A SYSTEM PROPOSAL FOR GENERATIVE DESIGN PROCESSES AND SPACE ANALYSIS IN ARCHITECTURE

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Doctoral Dissertation

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Programme in Building Design

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ABSTRACT

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Computational technologies have mostly been utilized in architectural design for visualization and representation purposes, as well as an optimal alternative for similar analogical applications. However, new improvements enabled architects to include generative approaches into design processes. The implementation of algorithmic design techniques and programming platforms also provides enormous potential, suggesting new methods to generate spatial layouts, environment typologies and allowing unique design patterns discovery. Additionally, recent generative design competencies permit data analysis, interpretation, and emergence of complicated forms and spontaneous evolving processes as well.

Due to the extensiveness of the study materials covered, interdisciplinary research methodologies were integrated, and the entire research was carried out in two parts; conceptualization (concept shift and development) and experimentation (data analysis and system implementation). The conceptualization part establishes the fundamentals of various conceptions' classifications and organizations for understanding the generative design paradigm, where essential features that had not been included in early studies were explored. The experimentation part of the research explains the development and implementation of a generative system with an algorithmic model that facilitates the collaboration of human creativity with computer capabilities. The data collection and site analysis phases were essential in defining the perspective of the case study area and establishing the generative design system's parameters. A design studio-based experiment, spatial and computational analysis techniques were involved to explore design problems and environment requirements. The gathered data were classified into several categorical dimensions based on the research intents.

The assessment process of layout and spatial arrangement, connectivity and accessibility, built area and open space was the emphasis of spatial analysis. Whereas computational analysis allowed for the inquiry of density and visibility measurements through several indicators and techniques such as GSI, OSR, FAR, and Isovist. Correspondingly, the generative design process examined designs based on three independent variables, “Functional connectivity”, “Responsive density”, “Design pattern”. Various performance operations were built into the algorithm model representation at each level to address the specific requirements of the relevant data collecting and analysis outcomes. The system supports the collaboration of generative design approaches and patterns optimization.

The main purpose of the research is to enhance the efficiency of design expansion and to develop a generative design system for Eskişehir Technical University's eco-campus development plan. It addresses the background of generative design in order to provide a more in-depth investigation into the domain of architectural design. The experimental study takes into account the usage of generative design approaches and systems in the design process, as well as the capacity to create and evaluate a diverse range of possibilities that an architect could accomplish. Compared to other patterns, the results of the third pattern optimization showed effective evolutionary mechanisms with self-generated design possibilities, spatial morphologies, and building typologies for the university campus master plan.

This research offered then a conceptual design comprehension as well as a proposed generative design system for architectural design. The system interconnection represents the predominant research contribution, while other contributions were presented through system application and optimization. The results also reveal that the proposed system may be effectively incorporated into design education and architectural practice, enhancing the learning and use of algorithmic design systems in architecture.

Keywords: Generative Design, Architectural Spatial Planning, Algorithmic Model, Generative Process, Spatial and Computational Analysis.

ÖZET

MİMARLIKTA ÜRETKEN TASARIM SÜREÇLERİ VE MEKAN ANALİZLERİ İÇİN BİR SİSTEM ÖNERİSİ

Hemza BOUMARAF

Mimarlık Anabilim Dalı

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Anadolu Üniversitesi, Lisansüstü Eğitim Enstitüsü, Ocak 2022

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Hesaplamalı teknolojiler, mimari tasarımda çoğunlukla görselleştirme ve temsil amacıyla ve benzer analojik uygulamalar için optimal bir alternatif olarak kullanılmıştır. Ancak yeni gelişmeler, mimarların tasarım süreçlerine üretken yaklaşımları de dahil etmelerini sağlamıştır. Algoritmik tasarım tekniklerinin ve programlama platformlarının uygulanması da engin bir potansiyel sağlayarak, mekansal düzenler, çevre tipolojileri oluşturmak için yeni yöntemler öneriyor ve benzersiz tasarım paternlerinin keşfedilmesine izin vermektedir. Buna ek olarak, en son üretken tasarım yetkinlikleri, tasarımda veri analizine, yorumlanmasına imkân vermekle birlikte karmaşık formların ve öngörülemeyen süreçlerin ortaya çıkmasına yol açmaktadır.

Bu çalışmada materyallerinin çeşitliliği nedeniyle, çok disiplinli araştırma metodolojileri entegre edilmiş ve tüm araştırma iki bölümde gerçekleştirilmiştir; kavramsallaştırma (konsept değişimi ve gelişmesi) ve uygulama (veri analizi ve sistem uygulaması). Kavramsallaştırma bölümü, eski çalışmalarda yer almayan temel özelliklerin keşfedildiği üretken tasarım paradigmasını anlamak için çeşitli kavramların sınıflandırmalarının ve organizasyonlarının temellerini oluşturmaktadır. Araştırmanın uygulama bölümü ise insan yaratıcılığının bilgisayar yetenekleriyle işbirliğini kolaylaştıran algoritmik bir modele sahip üretken bir sistemin geliştirilmesini ve uygulanmasını açıklamaktadır. Veri toplama ve saha analizi aşamaları, vaka çalışması alanının perspektifini tanımlamada ve üretken tasarım sisteminin parametrelerini belirlemede çok önemliydi. Tasarım problemlerini ve çevre gereksinimlerini keşfetmek için tasarım stüdyosu tabanlı bir deney, mekansal ve hesaplamalı analiz teknikleri dahil edilmiştir. Elde edilen veriler, araştırma amaçlarına dayalı olarak birkaç kategorik boyutta sınıflandırılmıştır.

Düzen ve mekansal yerleşme, bağlantı ve erişilebilirlik, yapılı ve açık alan değerlendirme süreci, mekansal analizin vurgusuydu. Hesaplamalı analiz ise GSI, OSR, FAR ve Isovist gibi çeşitli göstergeler ve teknikler aracılığıyla yoğunluk ve görünürlük ölçümlerinin sorgulanmasına izin vermiştir. Buna uygun olarak üretimsel tasarım süreci, tasarımları "Fonksiyonel Bağlantı", "Duyarlı Yoğunluk", "Tasarım Patern" olmak üzere üç bağımsız değişkene göre incelenmiştir. İlgili veri toplama ve analiz sonuçlarının özel gereksinimlerini karşılamak için her düzeyde algoritma modeli temsiline çeşitli performans işlemleri yerleştirilmiştir. Sistem, üretken tasarım yaklaşımları ve model optimizasyonunun işbirliğini desteklemektedir.

Araştırmanın temel amacı, Eskişehir Teknik Üniversitesi'nin eko-kampüs geliştirme planı için tasarım genişletme verimliliğini artırmak ve üretken bir tasarım sistemi geliştirmektir. Mimari tasarım alanında daha derinlemesine bir araştırma sağlamak için üretken tasarım bilgisini ele almaktadır. Deneysel çalışma, tasarım sürecinde üretken tasarım yaklaşımlarının ve sistemlerinin kullanımının yanı sıra bir mimarın başarabileceği çeşitli olasılıkları oluşturma ve değerlendirme kapasitesini de hesaba katmaktadır. Diğer paternlerle karşılaştırıldığında, üçüncü patern optimizasyonunun sonuçları, üniversite kampüsü master planı için kendi kendine oluşturulan tasarım olanakları, mekansal morfolojiler ve bina örüntüleri ile etkili evrimsel mekanizmalar gösterdi.

Bu araştırma, mimari tasarım için önerilen bir üretken tasarım sisteminin yanı sıra kavramsal bir tasarım anlayışı da sunmuştur. Sistem ara bağlantısı, baskın araştırma katkısını temsil ederken, diğer katkılar sistem uygulaması ve optimizasyonu yoluyla gösterilmektedir. Sonuçlar ayrıca, önerilen sistemin tasarım eğitimi ve mimari pratiğe etkin bir şekilde dahil edilebileceğini, mimaride algoritmik tasarım sistemlerinin öğrenilmesini ve kullanımını geliştirebileceğini belirtmektedir.

Anahtar Sözcükler: Üretken Tasarım, Mimari Mekansal Planlama, Algoritmik Model, Üretken Süreç, Mekansal ve Hesaplamalı Analizleri.

الملخص

مقترح لنظام عمليات التصميم التوليدي وتحليل الفضاء في الهندسة المعمارية

حمزة بومعراف

قسم الهندسة المعمارية

برنامج دكتوراه في الهندسة المعمارية ، تخصص التصميم المعماري

جامعة الأناضول، معهد برامج الدراسات العليا ، جانفي 2022

إشراف الدكتور: محمد إنجه اوغلو

غالبا ما يتم استخدام التقنيات الحسابية في التصميم المعماري لأغراض العرض والتمثيل ، فضلاً عن كونها البديل الأمثل للتطبيقات التناظرية المماثلة. ولكن، مكنت التحسينات الجديدة المهندسين المعماريين من تضمين المقاربات التوليدية في عمليات التصميم. توفر منصات البرمجة الحديثة و تقنيات تنفيذ التصميم الخوارزمي إمكانات هائلة أيضًا، مما يقودنا إلى طرق جديدة لإنشاء تخطيطات مكانية وأنماط بيئية والسماح باكتشاف أنماط تصميم فريدة. بالإضافة إلى ذلك ، تسمح كفاءات التصميم التوليدي الحديثة بتحليل البيانات وتفسيرها وظهور أشكال معقدة وعمليات تطور تلقائية أيضًا.

نظرًا لاتساع نطاق مواد الدراسة التي تمت تغطيتها ، تم دمج منهجيات بحث متعددة التخصصات، وتم إجراء البحث بأكمله في جزأين؛ التصور المفهومي (تحول المفهوم وتطوره) والتطبيق التجريبي (جمع وتحليل البيانات، إنشاء نظام توليدي واختبارمدى فاعليته). يحدد الجزء التصوري أساسيات تصنيفات المفاهيم المختلفة وأنظمتها لفهم نموذج التصميم التوليدي ، حيث تم استكشاف الميزات الأساسية التي لم يتم تضمينها في الدراسات السابقة. و يوضح الجزء التطبيقي من البحث تطوير وتنفيذ نظام توليدي بنموذج خوارزمي يسهل الربط بين الإبداع البشري مع قدرات الكمبيوتر. كانت مراحل جمع البيانات وتحليل الموقع ضرورية في تحديد خصائص منطقة دراسة الحالة وتحديد متغيرات نظام التصميم التوليدي. تم أيضا تضمين تجربة التصميم القائمة على درس الاستوديو المعماري ، وتقنيات التحليل المكاني والحسابي لاستكشاف مشاكل التصميم ومتطلبات بيئة دراسة الحالة. تم بعدها تصنيف البيانات الناتجة إلى عدة أبعاد فئوية بناءً على أهداف البحث.

كانت عملية تقييم التخطيط والترتيب المكاني، الربط وإمكانية الوصول والمساحة المبنية والمساحة المفتوحة هي جوهر التحليل المكاني. بينما سمح التحليل الحسابي بالتحقيق في قياسات الكثافة والرؤية من خلال العديد من المؤشرات والتقنيات مثل GSI و OSR و FAR و Isovist. في المقابل ، درست عملية التصميم التوليدي التصاميم بناءً على ثلاثة متغيرات مستقلة ، "الاتصال الوظيفي" ، "الكثافة المستجيبة" ، "نمط التصميم". تم دمج عمليات الأداء المختلفة في تمثيل نموذج الخوارزمية في كل مستوى لمعالجة و تحليل المتطلبات المحددة لنتائج مرحلة جمع البيانات ذات الصلة. كما يدعم النظام أيضا التعاون بين أنظمة التصميم التوليدي وتحسين الأنماط.

