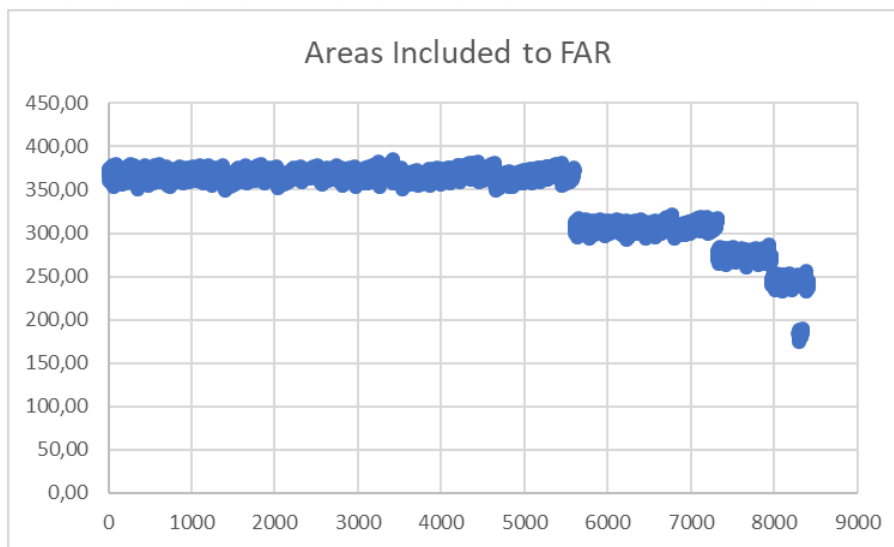


Figure 4.34. Area Distribution

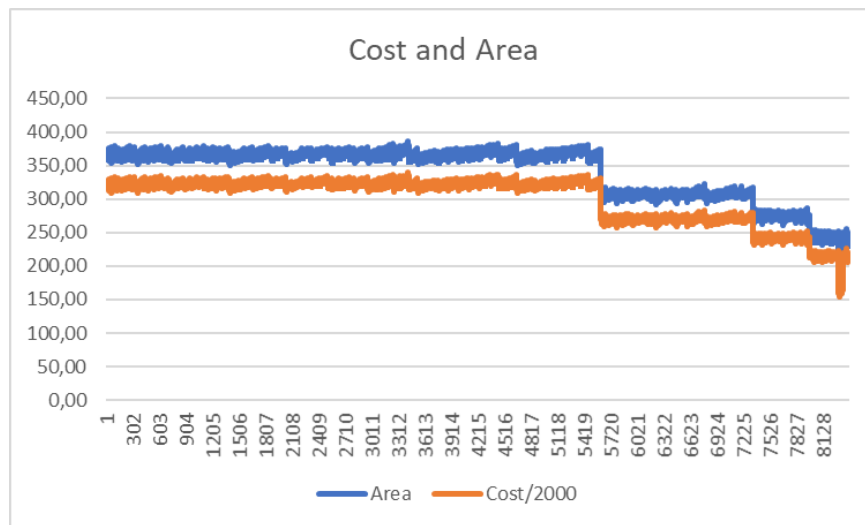


Figure 4.35. Cost and Area relations

As it can be seen in there is accumulation in certain areas. If there is no articulation, that the system generates solutions for which their sizes are closer to each other. However, the articulation creates a gap in the data in terms of both area and cost values. On the other hand, at a closer glance of the data, it is seen minor differences in the models (Figure 4.36.). Therefore, the precision of the model is decreased at the moment in order to simplify the problem at the beginning to calculate the area and cost-optimal solutions. After, the group will taken as an entire set.

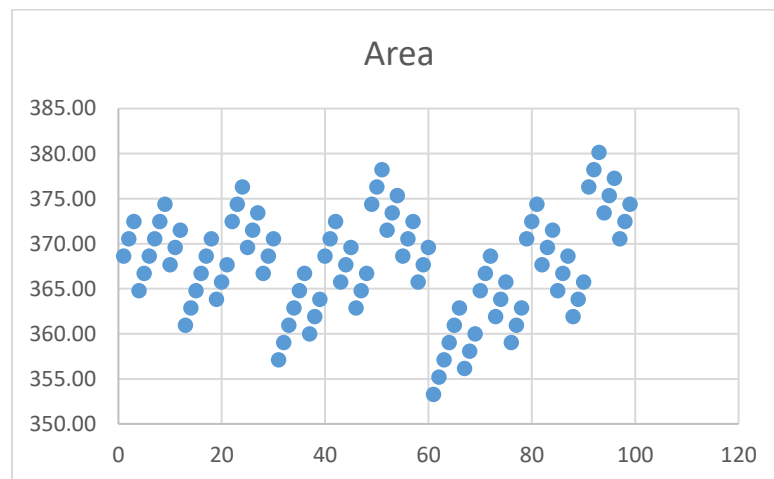


Figure 4.36. Area distribution 100 selected instances

While clustering the data, there are apparent agglomeration clusters, which refer to the articulation level at the same time. The average values of each cluster are calculated. Accordingly, the new table constructed as such:

Table 4.8 Simplified Table by Clustering the Data

Type No	Avarage Area	Avarage Cost (tl)	Count (Variabl	Total Area	Total Cost	Objectiv e Area	Objectiv e Cost	Area Differan	Cost Differan	Total Height
0	367,18	₺616.517,36	3	4141,53	7894760	5360	12500000	1218,47	-4605240	45
1	307,19	₺589.778,28	3							
2	278,46	₺539.442,96	3							
3	245,93	₺432.297,15	3							
4	181,75	₺453.550,77	3							

As shown in the table, by changing the count of each type of storey, the objective is to find a combination of the clusters that would minimize the differences between objectives (both area and cost) and generated values. However, in order to find an optimal solution that is satisfying in terms of both area and cost, the weight of the parameters should be normalized. To that, cost values are normalized by using the decimal scaling method between the maximum and minimum values of the area.

4.3.2.5.3 Optimization (Step 1)

After reaching the normalized data table, the first step of finding optimal solutions that would satisfy both cost and area objectives is begun. At this point, since the effect of area and cost values are standardized for the optimization, the overall objective of the algorithm is to minimize the total value of differences between the generated and desired values in certain constraints. Therefore, the objective is;

$$f = \text{minimize: } |(Objective Area) - (Generated Area)| + |(Objective Cost) - (Generated Cost)|$$

By using excel solver with a nonlinear regression method, the results are shown in the tables below for different cost values:

Table 4.9 Optimization Results for Different Cost Values

Type No	Count	Total Area	Total Cost	Type No	Count	Total Area	Total Cost	Type No	Count	Total Area	Total Cost
0	13	4771	₺8.014.721,00	0	8	4777	₺8.470.804,00	0	5	4767	₺ 9.010.451,00
1	0			1	6			1	5		
2	0			2	0			2	3		
3	0			3	0			3	0		
4	0			4	0			4	3		

As seen in the tables, it can be considered quite successful in converging to the user objectives. Moreover, it shows that if the budget of the building increases without changing the area parameter, the same system generates an articulated version of the design by having different types of models.

4.3.2.5.4 Optimization (Step 2)

After deciding on the required type of models, finding models for each type that would satisfy the user's programmatic objectives is the main phase. Moreover, fine-tuning in terms of the area will be conducted as well since, in the previous steps, many models are clustered and act as one single model. While the total number of all types is decided in previous actions, the objective here is to find floor plans that would satisfy the user's program value in terms of the room number of each flat.

There is a pool of floor plans for each type that their content is listed. In this pool, the instances that contain flat types that don't requested by the user, are eliminated first. After, on the culled list, the optimization tool of Google OR Tools is used to find the proper solutions for the programmatic demand from the building. Before this process, it is needed to point out that, , area differences are not considered in this stage. Some instances belong to the same type and have the same number of flats preserving the same properties but small changes in area due to the parametrization of the flats mentioned. Here, those instances are clustered and counted as one. After solving the program, the fine-tuning of the area will be conducted.

Table 4.10 Example Table for Optimization

No	model name	1 room	2 room	3 room	4 room	COUNT
1	ST_03_00_001	a_1	b_1	c_1	d_1	x_1
2	ST_03_00_002	a_2	b_2	c_2	d_2	x_2
3	ST_03_00_003	a_3	b_3	c_3	d_3	x_3
n	ST_03_00_n	a_n	b_n	c_n	d_n	x_n
	USER VALUE	A	B	C	D	total=t

According to the table shown, the objectives and constraints are explained.

x values are integers and $\sum_{k=1}^n x_k = t$;

Accordingly;

let X be total number of flats according to this formula;

$$X = \sum_{k=1}^n [(a_k + b_k + c_k + d_k) \times x_k]$$

Then the objective function is;

$$f = \text{minimize} \quad \left| A - \left[\frac{\sum_{k=1}^n (a_k \times x_k)}{X \times 0.01} \right] \right| + \left| B - \left[\frac{\sum_{k=1}^n (b_k \times x_k)}{X \times 0.01} \right] \right| \\ + \left| C - \left[\frac{\sum_{k=1}^n (c_k \times x_k)}{X \times 0.01} \right] \right| + \left| D - \left[\frac{\sum_{k=1}^n (d_k \times x_k)}{X \times 0.01} \right] \right|$$

After implementing the data table, objective function, and constraints to the optimization tool, the algorithm found quasi-optimal solutions for the problem. The results for three different cases, which differed in terms of the cost value, are shown below. It can be observed that if the budget is increased, the system generates solutions with more articulated masses.