الغرض الرئيسي من البحث هو تعزيز كفاءة التوسع في التصميم وتطوير نظام التصميم التوليدي لمخطط تطوير الحرم الجامعي البيئي لجامعة إسكيشهير التقنية. يتناول البحث الخلفية النظرية للتصميم التوليدي من أجل توفير

دراسة أكثر تعمقًا في مجال التصميم المعماري. تأخذ الدراسة التجريبية في الاعتبار استخدام مناهج وأنظمة التصميم التوليدي في عملية التصميم ، فضلاً عن القدرة على إنشاء وتقييم مجموعة متنوعة من الاحتمالات التي يمكن أن يصممها المهندس المعماري. مقارنة بالأنماط الأخرى، أظهرت نتائج تحسين النمط الثالث آليات تطورية فعالة بإمكانيات تصميم ذاتية الإنشاء ، وتشكلات مكانية ، وأنماط بناء فعالة للمخطط الرئيسي للحرم الجامعي.

قدم هذا البحث فهماً للتصميم النظري بالإضافة إلى نظام التصميم التوليدي المقترح للتصميم المعماري. تمثل خطوات الربط بين مختلف عناصر النظام المساهمة البحثية الرائدة ، بينما تم تقديم مساهمات أخرى من خلال تطبيقات النظام وبعض طرق التحسين. تكشف النتائج أيضًا أن النظام المقترح يمكن دمجه بشكل فعال في تعليم التصميم والممارسة المعمارية ، مما يعزز التعلم واستخدام أنظمة التصميم الخوارزمية الحديثة في الهندسة المعمارية.

الكلمات المفتاحية: التصميم التوليدي ، التخطيط المكاني المعماري ، النموذج الحسابي ، العملية التوليدية، التحليل المكاني والحسابي.

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Hemza BOUMARAF

05/01/2022

STATEMENT OF COMPLIANCE WITH ETHICAL PRINCIPLES AND RULES

I hereby truthfully declare that this thesis is an original work prepared by me; that I have behaved in accordance with the scientific ethical principles and rules throughout the stages of preparation, data collection, analysis and presentation of my work; that I have cited the sources of all the data and information that could be obtained within the scope of this study, and included these sources in the references section; and that this study has been scanned for plagiarism with “scientific plagiarism detection program” used by Eskişehir Technical University, and that “it does not have any plagiarism” whatsoever. I also declare that, if a case contrary to my declaration is detected in my work at any time, I hereby express my consent to all the ethical and legal consequences that are involved.

Hemza BOUMARAF

CONTENTS

PAGE

LIST OF TABLES

Page

LIST OF FIGURES

Page

GLOSSARY OF ABBREVIATIONS

ADC	:	Architectural Design Concept
ADA	:	Architectural Design Application
AEC	:	Architecture, Engineering and Construction Industry
AI	:	Artificial Intelligence
BIM	:	Building Information Modeling
CA	:	Cellular Automata
CAD	:	Computer-Aided Design
CAM	:	Computer-Aided Manufacturing
CD	:	Computational Design
CGD	:	Computational Generative Design
CNC	:	Computer Numerical Control
CMP	:	Compactness
CRL	:	Circularity
DD	:	Digital Design
DL	:	Deep Learning
EA	:	Evolutionary algorithms
FAR	:	Floor Area Ratio
GA	:	Genetic Algorithm
GD	:	Generative Design
GDA	:	Generative Design Approach
GDS	:	Generative Design system
GH	:	Grasshopper Plugin
GS	:	Generative System
GSI	:	Ground Space Index
MOGA	:	Multi-objective Genetic Algorithm
NURBS	:	Non Uniform Rational Basis Spline
OSR	:	Open Space Ration
OSS	:	Open Source Software
PD	:	Parametric Design
SG	:	Shape Grammars

1. INTRODUCTION

The paradigm of generative design is more than simple advanced technologies or computer software; it is a frame of reasoning that promotes innovation and architectural design possibilities by employing a variety of approaches, systems theories, and techniques influenced by geometry, nature, algorithms, and biology. According to Hesselgren (Stocking, 2009), generative design is not about setting up a layout; it is about establishing the mechanism that generates a project. However, Kolarevic (2003) argued that the generative design develops the significance beyond “making” towards “finding” in order to reform architectural design and fabrication. The primary motivation of this research is to better appreciate the mechanisms that determine current architectural design and urban planning. The crucial challenges are fully enfolding the process behind the commonly named generative system and its variations. Addressing this means elaborating the essence of effective conventional space planning methods by capturing the operational processes of various systems and approaches. Design application and design concepts are rapidly evolving and have developed dramatically in recent decades. Conventional design methods that depended mainly on cognition, perception, and visualization are unable to properly guide the designer regarding how the final product will perform. An effective design system should incorporate both technical and conceptual components. Designers and architects expend considerable time seeking the optimal possibility for their design considerations. Unfortunately, the reached final alternatives are generally never the optimum appropriate alternatives and may not even be in accordance with the system’s fundamental development ambitions and limitations. Accordingly, this thesis promises to present an interpretive system for generative design applications and methodologies. The systems and approaches discussed are theoretical and conceptual in origin, and they are intended to illustrate a prospective potential path of generative design system application.

General features of what current modern practice in architecture and urban design is experiencing in respect of the rising data dimensionality are explored to highlight the possibilities of this problem-solving path. In the context of architecture, the notion of generative design is attributed to the parametric approach. However, the generative methods discussed in this thesis, are more algorithmic. A generative design workflow usually initiates with the definition of a set of integral rules, a series of components, and several conditions, managed to perform in a series of procedures. These new hypothetical frameworks might serve as the foundations for a new type of design in which computational techniques combine performance and generation strategies. Spatial architecture depends frequently on data collection and analysis which plays a crucial role in every design project. Taking time on a site and attempting to comprehend it is dynamic and interactive, allowing for what designers describe as a real perspective of an area. It may be regarded as much more than a representation of lines or mapping illustrations in this sense, but also as a practical and subjective setting. Designers may use site analysis to assign relevance and insights to an area, as well as uncover and comprehend its qualities. The major disadvantage of seeing a site, in reality, is the direct connection that is created between the user and the physical location.

As Lynch (1984) states, *"any standardized schedule of information must be viewed with suspicion as there simply is no universal list"*. Such intertextuality among cognitive and quantitative recognition approaches is experienced during site analysis. In an attempt to perform a spatial and computational site study, the investigations employed in this thesis combine subjective and experience aspects with data and attention to integrity. The analysis through this process focuses on design proposals in university campus masterplan expansion. The configurations resulting from this system are introduced to act as seeds with the opportunity to expand into something broader and more inclusive, or as a reference step for other initiatives to associate and refer to. Conceptual and comprehensive analysis, as well as the synthesis of the two, are required to support a designer's workflow and requirements. Rather than expressing contemporary challenges and circumstances as inflexible site limitations, the representation introduced through site analysis ought to be generative of solutions and understandings. The site analysis tended to be adaptive, flexible, and informative.

This research study is associated with computational processes, architectural design, and spatial planning, and it examines the possibilities of generative methods in architectural design. It investigates how architects might start to utilize computing as part of the design process to generate layout and data rather than just illustration. This system examines three ESTU master plan patterns generations, determining that they are segmented. The important concept is that a design system must examine a wide range of design factors to perform "Functional Connectivity, Responsive Density, Design

Pattern”, as stated in the system development guidelines (see chapter 4 p 116). Grasshopper inside Rhino, for example, is a sophisticated generative tool that enables simulations of the design object's functionality before it is developed and exposed for examination in the final environment. However, using such particular software tools necessitates a strong knowledge of the design challenge as well as the complicated interconnections that exist between constraints, needs, and goals inside the system. The effective combination of these tools requires the careers of a new type of designers, who are computer competent and capable of creating their personalized system frameworks as well as developing strategies for their application. The possibility of investigating new methods for the design process appeared during the process of developing research key concepts. To preserve the research study within the field of architecture, it was agreed early on in the experiment that the concentration would be placed on the computational methodology while ensuring a spatial arrangement. In this research, two significant contributions to the establishment of a computational methodology for the formulation of research strategy are introduced (Figure 1.1.). The very first contribution is a descriptive classification of diverse generative design principles, systems, and approaches into separate category dimensions that we considered quantitatively important, which was based on an analysis of contemporary case studies. The second contribution is the development and implementation of a set of algorithms and strategies that address the needs of the different components. It also provides key components and guidelines for a computationally intensive digitized generative design system. The system's operation is dependent on an analogy between a design process and multiple generative methods. The presented generative design system is designed to empower architects by creating several variants of architectural models, the automated generation of which is directed by design objectives submitted by a system's user.

A computer-based platform or a future computer-aided architectural design software might also be a tangible execution of the ideas proposed and addressed in this thesis. During the representational phases of architectural design, such a system would perform as a creative design involvement. The experiment study, however, does not provide only an operative system, but also the first ground formulation for its application.

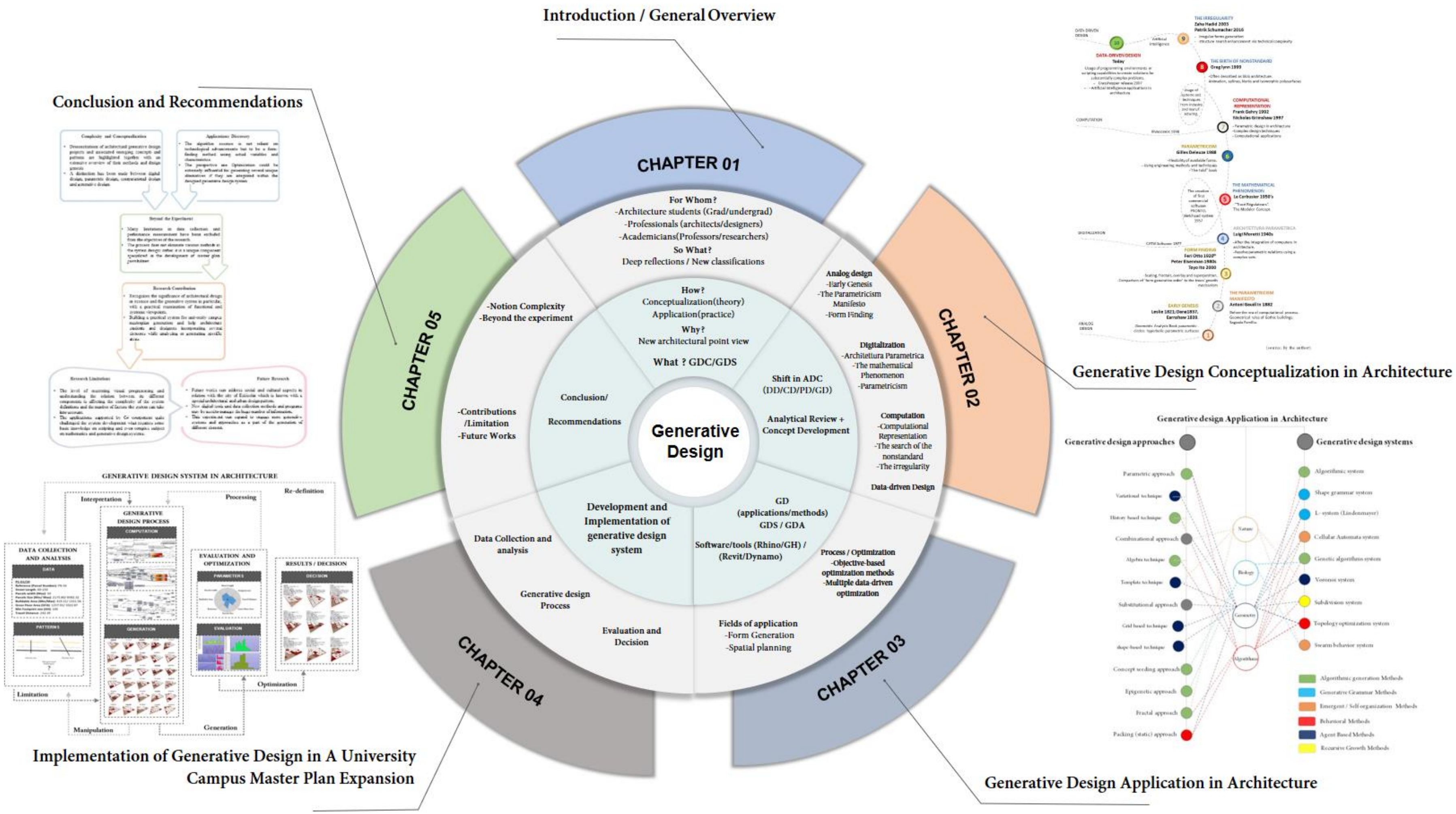


Figure 1.1. *General strategy of the research. (source: by the author).*

1.1. Problem Statement

Innovative design capabilities such as generative, adaptive, and interactive design are expanding in the field of spatial design, according to research, and design institutions are attempting to teach them, but they are still not commonly recognized as a qualification for architects accessing the employment sector (Bentley, et al., 2016). There is no comprehensive conceptual framework for architecture and urban planning that summarizes and illustrates the central notions and provides interconnections between them. A few demonstrations are relevant to the development usage of GDS in the execution of affordable projects, artworks, and other architectural applications such as building patterns or floor planning are available. Nevertheless, there are few illustrations of these technologies getting utilized in space planning. (Caetano et al. 2020).