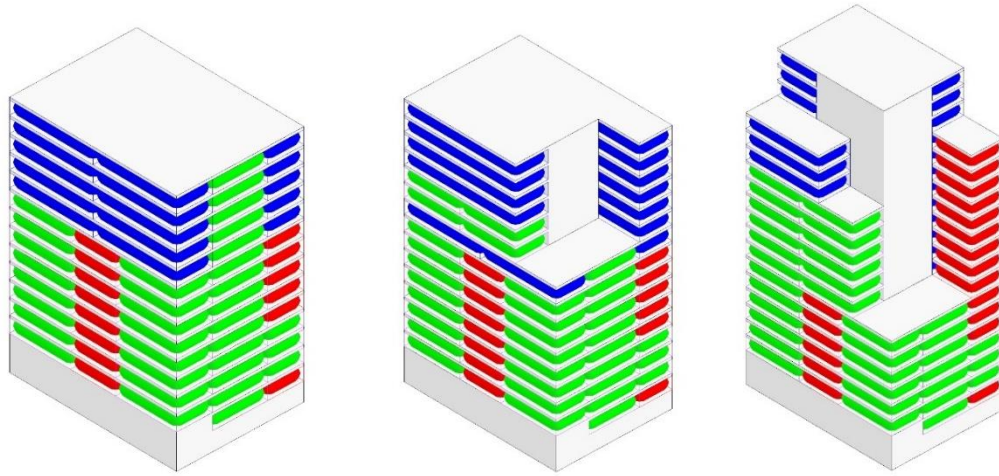


Figure 4.37. Different articulation models of the same program with the same area but different cost inputs

At the end of this stage, each floor plan is selected. The only thing that is still not determined is the selection of the instances of the clusters. By referring to the figure above, if there are different instances of each of the flats that would make the system closer to the input in area aspects, that solutions will be searched. This process is another step in the optimization process.

4.3.2.5.5 Optimization (Step 3)

In this process, one instance is selected for each cluster (Table 10). By starting from the clusters having the least instance, a simple recursive algorithm initiates the correct instance to converge the user input.

Table 4.11 Example table of Cluster

No	model name	1 room	2 room	3 room	4 room	Area
1	ST_03_00_001	a	b	c	d	x_1
2	ST_03_00_002	a	b	c	d	x_2
3	ST_03_00_003	a	b	c	d	x_3
4	Avarage x value of the type:					x_4
5	Difference of user value and generated one					x_5

According to the table shown, the algorithm compares the x_1 , x_2 , and x_3 values in terms of their differences of x_4 and see if it makes the system closer to the input value. After it founding it, the x_5 value is updated for the next cluster. At the end of this process, area results (user input is 4770) for three different cases results are;

For case 1; 4770,12 m²

For case 2; 4770,68 m²

For case 3; 4769,81 m²

4.3.3 Results and Evaluations

After testing the model, the model's potentials, limitations, and errors will be explained.

4.3.3.1 Potentials

In model 3, much detailed end-product is obtained at the end of the process. Since all the possible elements that will be used are pre-defined with necessary details, the result of the process provides a more accurate design. Moreover, this model allows the same elements to be used in different design problems as well. Therefore, even a single element can be used in different sites, architectural programs, and user expectations.

Moreover, since the number of elements is limited compared to other models, the optimization process has lower computational time, and it creates more precise results, as can be seen in the example above.

Finally, since all the elements are created in BIM by matching related products with reference models, different optimization objectives such as material selection according to the total cost can also be implemented to the model. Therefore, it can be said that this model can extend to different directions.

4.3.3.2 Limitations

In this model, since the number of elements used is limited, it creates a limitation for the model. Each element has a definition of how those elements are combined. Therefore, each of the models that could ever be constructed with this methodology has a limitation in the design problem. For instance, all elements have boundaries on the site's size and the construction area's size, and they limit the user on the phase of definition of the design problem. As a result, different models that use the same methodology for each design problem category need to construct from scratch. However, the same optimization and model generator systems can still be used with minor modifications.

CHAPTER 5

CONCLUSION

Throughout this research, to make the architectural design process more efficient, different design models that can be numerically defined with phases and flow of information are constructed and tested. Within three different models, each of them has various advantages and disadvantages. In this chapter, models will be compared, results will be shared, and suggestions for further research will be explained.

5.1 Comparison of Models and Evaluations

In this research, three different methodologies are developed and their methodologies are discussed in terms of various aspects. First of all their method in abstract level is shown in the figure below. Accordingly, models are compared in terms of their method if it is closer to the tectonic or stereotomic approach. In the first model, the design process begins with an abstract prism, and the procedure is based on manipulating the geometry and dividing it into sub-spaces. So, it is the one closest to the stereotomic approach.

On the other hand, the method of the second model depends on the generation of the smallest objects in the model hierarchy and their combinations. The rules of the neighborhood and combinations of the elements are defined. Therefore, this model is closer to the tectonic approach towards architectural design. Finally, in terms of the tectonic/stereotomic evaluation, the third model stands in between of the two models. The main geometry of a plan and circulations with cores of the building are defined beforehand. This situation dictates the main form of the structure. However, designer 2 is freer in terms of generating the elements. Moreover, even though it is

at a higher level(organism) in terms of the stored elements, the combination of the floors requires rule sets of neighborhood relations and combinations.

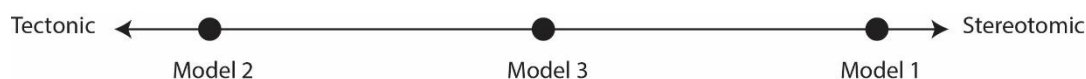


Figure 5.1. Comparison of the models in terms of their methodology

In the tables below, three models are compared in terms of the designer roles, sets of the models, and elements. In the first table, fields are explained more abstractly. Fields related to the model construction processes are presented and compared. On the other hand, in the second table, models are compared according to the example cases explained previously.

As seen in the tables, the process definition itself and division of the responsibilities directly determine the end product. Moreover, different types of results can be achieved by changing the method of models. Depending on the scale of the selected design problem, the definition of the model's user (designer 3), the level of stored elements determines the model's success.

Table 5.1 Model Method Comparison

Variables		Model 1	Model 2	Model 3
Designer Roles	Designer 1	Defines flow. Sets the parameters and phases that would shape the design. Parametrize overall structure and elements.	Designer 1, determines the rulesets, develops the system that would calculate and generate all possible alternatives in the model. S/he defines problem group, organism, and their relations.	Designer 1 assigns designer 2 for element group designs. S/he develops the system that combines them to satisfy designer 3's needs.
	Designer 2	Design and parametrize specific objects for the model such as furnishing for the office. For each specific space, designer 1 assigns him/her for the development of the objects.	Designer 2 is only responsible for designing and developing product-level objects.	Designer 2, defines products. S/he combines them to become an element. Moreover, s/he develop a parametric model for each element group and generate all possible alternatives for element groups.
	Designer 3	Designer 3 is an architect who uses the system to validate design ideas and rapidly prototype the design decisions. S/He is responsible for finding the proper solution for the design problem.	Designer 3 is the end-user in the model. S/he defines the design problem according to designer 1's definition of the model.	Designer 3 is the end-user in the model. S/he defines the design problem according to designer 1's definition of the model.
Model Sets	Universal Set	Since the model depends on a parametrization of a typology, according to the parameter value, the number of all possible building configurations is quite large. A large range of the universal set let the designer 3 be freer while s/he "designs"	The universal set in the model is more limited since different levels of the design process are combined and instead of letting the end-user define the relations, it is constructed in the model, the limit of the set is decreased.	Since the element groups are predefined in the model, the universal set is quite limited in this model
	Design Set	The limits of the design set are not defined in model 1. Since designer 3 is operating the system, the definition of the design set depends on the decision tree s/he make.	Design set is the elimination of instances that would not satisfy the numeric needs of the design problem. In the model, the number of members of the set depends on the design problem. It is also a criterion for evaluating the success of the model.	Design set is the elimination of instances that would not satisfy the numeric needs of the design problem. In the model, the number of members of the set depends on the design problem.
	Optimization	In model 1, there is no optimization process.	In the optimization process, in the eliminated list (design set), possible combinations are calculated and lists that would satisfy the user needs are shown.	In the optimization process, in the eliminated list (design set), possible combinations are calculated and lists that would satisfy the user needs are shown.
Model Elements	Used Elements	In model 1, product and element level objects are designed and parametrized by designer 2. Higher levels are generated according to the user definitions.	In model 2, only product-level objects are predefined. All other levels of objects are generated simultaneously in the model according to the needs of the user.	In model 3, "element groups" are used in the overall system. They are predefined for the system, however, the generation of element groups is parametrically constructed.
	Final Product	The final product of model 1 is a BIM model. Since objects that have a higher level than "element" are generated within the model without any predefinitions, the detail level of the structure is limited.	The end product of the model is the BIM model. To increase the detail level of the end product, the scale of the building is decreased and a more detailed model is obtained.	Since the element group level objects are used, larger-scale buildings with more precision and detail level are possible to be generated in the model.