To establish building innovative solutions, generative design approaches and systems might combine parameterized architectural elements into data transmission phases guided by a set of restrictions assigned by the designer. Furthermore, algorithmic design techniques may incorporate a multidisciplinary design process frequently evaluating and assessing the created design alternatives employing fitness functions provided by the designer that integrate elements across various domains. Similarly, generative design systems represent design possibilities in response to the intended implementation criteria, which are specified as fitness functions and input into the evolutionary computational tool. The system can fulfill a variety of fitness functions that highlight the multidisciplinary objectives of architectural design. Data collection and analysis are typically performed as an alternate option in many studies. Indeed, it is necessary to go into further detail when addressing multiple spatial and computational techniques. Accordingly, digital technologies have become indispensable in the conceptualization and implementation of contemporary architecture by introducing solutions for qualitatively presenting propositions and controlling output and design information.

The study correlates some of these approaches that differ from the systematic process to the establishment of complex operational configurations. It evolves from conventional design techniques in preference of a more interconnected system for architectural design. While the primary focus was on creating these novel types of underlying consistency, a key task was to integrate these methods with various types of existing systems (or at least geometrical principles) and performance-focused modeling methodologies. The comprehensive research effort aims to provide a design method and system for generating architectural designs by setting the basis for the entire mechanism, which will result in the layout of a generative system, from which prototypes will be created. The study focuses also on the early conceptual stage of the design process, where the most significant design decisions are made within several areas of relevance and contribution such as algorithmic architectural design, computational design, and integrated interdisciplinary design. The research investigated the significance and comprehension of generative design as a concept and as a methodology for architectural design. Although this concern is experienced by introducing a basic set of definitions and a description of relevant software applications, the theoretical section of the study appeared to respond to inquiries with a constrained understanding of the general idea of generative design.

Although algorithmic modeling techniques present immense potential for architects and designers, they may also bring significant challenges. These challenges are frequently connected to the development of programming abilities that have previously been outside of the architect's toolbox and design curriculum. The same problems are raised by the absence of descriptive research, particularly in the area of computational model representation in architecture. The real issue, then, may not be learning computing tools, but rather embracing the way of algorithmic design thinking. In order to enable integrated architecture design and enhance a collaborative connection between human creativity and computational capacity, this study develops a generative design system relying on adaptive design methodologies. It is essential to identify the perception from which the research studies were conducted; as a result of these investigations and associated interpretations, a number of crucial questions have taken place as the following:

- *What is “Generative Design” concept? What are its advantages and limitations?*
- *What are the generative design systems and approaches? What is the relation between them?*
- *How can the generative methods provide new and interesting solutions for specific problems in architecture?*

- *To what extent was generative design application introduced into the field of architecture and space planning?*
- *What are the main influential aspects of integrating advances in GDS for master plan expansion processes on university campuses?*
- *How can generative design methodology be applied to a specific site's design process? In which degree does the process contribute to the complexity of architectural design?*
- *How do the systems allow for new sorts of form-generating process interactions to be integrated?*
- *How do we maintain the spatial quality, geometric constraints and context requirements during the generative design process implementation?*
- *How can the generative design method interpret different constraints and requirements while respecting different characteristics?*
- *What are the prospects for generating new types of feedback loops in the operation improvement process using generative capabilities? Which characteristics distinguish design from standard CAD?*
- *Does the designer's position in the design process shift as a response to generative methods? Is the design process entirely dependent on generative software?*

1.2. Purpose and Scope of Research

The examination of several studies on this subject has made for a better knowledge of previous and present applications of generative design in architectural design and urban planning. Digitalization techniques are being used to investigate the current architectural design possibilities. In the design process, new techniques have been developed that are better adapted to dealing with transformation. One of them is generative design, which may be considered as the generation of forms based on algorithms. The notion "generative design system" has been used in a diversity of fields and has a multiplicity of interpretations. The ability to programmatically create or modify a design model focused just on generally formulated characteristics of the proposed project is the underlying measurement for all generative systems. Algorithms are not a new concept in design and maybe dating back to an era when computers didn't even exist. However, most early conceptions and applications of algorithms were centered on specifying and projecting the design processes or intentions to generate possibilities with specific qualities.

These techniques, originally called digital architecture, encompass form generation as well as transformation. This research investigates the validity of digital generative systems, which are associated with ideas such as performative design and computational analysis tools. The focus is on process discovery using digital generative approaches. The area of generative design is strongly dependent on natural principles and architectural techniques that have acquired universal recognition in the professional field. It facilitates the exploration of new possibilities that exist in revolutionary architecture design concepts.

Computation seems also to be one of the most fast-growing architectural design shifts. It enables architects to a-one-of-a-kind way to transform a concept into a morphology by implementing a basic sequence of operations and criteria that can connect the form to larger environmental aspects. Theoretically, despite the sort of software programs presently or in the coming years adopted by architects, the concepts of combining conceptual and specialized algorithmic methods will continue the same. However, several systems and approaches are investigated in the scope of this study employing visual programming using Grasshopper/Rhino. This section goes through the study's boundaries in further depth.

The majority of the presented conceptual classifications and concretizations are regarded as functional recommendations rather than philosophical assumptions. The purpose is not to make definitive generalizations about how the system should be implemented, but rather to systematically investigate the topic of a generative design in a particular context to have a well-informed basic framework for its execution.

The experimental study emphasizes the important architectural design advancements and technologies, such as design-process techniques, computer-aided designs, simulation strategies, and evaluation tools. It primarily brings into question designers' degree of control over design processes and the unique interactions of processes in computational architecture design. The objective of this study is to compare and analyze current methods in architectural design. In association with various technological tools that are exploited not just for representation but also for design generation and possibilities evolution. Students, researchers, designers and architects, both beginner and expert professionals, are the study's target audience. Even though the potential participants were a broad mix of both students and instructors, their expertise with algorithmic modeling tools, notably Grasshopper, was limited.

The focus of the research described in this thesis is to develop and demonstrate a method that may be used to model and control the design process independently, customized to a specific design challenge, and in connection with the designer's personalized opinions. The procedure will be used as part of a digital design process in which modeling and analysis not only assist the project transformation process, but also interact with and contributes to innovative strategies, encourages a more expressive investigation of the solutions, and intends to integrate computational frameworks into the interpretation process and the designer's operations throughout the entire design process.

The concern evolved not only about designers' involvement getting replaced, but also about their creativity necessity. Therefore, the system appears to be fundamentally questionable. CAD tools have long maintained an important part in the design process, helping to improve efficiency. Their recent advancement has had a significant impact on design processes and architectural conceptions. The requirement to commit to restrictive limitations is viewed as a requirement on the quality of the final result of their innovative process. These limitations also involve the ambitions of software tools intended to enable designers in the generation procedure; practically all of them are related to the technical or information-based aspects of the process. Only a number of these technologies are responsive to the design process's fundamental innovative intentions.

This investigation is primarily constrained by basic architectural components that can be created in contemporary CAD and CAAD systems, as well as the integration of those needs that can be imitated by available tools. This research study does not intend to be globally applicable and will be limited to the use of spatial characteristics when input parameters are requested, as this kind of feature offers the maximum variety of practical characteristics and geometrical opportunity, thus marginalizing other more traditional components. However, the outcomes of the study may be applied to relevant contexts with minor adjustments.

The system essential was presented in the creation of a completely operational system framework that could reproduce the functioning of the suggested approach and its conceivable integration in a design process, with an emphasis on the combination of CAD software with simulation and analysis tools. The opportunity of a continuous organization of information across the various components of the software construct will be explored as an additional focus. The main objectives of the research framework construction are presented as the following:

- *Contribute to the body of existing literature by clarifying the generative design concept development and providing practical classifications for its systems and approaches.*
- *Explore the potential of generative design and its implementations in architecture and spatial planning.*
- *Propose a method to understand and discuss the different design stages using the generative system.*
- *Explore and structure relationships between architectural design and different generative methods through both spatial and computational analysis.*
- *Apply the system to a specific site, analyze and evaluate the results and discover its limitations.*
- *Integrate many pre-defined procedures for generating various design layout possibilities.*
- *Empower a prospective expanded basis (with various design possibilities) from which architects may choose pre-defined components. Likewise, additional features that match more particular design solutions could be implemented and incorporated into the process model, making it more comprehensive.*

The research major goal is to explore and develop the design features and concepts of a generative design system in various circumstances, as well as to examine them from various viewpoints, to provide the audience with a new classification on the field of computer-aided innovative design. The classification's primary aim is to guide architects in selecting methods that are more appropriate to their design objective. This research intends to determine the benefits and insufficiencies of each method, as well as to determine how each strategy may be developed and to recommend ways in which re-use of data could be incorporated into design education and practice, as well as if it would be convenient. Its purpose is to investigate and assess the potential of GDS as an instructive tool in the design process. It examines and assesses an algorithmic design approach, in which algorithms are converted into a visual programming language and parametrically described. The focus of this study is to better understand how generative design is being developed and included in the fields of architecture and space planning.

The study creates a preview of the present degree of adaptability to the innovation of GDS into spatial architecture using a qualitative research method to design studio-based experiment, spatial and computational analysis, and conclusions to the data implementation and manipulation. The generative design system investigates the position of key variables, the involvement of the designer, the importance of sketching, and the function of computer programs. It represents a methodology that helps architects to generate university campus master plan alternatives by using different systems and approaches. It also studies and analyzes many further design phases that compose an algorithmic-based design process, especially the interconnection of functional connectivity, responsive density, and design pattern during possibility generation.

1.3. Research Methodology

The transdisciplinary dimension of architecture and design research is one of its key differentiating aspects. The limitations of researching "out of a field" or "across subjects" have been addressed in transdisciplinary existing scientific studies (Woyseth and Nielsen, 2004). Consequently, this research has interdisciplinary considerations, which presents several problems. Building a visual algorithmic design tool that fully utilizes the capabilities of cutting-edge computers necessitates multidisciplinary collaboration between architects and professional engineers. It emerges that an absence of comprehension between the disciplines of architecture and computer science might be a challenge at times.