Table 5.2 Model Example Case Comparison in Terms of Designer Roles

Variables		Model 1	Model 2	Model 3
Designer Roles	Designer 1	S/he defines a process for a rectangular office building. Each phase and flow is determined. By using grasshopper s/he developed the system and parameters are constructed.	S/he defines possible room dimensions for each function in a house. Then possible layouts and combinations of them are generated. An algorithm that would eliminate the layouts and rooms according to the needs is developed. Finally, remained list is optimized according to the site boundaries program.	S/he develop an algorithm that eliminate instances that would not fit the site or exceed the program's needs. Then, s/he construct an optimization process to find instances that would satisfy cost, program, and overall area in the possible combination of the remained list. Finally, a script that would merge the model to generate the final product is developed.
	Designer 2	S/he designs Revit families and base files. Moreover, s/he develops certain algorithms for the overall system such as office furnishing scripts or façade language and parametric models of them.	S/he designs Revit families and base files	S/he develops base files, Revit families, and designs alternate housing unit layouts. S/he parametrize them. Within a threshold and precision, each instance of the units is generated in Revit. The properties of each unit are listed in a database that includes area, cost, and program information.
	Designer 3	Designer 3 follows the phases defined and by selecting each parameter, select the instance for the specific problem.	S/he defines, site boundaries and program needs or a single house.	S/he defines, site boundaries and program needs or a housing project.
Model Sets	Universal Set	Since there is no optimization process involved, the precision of each parameter is high. Designer 3, can generate by changing parameters, more than 10^{46} the different models can be generated. However, the model does not control them or there is no claim each of the instances would be meaningful results.	In this model, possible room dimensions are defined within 0.4 m grids and possible room combination layouts are defined. Therefore, it can be claimed that each result instance of the model has meaningful. The total number of combinations in this model exceeds 10^{11} .	In model 3, the limitation of the universal set is defined by the number of elements designed and generated by designer 2. In the example case, within 246 flat units, 51804 different floor plans can be generated. Therefore in overall, more than 10^5 different building can be generated.
	Design Set	The limits of the design set are not defined in model 1. It is designer 3's decision tree that determines it	In the example case, 12*12 m site and in total 110 m2 construction area is defined as a design problem. In that case, the number of members in the design set is 16256.	In the example case, in a 990 m2 site, a maximum 60 height, 4770 m2 floor area building is defined as an example problem. After the elimination of the list, the number of floor plan layouts that can be used is decreased to 1148.
	Optimization	In model 1, there is no optimization process	After the optimization process, 15 quasi-optimal instances are shown to the user.	After the optimization process, only one option that has the maximum score in different criteria is shown to the user
Model Elements	Used Elements	Products such as brick walls and elements such as a single meeting room are used as predefined objects in the model	Only Revit Families such as windows, doors, etc. are used as predefined objects in the model	Revit Families, room models, possible flat models are used as predefined objects in the model.
	Final Product	The final product of the test is the BIM model that is designed by the end-user. Therefore the spatial and architectural quality of the model depends on the decisions s/he made. However, the system imposes the user to stick to certain design decisions.	The final product of the test is the single-family house Revit model. The spatial and technical properties of the model cannot be guaranteed since all spaces are generated simultaneously in the model.	The final product of the tested case is the more detailed BIM model. Since models are designed by designer 2, the quality of them depends on his/her design and modeling ability. The model mostly guarantees the technical and spatial correctness of the result.

5.1.1 Summary of the Process

Throughout the research, what is aimed is to search for an answer to the question in the researcher's mind: Is it possible to model the architectural process in a way that increases the efficiency in the design process and redefine the design process by dividing it into different roles? It was obvious that it was a tough question to follow and answer. Therefore it was essential to be aware of the assumptions that are presented throughout the study.

First of all, to model any process, it is necessary to divide it into sub-phases and determine the relations of the phases. Any division of the architectural design process can be considered as a simplification of the process, and it limits what can be done by the free designer. However, as mentioned in the literature review, those limitations already exist in today's architectural practice due to the market conditions and tools we design. Therefore, it might be argued that today, it might be possible to define the overall design process, not because of the technology we have, but because of the current methods of practicing architecture.

In modeling the process and division of it to the sub-phases, several different roles are determined. The main reason for this division is to make designers unrelated to a single and unique design problem. What is meant by this is that, in the traditional design process, a single architect solves a single architectural design problem and reaches towards the issue as a whole. In the models, it aims to have designers work on a "design category" to generate objects that can be used in different design problems. Accordingly, the role of designer 2 is developed. According to the models, they are not trying to solve a single issue, but they are trying to design objects for a design problem category, such as a flat that can be used in many different housing projects.

On the other hand, a persona is developed to define the specific design problem named designer 3. S/he is the one who uses the model for the particular design problem. According to the models, the way s/he uses the model to get a satisfactory

result is changing; however, in every model, s/he sets the design problem and expects a satisfactory result from the model. On the other hand, designer 1 is a designer that develops and constructs the model. After that division, it is believed that a proper team hierarchy is built for the design modeling process.

After defining the designers in the models, the objects of the design process are determined. They are categorized in terms of their scale. This determination of the elements has an essential role in the success of the models since depending on the level of the hierarchy of those elements model use, the complexity and flexibility of the models are identified. If the model uses developed high-level elements, the scale of the overall structure can increase. In contrast, the precision of the model decrease while if the model uses low-level elements as predefined elements, the complexity of the model increase enormously, but the accuracy of the model improves.

The number of possible buildings that the model can generate is shown for each model. While evaluating the model, there are two main criteria. The first is how large this set is and how hard it is to find instances that cover design objectives.

In this study, three different models are developed. Each serves a specific design problem category: a rectangular office building, a single-family house, and multistorey apartments. Each model and its results are explained in detail.

A diagram of the summary of the research, motivation, aim, and methodology is simplified and shown in the figure in appendix H. Moreover, different models, their properties, and relations with the overall methodology are shown as well. Moreover, for each model, a detailed flow diagram and input/output relations are shown in the appendix too.

At the end of this journey, according to the followed methodology of developing models, the potential of modeling the architectural design process is understood. Accordingly, different models can be constructed by categorization of the design problem. They have the potential to be developed further so that they can be used in the practice of architectural design. Even each model has several disadvantages; it

can be said that defining the process can increase the efficiency of the design process. Three different models show us that the definition of the design problem category and the method determines the model's success and limits.

5.2 Inferences and Suggestions

In this research, I have tried to investigate the possible result if we, as an architect, define the design process and divide roles with each other by using computation instead of designing all the processes by ourselves with manual and subjective methods. This research shows us that many different models can be developed for various purposes. They might have required more time than a single project's design process. However, once a model is completed, it can serve similar categorical cases in a way that they increase time consumed, lower the errors, and it delivers architectural design projects more efficiently to the customer. Different models with different methodologies that can be seen in the overall design process is getting popular each day. Different entrepreneurship has been founded that attempts to model the design process. Each of them has a different approach and aim. However, one thing in common, they all define the design process. They select a phase, define inputs, outputs, and flows. Finally, they optimize the process and let the algorithms do several phases of the design process. For example, you can see the works as sidewalks lab (Ikhen, 2020), digital blue foam (Sayjel Vijay Patel, Camiel Weijenberg, 2021), giraffe build (Asher, n.d.), and much more.

It seems clear that the way we design the built environment is changing. I had tried to demonstrate that by changing the way we design collaborate more with different disciplines, and as a designer, we can share the increased responsibility in the field. To achieve that, the design is divided into phases, different roles are developed, and digital tools that shape the design process itself are constructed.

I hope that in the near future, the design process will be undertaken way more differently than we are today because of the research and attempts such as this research and many others.



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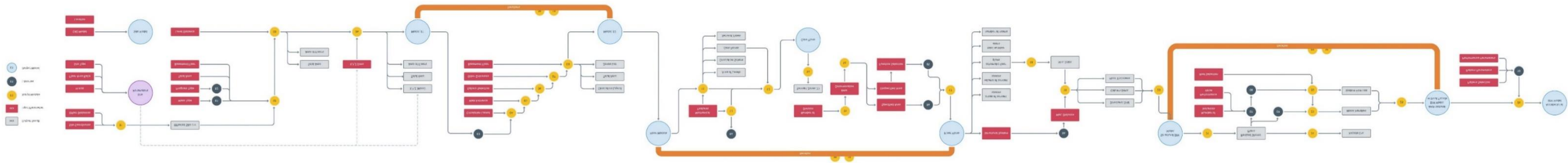
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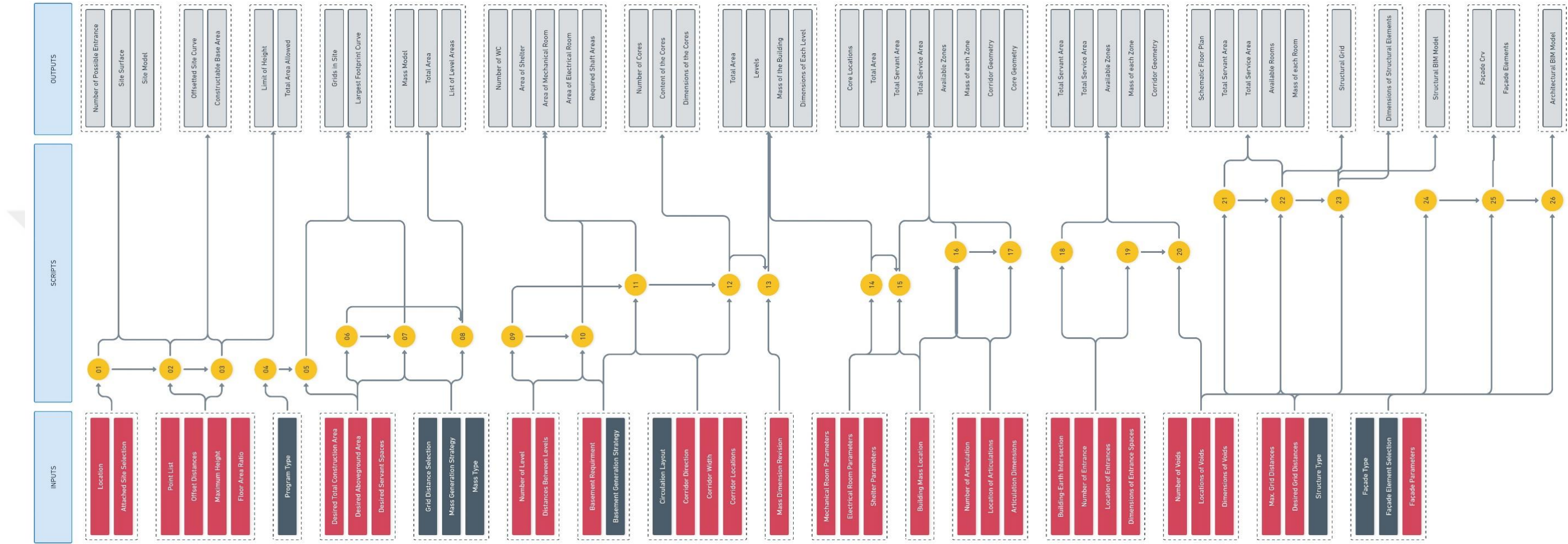
APPENDICES