The study methodology combines a number of diverse sub-areas of research, such as conceptualization research design “ground theory”, qualitative and quantitative investigations “correlational research”, spatial and computational analysis “experimental research” and “comparative research method”, algorithmic applications “simulation research” (Groat and Wang, 2013), and other related strategies. Engaging in these various research fields is a methodological challenge (Figure 1.2.). To address a given research concern, one must first acquire appropriate data from various study fields and then integrate them while ensuring compliance with environmental and design limitations. However, when the information is being utilized beyond its interdisciplinary perspective, it cannot be confirmed using the scientific procedures unique to the discipline from which it was acquired.

This study was conducted as a method of research by design. Without going into contemporary discussions over practice-based research terminology, the methodology concentrated on innovative approaches to applying in architectural design via experimental investigation rather than just examination of manuscripts in the field. The hypothesis was that by employing this method, considerable insights into emergent possibilities in generative design and architectural design limitations would be discovered for the benefit of students, architects, designers and even academicians in the relevant fields. Based on the highlighted traditional challenges, this study attempts to understand more about how architects and designers behave when spatial generation in architecture is considered throughout the conceptual design process. The methodological stages to maintain the intended objectives are divided into four steps: (1) a comprehensive examination of the literature review, (2) case study area identification and management, (3) spatial and computational analysis, and application of numerous visual integrative methods for generative design systems, (4) establishment of overall evaluations, conclusions and recommendations.

The first step, the literature review, resulted in a bibliographical investigation focusing on computational design tools, design systems and approaches, and conceptual frameworks (Jabareen, 2009), particularly generative design. This part enabled a holistic understanding of the fundamental concepts of digital design, computational design, parametric design and generative design following a grounded theory methodology (Tan, 2010; Cho & Lee 2014). Furthermore, the actual position of the practical application is discussed in relation to the contextualization of these concepts in architectural design over the years. The second step proceeded with the identification of the case study, which followed a search for developments with features that would allow the suggested method to be evaluated (Cho & Lee, 2014). Throughout the design process, it is required to examine the university campus master plan and establish a comprehensive order of considerations and perspectives (Voordt et al., 1997). The third step formally established the design principles of the various layout parameters through the use of a design studio-based experiment. It also engages spatial and computational analysis techniques to analyze data like street networks (Berghauser and Haupt, 2007), GSI, FAR, OSR variables (Pont and Haupt, 2010) and Isovist visibility analysis (Davis & Benedikt, 1979), produced explanations of the procedures researched, generated hypotheses about the significance of the processes investigated, and essentially described the challenges encountered and the further problems to be investigated. Following that, several algorithms based on diverse systems and approaches such as evolutionary generation systems (Frazer, 1995) (Pohlheim, 2006), algorithmic system (El-Khaldi, 2007), subtraction approach (Trabell, 2003), parametric approach (Janssen, 2004), are developed and integrated with a visual programming language, with many functional interconnections. The related procedure is constantly evolving and being evaluated for future developments. The final section, evaluation and conclusion, discussed the research's outcomes and challenges and emphasized the research's significant contributions, relevance, and possible future developments.

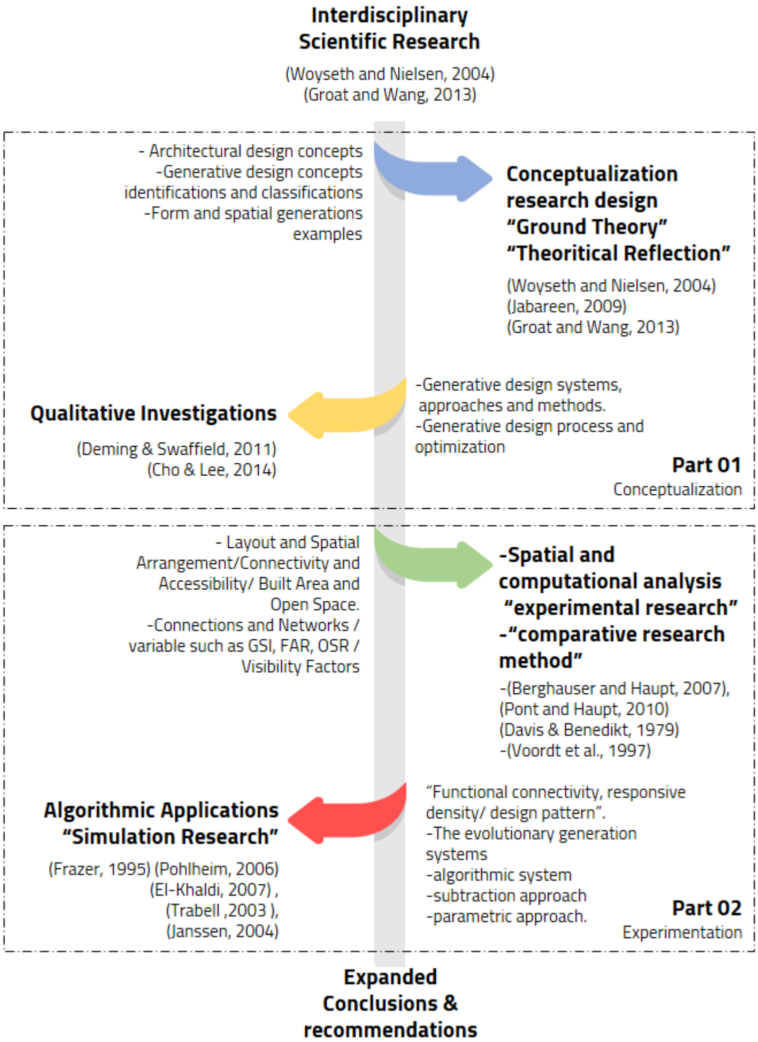


Figure 1.2. *Diverse sub-areas of the used research methodology. (Source: by the author).*

The method developed at the basis of this study represents a variety of aspects and measurements associated with architectural design (Figure 1.2.). The primary goal was to provide a system for architectural design and space planning that was based on a combination of well-established algorithmic principles. Each step of the methodology illustrates how much it is based on, and how much it varies from, the established system. For each part, additional frameworks or combinations could be effectively implemented. The research's multidisciplinary characteristics contributed to determining the number and type of design challenges, as well as the frequency of recurrent design practices. It explored respondent input on the extent of adaptability of the design output as well as their determination to generate more complex university campus master plan systems in the future.

1.4. Structure of the Thesis

The thesis is divided into two major parts organized under five chapters. The first part is focused on a contemporary conceptualization of the generative design concept, including a consideration of the established systems and approaches, as well as how they associate with architectural design and spatial planning in general. Many architectural examples are examined in significant depth to establish a consideration of certain methods within an architectural framework. The complexity of technical information expands in the second part since chapters are concerned with the main body of research. In this part, the formulation and implementation of the generative design system performed within the case study area are described in detail. The two sections are fundamentally interconnected since the methods in the latter section assist to construct the discussion in the first one.

Chapter 1 offers an overview of the work, defines its context, and demonstrates some of the major concepts introduced and elaborated on in the subsequent chapters. This chapter offers a clear perception of the research problem statement, the purpose of the study, the research methodology, and the key term used while expanding on the literature parts. It also introduced the research's motivation in an attempt to outline the experimental part of this work.

Chapter 2 briefly reviews the paradigms and conceptual perspectives in architectural design. It engages a theoretical reflection on the definitions of different design concepts and their advancement in architectural design. In addition to that, practices' innovation and application in several methods are examined indicating the restricted limitations and future opportunities for the benefits of generative design thinking and practice in architecture. It focuses on examining digital advances and computational innovation in architectural design. It first discusses what digital and computational design are, why it is necessary to innovate in architecture and how it relates to architectural conception and practice. In addition to that; various methods, processes and improvements in parametric and generative design technologies are explored to fulfill a gap by better determining the degree of adaptability to these advances.

In Chapter 3 The essential generative design systems and approaches are identified, as well as the overall conception of a descriptive process for interactive generations is explained. It tends to provide a new classification of generative design systems and approaches and explore their applications in architecture. Besides that, generative design processes and optimization methods engaged in different architectural design applications are also reviewed and summarized. This chapter compares current generative design methods and offers some insights into what may be acquired from other generative systems and design optimization. The multiple functional components of the software employment are demonstrated and explored. These principles serve as a foundation for the formulations and implementations of the generative design system in the case study area and future architectural design applications, and they are an important component in the definition of a new discipline identified as generative digital design.

In Chapter 4 the presented generative design system is developed, evaluated, and implemented in the case study area. After providing a general overview of the case study area, this chapter focused on accurately identifying and classifying the design problems that should be solved with the generative design system engaging different techniques and qualitative and quantitative methodologies for data collection and analysis. It also introduces the formulation and application of generative design systems as a response to the specified design problems, design requirements and limitations. This chapter explores a flexible, adaptable system using the 3D modeling software "Rhinoceros" along with the parametric plug-in Grasshopper and different other Plugins. Many applications were established and maintained, and the outcomes from these simulations are illustrated in detail and briefly analyzed and evaluated.

Chapter 5 addresses the findings and limitations of this study, including research conceptualization, methodology, and several comprehensive parts of the development and implementation of the generative design system. It highlights the research's initial contributions, applicability, and potential future advancements. It summarizes the study by comparing the findings of the various experiments and simulations, as well as discussing and evaluating the presented concepts. The evaluation and practical implementation of the developed generative design system are extensively investigated. Some suggestions are also provided for future research work.

There is a great expectation that the following diagram will be beneficial and useful for anyone interested to have a structured overview of the generative design subject in architecture following the step by steps reading pathway (Figure 1.3.).

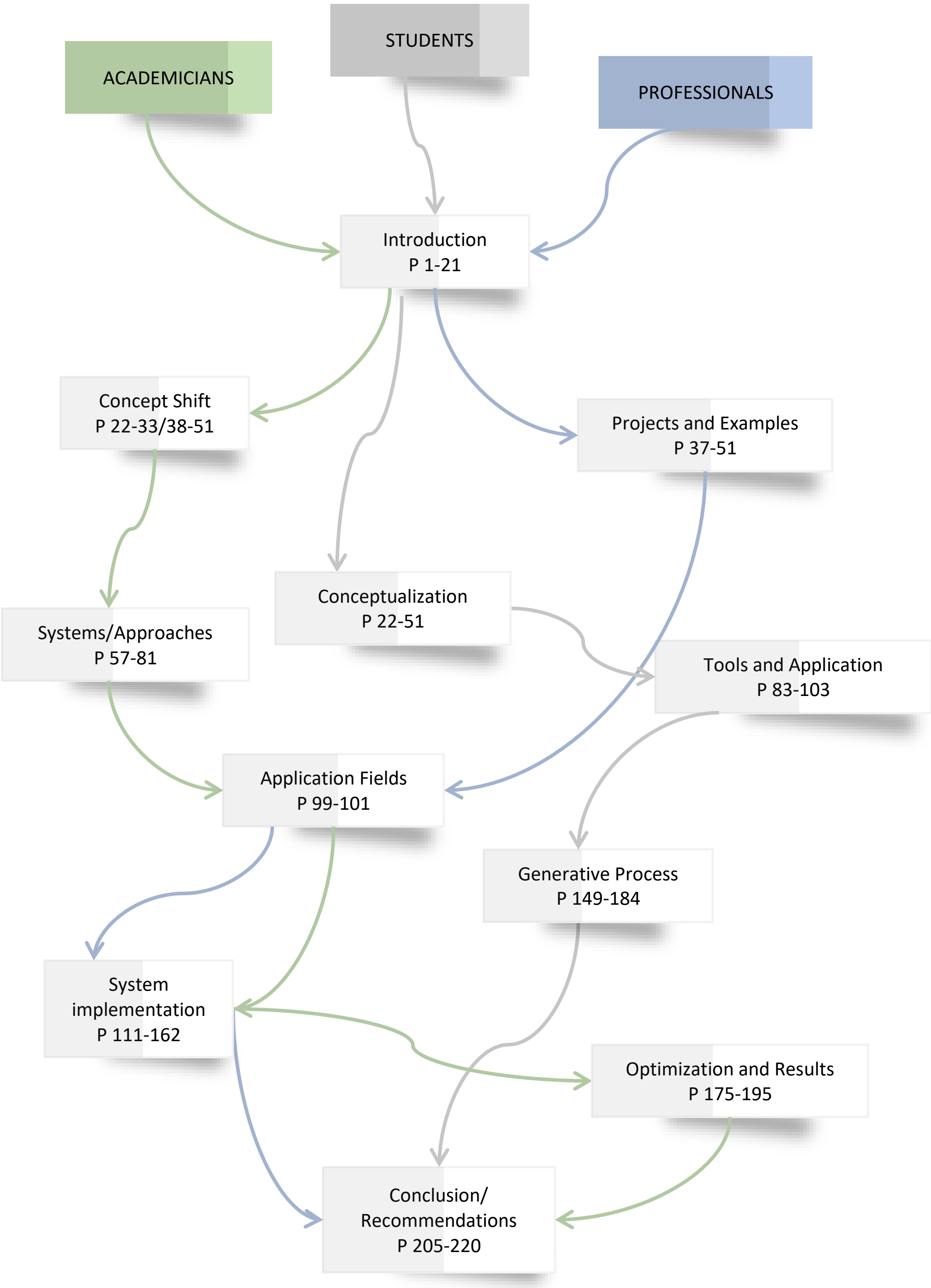


Figure 1.3. *Reading pathway for a structured overview of the generative design subject in architecture. (Source: by the author).*