A. Model 1 Flow Diagram



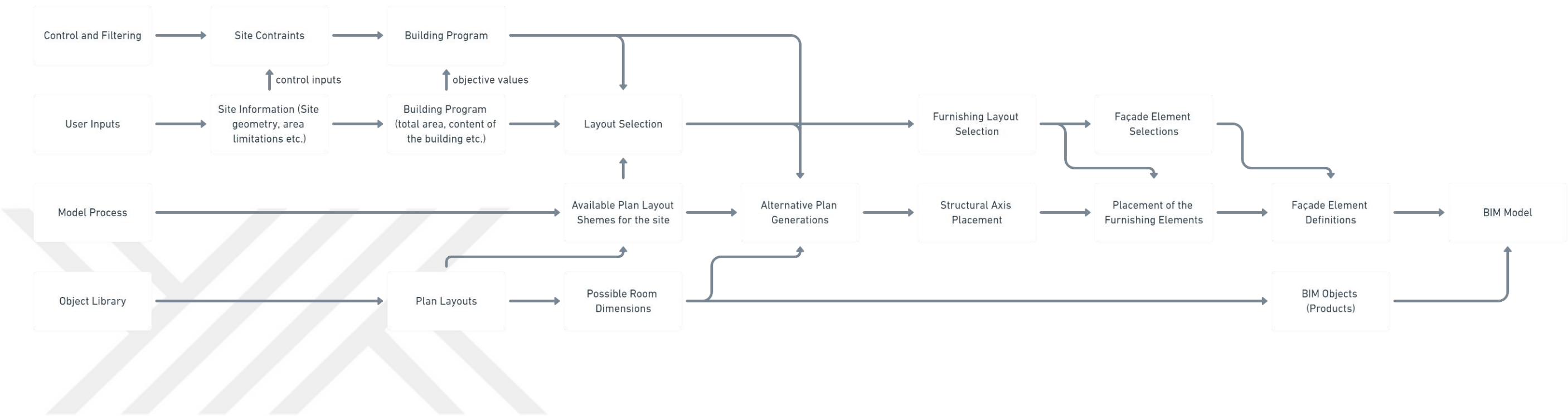


B. Model 1 Input/Output Relations



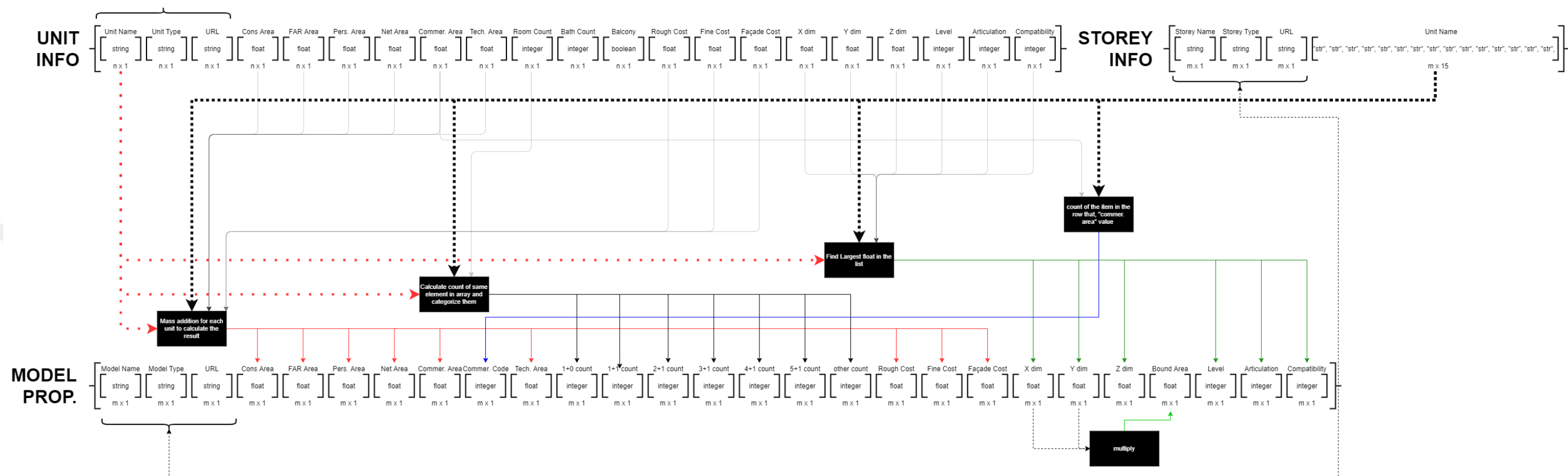


C. Model 2 Flow Diagram





D. Model 3: Model Properties Database Structure