1.5. Term Used in the Thesis

Some of the key definitions used all through this thesis will be described and addressed briefly in this section. It is not intended to be a glossary, but rather a useful explanation about how various concepts are connected to the generative design concept and system application.

Theoretical Reflections: definitions of different design concepts and their advancement in design. An introduction of relevant ideas from other fields enables architects and designers to change ways of thinking and combine novel concepts and practices.

Classification/Organization: theoretical search and conceptual review organized chronologically under several periods. Contextualization of a concept evolution linked to design concept and the identification of the emergent technical terms that better supported the process is addressed within each period.

Traditional Tools: An approach in which CAD instruments are utilized to demonstrate or conceptualize a design based on representational models generated through clear and specific modeling processes.

Analog Design: refers to the methods used to define and communicate architecture before the invention of computer systems. A non-computer-based procedure, also known as paper-based processes.

Digital Design: computer-assisted practices, as well as a variety of efficiency assessments and mechanisms that reflect the generated physical environment. The involvement of design applications such as CAD, CAAD, and CAM.

Computation: usually relates to the application of mathematical or logical methods with or without the use of a computer.

Computerization: the mechanism in which computers, various tools, and software are used in design practice.

Computational Design: the implication of software advances that have advanced design tools and processes, as well as design methods. use of appropriate design software and mathematical computer capabilities in specialized modeling and illustration.

Computational Approach: a design method that is controlled and adaptable to change. It enables the creation of different versions of the same design.

Computational Architecture: a strategy for addressing how important software and hardware components of a computer system are arranged and integrated. This encompasses the roles and reactions of several components such as mathematical formulas and many more. Mechanisms for communication and data formats can also be specified.

Parametric Design: a design process based on algorithmic reasoning that allows for the creation of variables and guidelines that identify, encode, and explain the link between design intent and design performance Parameters that influence the outcomes' complexity, flexibility, and representation.

Parametric Evolutionary Design: a design method that uses an adaptive system to find efficient or multiple objectives design alternatives to a well-defined design concern. The evolutionary system employs a collection of fitness characteristics or target functions to develop an optimal or deterministic set of parameters.

Generative: a rule-based strategy in which sophisticated behaviors originate from the combination of non-interconnected parts.

Generative System: a system that uses generative design principles to generate possibilities for a diverse variety of design challenges.

Algorithmic System: An approach that proposes to be incorporated into the design process. The application of a Generative Algorithmic System capable of dealing with evolution. Because the design is customizable, it is feasible to produce several iterations of the same design.

Data-Driven Design: the employment of various methodologies and procedures that rely on data collecting and user decision-making. It is treated considerably as data gathering, design output selections, and uses the same approaches to analyze the goal design objectives and provides unprecedented generation possibilities and alternatives.

Performative Architecture: an architecture that employs digital technology to question the design of the built environment in both research and practice.

Kinetic Architecture: a design paradigm in which structures are built to allow components of the building to move while maintaining overall fundamental integrity.

Biomimicry: It is an interdisciplinary science that takes inspiration from human challenges and design proposals from the study of natural patterns, structures, and mechanisms.

Self-organization: a flexible and adaptable process through which systems develop and retain structure without the need for external control. In biology, the terms self-organization and emergence are frequently used interchangeably, implying the same phenomena.

Emergence: a procedure by which a collection of interacting components obtains qualitatively new features that cannot be explained simply by just adding their respective contributions. In some cases, it is referring to "self-organization" mechanisms.

Algorithm: a set of instructions and regulations that can be expressed semantically or graphically A method of resolving a problem in a sequence of stages that employs the logic of "if/then/else" procedures.

Algorithmic Design: refers to the application of operational logic and calculation based on regulations. It is usually carried out using computer programming languages.

Morphogenesis: It is a wide notion that refers to the creation of structure and pattern by a controlled development process and/or mechanisms.

Computational Morphogenesis: In accordance with natural evolutionary processes, computational morphogenesis is a design method that takes the opportunity of the two primary aspects of evolutionary algorithms exploration of a large range of alternatives and exploitation of the optimal designs generated.

System Dynamics: is the study of complicated systems' responses over time. It considers how changes in one component of the system influence other components of the system, so a change in one of them may result in a change in many of them, which in turn impacts all the system.

Topological Transformations: Without cutting or merging, the evolution of one item to another preserves its topological characteristics. Because distances and dimensions are irrelevant in topological transformation, the element can be extended.

Program: A design that is represented in a formal direction. An algorithm is a set of detailed and precise guidelines expressed in a programming language that informs the device what particular actions to take.

Computer Program: a collection of procedures that work together to accomplish a given task on a predetermined computing platform.

System: is intended to describe a collection of combinations and computational applications that give a variety of design possibilities. It is a method in which a complicated process uses various pre-collected data to respond to design challenges by giving superior design choices.

Approach: is meant to express a tendency to make a proposal or suggestion to resolve a specific design challenge with the support of other applications that must be connected with and integrated inside a given system.

Process: is a setting in which a design system might be carried out utilizing one or more design methods. A component of a larger system that determines the underlying theoretical links and functional connections that exist between various methods or systems in a given domain.

Procedures: incorporating the whole design stages, setting the interconnections between them, expressing and integrating the many systems and techniques that address that design component, and for the computing that may be required to deal with specific design conditions.

Method: handles a diverse design challenge with approaches that can precisely answer a single aspect of the problem, such as managing data, organizing outcome possibilities, combining many perspectives, and so on.

Methodology: the precise strategy for identifying, selecting, processing, and analyzing information about a very specific topic. Multiple quantitative and qualitative evaluations and analysis processes are used to process data in response to design requirements and circumstances.

Algorithm: a collection of programming instructions. Procedures for addressing mathematical challenges insystematicallyAlgorithms typically begin with an input, proceed through a cycle, and then provide an output response.

Series and Sequences: A series in mathematics is the total of all the parts in an infinite sequence. A mathematical sequence is an infinitely long ordered collection of items (or instances).

Programming: the act of creating application programs The process of converting procedures into a computing expression so that they may be executed by a computer.

Programming Language: a framework for expressing computer programs components that could be used for multiple calculations and executions.

Scripting: the process of creating a computer script (a single passage of code for doing a specific task).

Parameters/Variables: a collection of variables that may be changed, edited to manipulated (separate /categorical -whole number continuous -decimal number permutation /grouping -whole number sequence A set of factors within an expression that limits the potential outputs of a math formula.

Objectives: functions expressing the problems minimize value/maximize value

Constraints: Functions that express the circumstances that lead to a valid outcome (equal to a predefined value / less than a predefined value / greater than a predefined value).

Design Intents: to provide design systems with a specified sufficiently structured goal so that they may be processed in the intended direction of application

Open Source Software (OSS): Computer program having its source code provided under a license in which the copyright holder grants the right to study, modify, and transfer the software to anyone and for any intention. This software, such as apps and plugins, is occasionally made accessible to the public for free to help the innovation capabilities.

Rhinoceros: Rhinoceros, commonly known as Rhino, is a stand-alone 3D modeling tool that provides accuracy and versatility for anything from industrial design to architecture and engineering. It also serves as the foundation for Grasshopper and numerous other plugins.

Plugin: a software component of a major program with specialized capabilities and functions inside the overall software framework.

Grasshopper: A generative modeling plug-in for the Rhino 3D CAD system that can accomplish extensive scripting using visual programming to explore 3D objects and structures via the input of a visual programming canvas.

Visual Programming Environment: a calculation mechanism inside the framework of a software integration that interacts with the geometry of a CAD model to modify the shape or layout of a parametric model by utilizing variables or components.

Functional Connectivity: equilibrate street networks responding to all mobility types (Car/bus, bicycle, Pedestrian), determine a parcels division logic that responds to all spatial requirements and design conditions and then place the functional location of the main entrances for main parcels as well as buildings blocks.

Responsive Density: allow density of land use, parcels division and university campus functions distribution to be implemented as input parameters to drive the process towards a variety of generic alternatives.

Design Pattern: It refers to the availability of a fundamental structure or system that is recognized and so, in principle, can be described using a set of requirements. The dimensions of each building block and its relation with the general parcel are calculated and defined inside a geometry cluster that contains a collection of functions in Grasshopper components.

2. GENERATIVE DESIGN CONCEPTUALIZATION IN ARCHITECTURE

Digital design, computation and parametric design have rapidly advanced the architecture and spatial planning fields, where performance, optimization and visualizations deliver significant advantages and novel development techniques compared to conventional design. However, generative design methods do not provide a technical means of doing the same as the knowledge obtained via the practice of design. To better understand the subject, this section of the research engages a theoretical reflection (Jabareen, 2009) on the definitions of different design concepts and their advancement in architectural design (Figure 2.1.). In addition to that, practices' innovation and application in several methods are examined using a grounded theory methodology (Tan, 2010; Cho & Lee, 2014) indicating the leading limitations and future opportunities for the benefits of generative design thinking and practice in architecture.

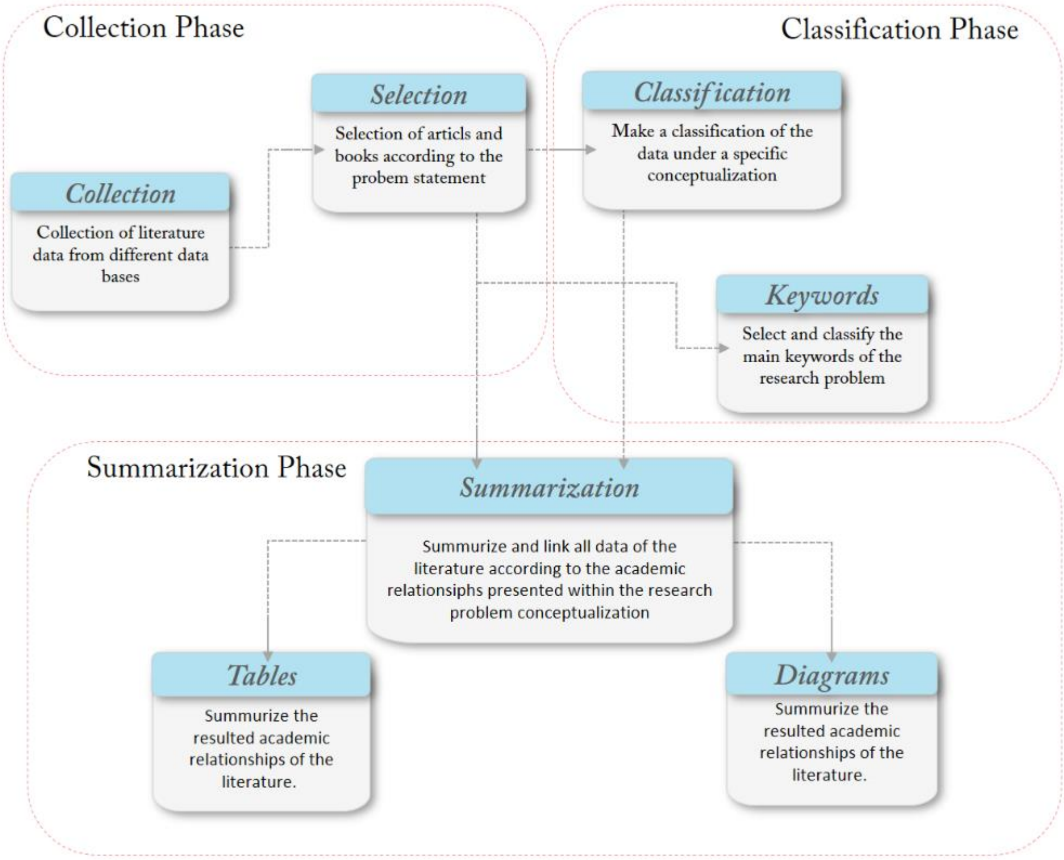


Figure 2.1. *Theoretical reflection on the definition of different design concepts. (Source: by the author).*

2.1. Conceptual Shift in Architectural Design Concept

The rapid evolution and use of digital design technologies have expanded both analytical and technical ability within theory and practice in contemporary architecture. It has also allowed to explore complex architectural systems and introduce effective innovative design possibilities. Computation has challenged the basic design paradigm, by introducing relevant ideas from other fields which enable architects to change ways of thinking and combine concepts and practice. As a consequence, through their research and works, many professionals, educators and researchers can experience the opportunities and limitations of generative design. It is mainly focused on more than just technological tools. Behind the development of methods, there are many conceptual ideas, approaches and frameworks, as well as logical processes that have led to other applications providing data, models and visualizations (Caetano et al., 2020).

Computer improvements and technology have been a constant for over fifty years, and it is as crucial as ever to be flexible to cope with newer technologies or processes when there is a request for them. In general, the literature research examined the origins, previous developments, and current technological tools for designers engaged in related disciplines. However, the prevalence of such advances in architectural design research and practice appears to be restricted and requires further profound examination (Zhang and Xu, 2018). The employment of generative design and related subjects is expanding, according to the existing literature. It is essential that design companies and educational establishments take a closer position at where they stand in the growing architectural design engagement, as well as the state of their digital and computational design knowledge-making progress.

This part of the research focuses on examining digital advances and computational innovation in architectural design. It first discusses what digital and computational design are, why it is necessary to innovate in architecture and how it relates to architectural conception and practice. In addition to that; various methods, processes and improvements in parametric and generative design technologies are explored to fill a gap by better determining the degree of adaptability to these advances (Figure 2.2.). Those methods and techniques are based on computer-aided design, parametric processes, algorithmic procedures and visual programing which propose the ability to change the limits of space planning and structures representation that are already applied in fields such as construction, manufacturing and industry. It explains how these methods have been applied, and how the design developments are used to enhance final architectural success.

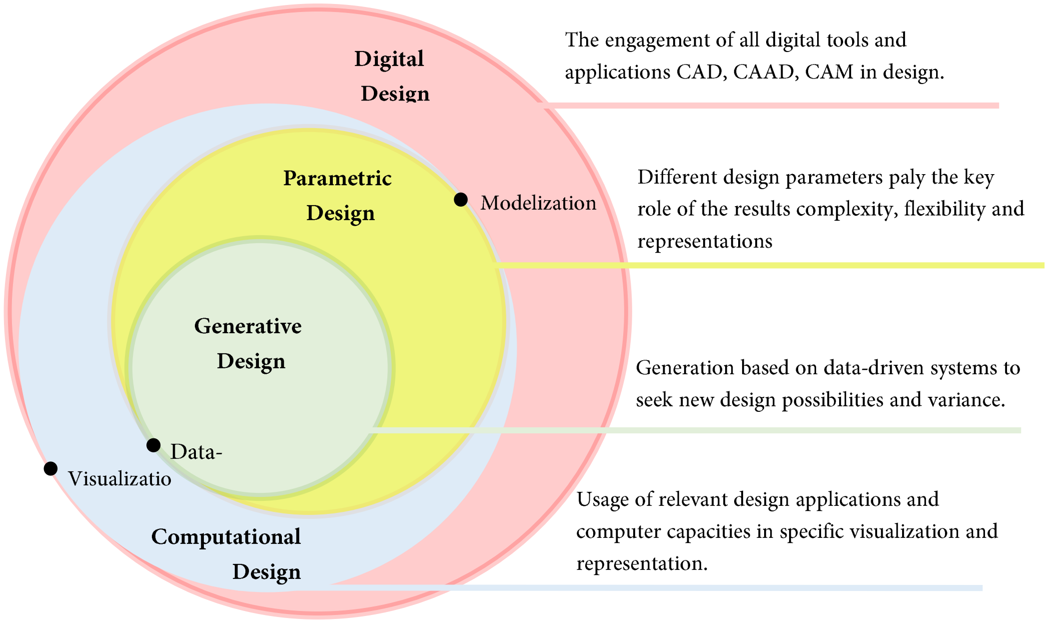


Figure 2.2. *Interconnections between different design domains in architecture (Digital design, Computational design, Parametric design, Generative design). (Source: by the author).*

2.1.1. Digital Design

For many years, computers were implemented as alternatives for drawing tools in architectural design studios. Significant Computer-Aided Design (CAD) software, was essentially computational variants of devices that architects had been using for decades. They primarily accompanied the architect in the modeling process, not so much in the formulation of architectural design methods and approaches. Innovations in these early stages of computation related to efficiency and accuracy, rather than considerable functional improvements to the architect's toolkit. Advances in computer illustrations, as well as 3D simulation tools, resulted in a collection of computer technology designed to generate 3D visualization (Figure 2.3.). These capabilities were initially developed for use in the filmmaking and media industries, but they rapidly made their way into the architectural domain (Park et al., 2016).

Models and simulation tools have been invented to evaluate heat exchanges on the building envelope, wind resistance of a skyscraper, solar radiation in building facades and roofing or extensive urban areas (Fink and Koenig, 2019a). All of these models provide architects with a variety of efficiency measurements that represent the physical environment they are creating. They all distinguish in terms of sophistication, validity, model instability, and processing time.

Advances in computer graphics, as well as 3D modeling technologies, have created a series of software applications for design and visualization. All Computer Aided Architectural Design (CAAD) programs use a database containing geometric and other entity characteristics; all have graphical user environments to modify visual representations, and all are used to create or evaluate structures from normal and non-standard materials. CAAD systems have two differences, first, they have a specific entity inventory with building parts and construction data, and second, they specifically help architectural model development. Their usage allows for distinct design, planning and manufacturing phases as well (Brown, 2015).

Educational and organizational challenges have stayed the most significant constraints to the use of software in the work of design fields (Göçmen et al., 2010). Despite the widespread use of computational technological advances in contemporary applications, the majority of architects and designers are still unfamiliar with the principles and advancements of algorithms included inside the computing tools they employ. They promote analytical philosophy which involves an approach to solving design problems and developing computer science-based systems (Cantrell and Holzman, 2015). They are auxiliary design instruments where design can be managed from design ideas to fabrication (Oxman, 2017). Compared to the more standard format of coding, open-source software makes it easy to improve the capabilities of a software application. It is integrated into the code base of the program and enables a copyright holder to study and adjust the software to perform new purposes (Laurent, 2004). According to the latest studies, open-source software digital platforms as SketchUp have achieved success in the design disciplines; and it is currently one of the most frequently selected tools for new environmental design applications (Bentley, et al., 2016).

Commercialization of the first CAAD software in the ' 80s, brought up to help make sketches, has gradually become part of the tools of the designer (Giuseppe and Alessia, 2017). With many millions of copies sold in 1995, Autodesk positioned itself as the leading company in computer-aided design software. This was the first year they launched implementing 3D Studio Max for the Microsoft Windows platform. AutoCAD availability was upgraded in 1997, and an adjustment cloud was introduced for reviewing and redlining drawings along with the creation of visualization and many other compliant applications (Caetano et al., 2020).

A number of improvements in 3D modeling, lighting and rendering were made earlier. It was another significant year for evolution. Architecture, industrial engineering, and geoengineering became the emphasis of Bentley's Software technology. Thousands of copies of AutoCAD LT have been sold in one year (Hurley, 2017). Revit Technology Corporation thereafter released the first commercially accessible parametric building information modeling solution for the AEC sector (Jin, 2003). After a few years of preparation, SketchUp was released in 2000. SketchUp's successes, as well as their cooperation with Google Earth to develop a plug-in to map SketchUp models into space, encouraged Google to purchase the enterprise (Donley, 2011).

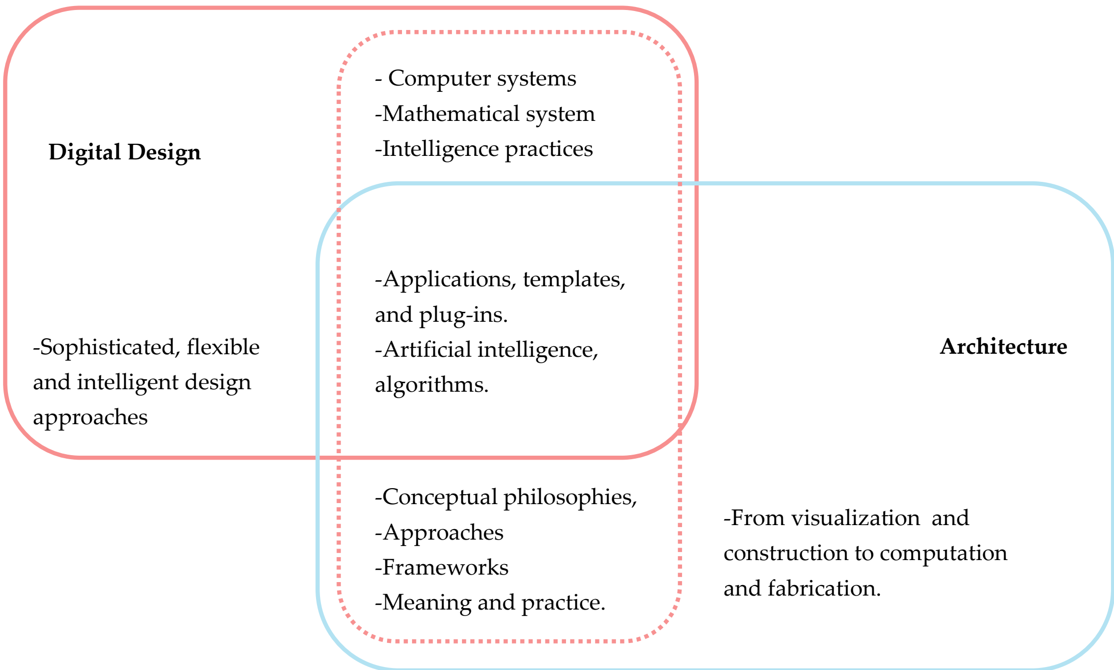


Figure 2.3. *Model representing the intermediate concepts between digital design and architecture. (Source: by the author).*

New tools for digital urban design tend to strive for imitating the role that CAD provides for architects where there is no process modeling but data management in the form of regulation is the only way to drive architecture. Although significant amounts of data tend to be combined and connected, the author as a user considers himself outside the process and interacts only with quantities of input/output (Derix, 2009). Urban designers and architects are strongly recommended to explore how a mix of analytical resources will better complement the decision-making process and ultimately help turn practical work from one method to various ways. This would have an emphasis on the productivity of architects in developing, engaging, assessing and reflecting project ideas (Carmona et al., 2010; Neto, 2006).