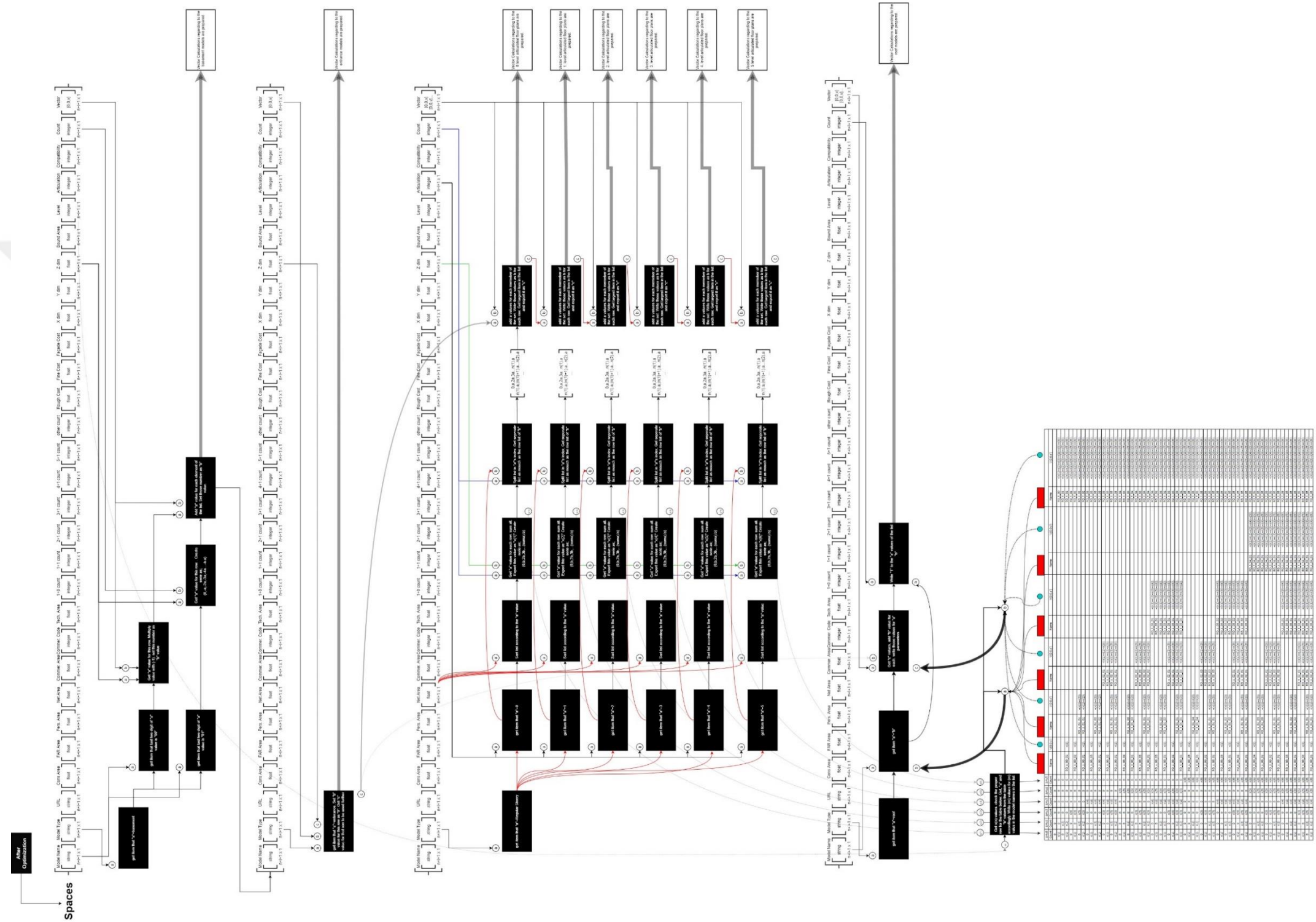


E. Flow Diagram of Process Before Optimization



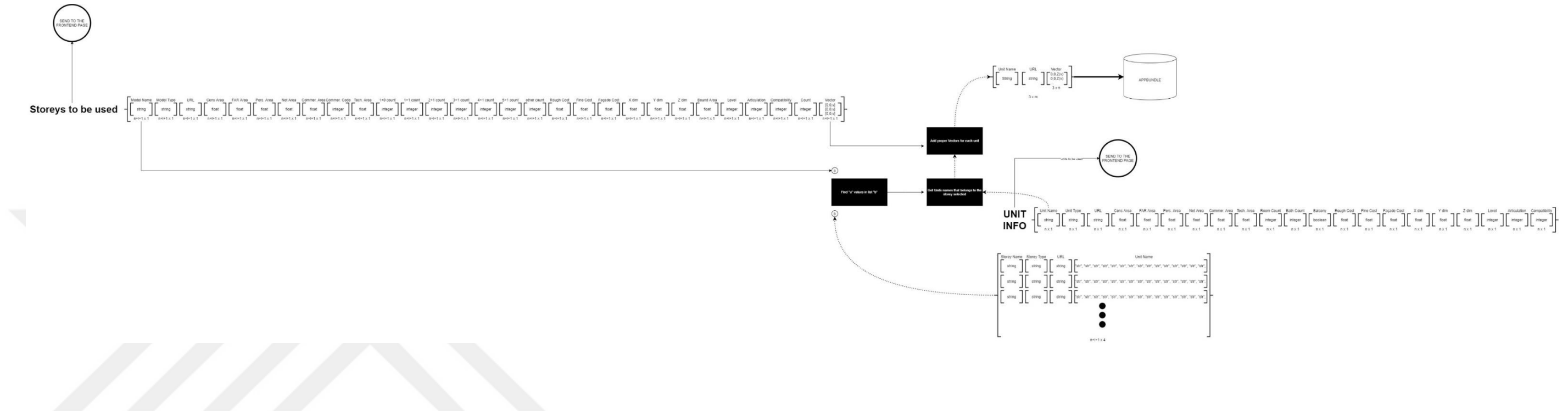


F. Model 3: Model Finder and Vector Calculation Process





G. Model 3: Vector Calculation





H. Summary of the Thesis