Initially, knowledge about the area and its features are collected and extracted from software for the geographic information system (GIS), as well as existing building requirements from the original building records and the BIM model. To build design concepts such as Revit, Archicad, Rhino3D and 3ds Max, various software tools have been used (Aksamija, 2016). Simulation and data assessment software were implemented during the design phase. Parametric modeling software such as Grasshopper and Dynamo plug-ins are used to scale and place components and to evaluate sophisticated shapes and configurations based on the results of the experiment. The innovation in computational software has not stopped growing and supporting the improvements of architectural design. Today, digital technologies will help architectural design processes at any point, from architecture to engineering, manufacturing, and construction.

2.1.2. Computational Design

Computational advancement in architectural design is a result of software developments that have expanded tools and techniques for design applications as well as design methods. It is fast becoming a key instrument through both theoretical and practical aspects. Computer software has become more capable of advanced aesthetics and analytics, as well as becoming more intuitive to use. The use of software, visual programming, parametric design methods and scripting strategies to assist the design process is growing. Compared to traditional 3D modeling software applications, these new methods of using computational design techniques may be more complex, and require advanced shape discovery. This development enhances both intellectual and technical capacity in contemporary design theory and experience to exploit dynamic spatial structures and implement educated and embodied visionary computational design possibilities (Tsiliakos, 2012).

Within the scope of computational design advancement, many software uses representational strategies during the modeling experiments. This revolutionary technology allows for the creation of curves and shapes that integrate math and structural studies, making three-dimensional design convenient and more effective than before (McNeel, 2015). This representation encouraged an exponential increase in using the application as a proper computational and even parametric design tool, as shown by mid-nineties' works (Jabi, 2013). The capacity to three-dimensional space form employing dynamic volume instead of conventional directed assembling is one of the many designing processes made possible by modern advances in computer modeling. This improvement permits extremely personalized complex environments. It attempts to increase the human interaction via their environment, as well as to discover a new spatial feeling and balance in a segmented urban space (Mayne, 2011).

Architectural design has been able to experiment with novel geometry due to modern computational methods. Through organic expression, they expect to reflect the cultural, behavioral, and geographical variety of places. Designing using computational tools offers remarkable possibilities, but they must be considerably managed. However, it is a significant concern in the modern urban planning field to incorporate the best features of traditional characteristic value and perception of place with the cutting-edge advanced technology while remaining neither unpredictable nor excessively simplified (Mayne, 2011).

The technological developments and computing methods in the twentieth century, as well as research in mathematics, geometry, and physics, brought about fundamental changes in architecture as a consequence of its close connection with other disciplines (Kolarevic, 2013). The computational design concept provides a link between mathematical method and global approach to architecture based model that evolves complex particular processes interrelated to their context, spatial and environmental movement (Ahlquist and Menges, 2011). It has evolved in the field of architecture as a sub-discipline that is collaborative in concept and uses actual computational technologies to consider and solve complex architectural design problems. This offers tools for architects and designers to utilize throughout the engine a more systematic and active process. After that, the principle of computer design concept started to be defined as algorithmic, based on computer design thinking, computer design frameworks as well as many other methods (Çolakoğlu and Yazar, 2007). Recently, Computational design reach and execution processes often depend on the size of the corporation and whether the career perceives itself as producing a design style (Derix, 2010).

In this context software applications such as CAD and 3D modeling, BIM, visualization, parametric design and form generation and simulation tools, as well as specific platforms are recently employed in the architectural domain and design practices. CAD and 3D modeling applications are generally used for modeling and design representation. BIM applications are used for model-based design and construction. Visualization applications are used for rendering, while parametric design and form generation are used for design capabilities and form finding possibilities (Figure 2.4.).

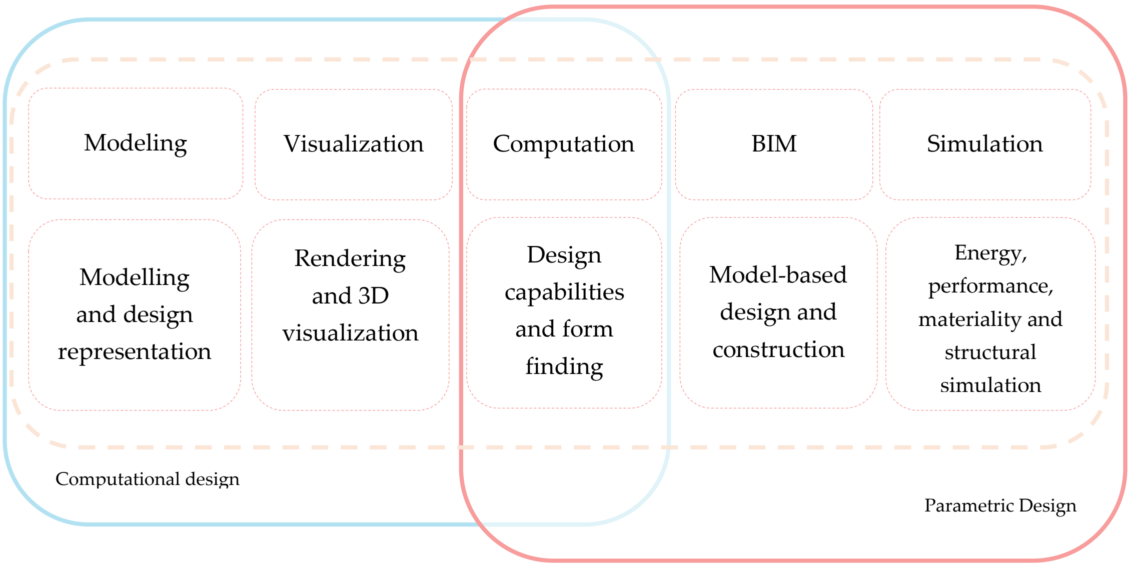


Figure 2.4. *Categories of computational and parametric design domains' application in architecture. (Source: By the author).*

Computational design methods and processes are not only used for the modeling, manipulating or simulating of already conceptualized ideas in the demanding science and design field (Terzidis, 2004). Whereas, their usage facilitates the creation of design ideas as well as their representation and development through the very same platform these resources provide (Kolarevic, 2000). With the integration of innovative techniques, indeed, computation design has supported architecture connectivity, model simulation, and constructed as the design process producing tools. Specific technical advances detailing their use through the design process have not assisted innovations of numerical and simulation technology in particular (Batty, 2007). Due to the widespread use of computational mathematics algorithms and algorithmic methods, their use in architectural design happens primarily when modern computational design strategies have been implemented, suggesting a fundamental change in practice. In this phase, algorithmic geometry and procedure explanation are activated through a framework of mathematical models where a range of parametric features and restrictions are defined by a common key (Terzidis, 2004).

Small solution space can be generated automatically using computational design complexity and a high number of design attributes can be explored easily without sticking to specific designs. Many examples of these computational systems are already adapted in computer science, aeronautics and mechanical engineering (Kalogerakis et al., 2012). New design and representation techniques, better known as parametric and algorithmic processes, distinguished various types of computational architecture calculation and abstract, so it suggests logic and mathematical system. Methods and techniques for computational design such as parametric architecture, associative geometry, algorithmic procedures and scripting propose the ability to change the limits of architectural planning and representation structures that are already applied in fields such as construction, manufacturing and industry (Kolarevic, 2005).

2.1.3. Parametric Design

The parametric design might indeed be considered as an extensive explanation of procedures that enhance progress in highly complex designs (Noennig and Wiesenhütter, 2013). Parametric design is continually evolving, and a research overview of current advances shows that it is extremely difficult to catch up with all the latest developments. The application of parametric modeling somehow doesn't fully use the capabilities of parametric design. Additionally, expressing requirements or techniques, is required to obtain innovative and process alternatives. Yet, architecture is a discipline which then, as of today, can be completely derived into parametric elements, and even elementary representations lead to extensive complexity that is not yet entirely under control. Mathematics and computational approaches, which take basic patterns and consider them more involved, are strongly influencing parametric design in architecture. It is possible to design shapes with parametric methods, but it is far extremely difficult to consider it simple for the human mind to interpret or practically manufacture. The architect's responsibility is to generate a comprehensive set of components and processes to achieve a definitive design (Meredith et al., 2008).

The manipulation of 3D modeled objects by adjustment of specific qualities of a building model is essential to parametric design. Rather than subjective adjustments to the designer's capabilities, these improvements are driven by mathematical methodologies, data values, components and parameters. The parametric design also demands the use of a particular computer visual programming tool. A variety of design tools are available in parametric design, which is discussed in a variety of resources (Burry, 2011). It is also implemented in various domains of architecture (Turrin et al., 2011) as well as other design fields such as urban design (Krish, 2011). By using parametric design, architects and designers may customize the design to a broader diversity of variables, and the processing power of a computer is a significant tool for doing so. There are numerous opportunities for parametric design, aside from the potential to develop parametric designs and structures for architectural objectives (Jabi, 2013, Petrusevski, 2010), it can also be used to enhance functional relationships in architectural and urban design (Beirao, 2011), (Beirän, 2012), perform resource simulations (Taleb et al., 2015), (Chronis, 2012), and execute numerical optimization (Skelton et al., 2014). It also encourages architects and designers to use a diversity of accurate designs and patterns.

Computer programs like Maya, Rhino and Grasshopper, as well as CATIA, SolidWorks, Inventor, and Bentley's Generative Components, are examples of software that offer parametric manipulation of complex shapes based on procedures and limitations. There are various illustrations of techniques and programming computation that may be applied to parametrically control the geometry of a design (Woodbury 2010) and allow the integration of analysis results into parametric programming systems (Aksamija et al., 2011). The features of parametric design software in the application have been recognized, but they have also been identified as expanding the difficulty and duration needed for particular design jobs. (Aish et al., 2005). There are published experiments where parametric design approaches were adapted to predict building shape and façade bending for stadium structures (Hudson, 2008) as well as numerous Other applications involving the parametric design of high building designs (Park et al., 2004).

The ability to easily transform the parameters of a model relying on specific criteria is a fundamental advantage of a parametric design approach, allowing designers to avoid constructing a new model for each iterative process or application. While implementing a parametric system has some evident advantages, it also has certain disadvantages. The use of metric design allows for the creation of more dynamic systems of interactions between the forms in an environment. The recent practice in architectural parametric design is focusing on formulating the system that generates the design first, as opposed to the traditional approach of designing the spaces first and then designing the form inside the space (Nagy et al., 2017). On the one hand, some structures, such as the sophisticated surface employed in a complex organization, are challenging to recognize manually, and using a parametric approach comes essential to get accessible outcomes in a reasonable period. Parametric modeling, on the other hand, is not necessary when building a typical rectangle environment with a restricted number of forms.

2.1.4. Contemporary Architectural Design Representation

Architectural design is based on more than just computational programs; there are many conceptual philosophies, approaches and frameworks behind its development, as well as logic processes that have led to providing more than visualizations, data or applications. Learning more about basic design through visual programming tools in the design studio may pave the way for many new methods to be discovered. Addressing the incoherence and indeterminacy of the design process should be excellent and can be inspired from the viewpoint of design education. Such generative processes should establish design strategies that are capable of transmitting details of design information efficiently, including computational awareness of design and design reasoning (Zhang and Xu, 2018). As a result, this will help build very valuable projects interpreting design concepts and problem-based reasoning in a very structured and understandable manner.

Digital technologies may assist design practices and enhance various aspects of the design process, including representation of 2D, 3D and 4D models, and performance of decision making (Al-Douri, 2013). On the one side, this will make it possible to recognize the project's complicated geometric problems and to realize the ability of computer design to manage such complexity (Daniel and José, 2017). On the other side, together with computer architecture and construction methods, software modeling and simulation techniques encourage the creation of many futuristic buildings in complex forms. Such techniques and methods are one of the opportunities to explore completely the potential benefits of biological concepts for performative design. The use of those techniques in processes of architectural design impacted and complicated the relationship between the context and the evidence, between the virtual and the physical, and also between the design ideas and their architectural representation. Based on that, a summary about the limitations and opportunities of different design implementation in architecture is structured as follows:

Table 2.1. *Summary of the limitations and opportunities of different design implementation in architecture. (Source: By the author).*

	Specialization	*Limitations*	*Features*
Digital Design	-CAD, CAAD, CAM -Sketching, -2D/3D Designing, -Modeling and Rendering.	-Difficulties in identifying and managing analytical mechanisms. -Problems of conceptual transmission and geometrical precision.	-Facilitating the creation of design ideas. -Design representation and development. -Engagement, representation of 2D, 3D and 4D models.
Computational Design	- Mathematical Functions employment -Model editing, and manipulation -Conversion and data representation.	- Time limitations - Accessibility for all users - Complexity providence - Data engagement	-Supporting connectivity. -Combination possibilities for increasing the system's structural evaluation. -Recognize the project's complicated geometric problems.
Parametric Design	-Parameters' manipulation - Scripting and generation -Complexity search	-Parametric features and restrictions are defined by a common key. - Number of data used affects the results. - Need specific scripting environments. -Usage and application complications	-Realize the ability of computer design to manage such complexity. -Optimize the capacity of subjectivity. -Build, expose, improve and establish logic in a creative process. -Data management,
Generative Design	-Generations of the generation systems - Solutions optimization -Analysis and technical studies -Manufacturing, Printing and production	-Little interacts with the design and assessment of function or organization. - Need data for launching processes. -Materiality restrictions - Machines' work specifications	-Allows for nuanced investigations. -Quantitative methods of estimation and measurement. -Configuration, environment efficiency. -Encourage the creation of many futuristic buildings. -Producing tools -Combining theory with practice.

Applying computational and parametric design techniques along with environmental simulations illustrated that such artificial intelligence practices are worth pursuing the progress they have shown in environmental efficiency. The framework is not technically linear in terms of procedural development; it incorporates different applications, templates, and plug-ins supported by machine learning algorithms which promise a range of opportunities to build experience in computer design (Dutt and Das, 2013). These types of design approaches and systems have been particularly useful in finding the best results where opposing targets are required.

2.2. Generative Design Concept in Architecture Literature

Contemporary experience in architectural design is guided by algorithmic modeling, which is used for all phases of the project life cycle. It is improved by decision-making and assisted by performance analysis and visualization techniques to enhance communication. Different computational technologies and techniques can improve design processes rapidly. In addition, for measuring and assessing design options and approaches, architectural design needs the use and application of developed computational methods, particularly simulation and modeling software. It should be remembered that, with the introduction of new emerging technologies, specific software frameworks and methods should adapt and strengthen with time or may become unnecessary. Generative design is becoming an independent performative computational domain through the alternatives provided and the decisions made. Multiple research and design projects revealed how innovative generative methods were used to analyze and assess projects and their properties, structural behavior, energy efficiency, management of development and planning design.

Generative Design may be considered as a technique in which algorithms generate numerous viable design alternatives. As Lars Hesselgren pointed out, *"Generative design is not about designing a building. It's about designing the system that designs a building.*" (Stocking, 2009). The application of Generative Systems in architecture began even before the advancement of architectural computational technology emerged in the mid-twentieth century. The paradigm of generative design should not be regarded as a systematic process with techniques and applications, but more as a fundamental shift in design thinking. It is a creative approach in which the outcomes are generated through algorithms and the execution of computer applications (Terzidis, 2004). The capacity to regularly analyze a project and create several possibilities effectively and accurately is the principle of generative design's fundamental advantage. It is sufficient to apply generative design systems and approaches to several other structures, presenting procedures for the generation of original designs that respond to socioeconomic and technically imposed limitations. This facilitates the generation of numerous possibilities in a short period, minimizing the repetitive and uninspired procedures necessary when traditionally modeling development, even when using innovative design techniques such as computational design and parametric modeling (Kuhn,1996).

Besides that, generative design assist and fosters manufacturing solutions by directly transferring data from the design to the Computer-Aided Manufacturing workflow (Fernandes, 2013). It implies a revision of the continuous processes and functioning that modify it for architects. The employment of generative systems has assisted to a period in which design technique is computational, and both the outcome and the system are operational. The final output is complicated and dynamic behavior created by algorithms. These approaches are intended to convert the static design procedure to a computational one. But since generative systems have empowered us to design diverse models' associations, patterns, and geometries to demonstrate transformational behaviors, it has resulted in the diversification of real-world growth processes. Rather than adopting a learning paradigm of digital technology specialization, a creative and systemic approach to architectural education could encourage a new generation of architects to design and develop computing and manufacturing at the root of architectural output. Digital fabrication can therefore be considered an essential part of the design phase and can be identified as a kind of sketching system with implications in architectural design for the creation of ideas and concepts.

A history of worldwide scientific comprehensive reflection on generative design definition, tools and techniques in architecture opened up new fields for developing with design ideas (Figure 2.5.). Simultaneously an analysis of the main international journals and conferences relevant to the literature has proceeded. Many international journals such as Design Studies journal 1979, Journal of architecture and engineering 1995 and International Journal of Architectural Computing 2003 are among many of the field's pioneers in developing an understanding of design processes. The researches presented within these journals covered all application disciplines, including architectural and urban design along with encouraging interdisciplinary computer-aided architectural design research and innovation**.** Since its early integration in architecture, the design theory has undergone several transformations. The role of development in architectural education is important for the design paradigms-shift. Different perspectives, thus new experimental practices for the architect, are believed to be made. The ACADIA Conference in 1981 introduced a new design view emerging from a knowledge of the foundations of digital systems for architectural design, as well as the technology that facilitates their creation and implementation. Later on, a number of international conferences has grown significantly. ECAADe Conference 1983 and CAAD Futures conference 1985 promote architectural design innovation by examining the role of computing throughout architecture (Celani and Veloso 2015). Many other Conferences such as SIGraDi Conference, Design computing and cognition, Digital Architecture London conference and many more present education as a new research priority on integrating generative design in architecture (Peters and Peters 2014), exploring the boundary between mathematics and computation, and the impact of performance in architectural design.

In order to accomplish this transfer, architectural education can introduce a method, both theoretical and practical, enabling the student to develop knowledge in recent architectural practices, information and parametric modeling capabilities and to gain experience in the model formulation for generative development. Therefore, this will provide students with expanded knowledge of design, a wider variety of outcomes alternatives, more advanced model and reasoning processes, and a greater understanding and control of design generation.

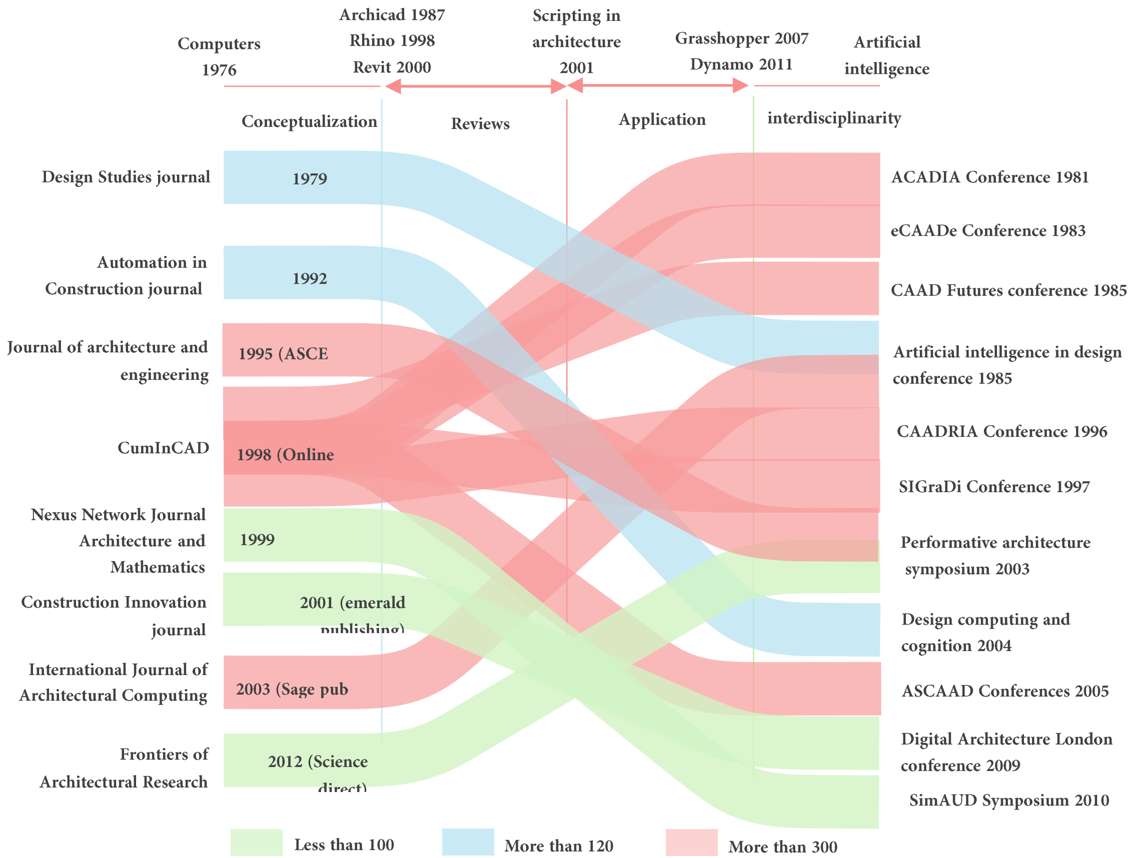


Figure 2.5. *A Comprehensive reflection on generative design literature. (Source: By the author).*

2.3. Generative Design Concept Development in Architecture

Recently as the generative design concept become the central research discussion in the field of architectural design, much variance in the literature focusing on the concept applications' development. The origin of the idea is not as novel as it sounds, nor linked to the improvements of computational and digital tools. Accordingly, within this part of the research the generative design concept is investigated from its early beginning, even the time before computational methods, inventions of the computer and design technologies. Exploring the origin of generative design concepts and managing their development relationships in architecture is a source of mystification.

Based on the conceptualization and definitions explored in the previous sections, this section provides an extensive theoretical search and conceptual review organized chronologically under several periods. The main goal is to promote an understandable and crucial view on the generative design concept development within both theory and practice. First, we focused on summarizing the existed literature on the history of generative design practices in architecture and we organized those that had a major contribution to the topic. After that, the contextualization of the concept evolution linked to generative design concept and the identification of the emergent technical terms that better supported the architectural design process is addressed within each period. In addition to that, the main focus was on analyzing many architectural projects available throughout time which explain practically the concept presented in each period. Finally, two classifications of generative design development; one structuring the main concepts and periods that were significant and the other organizing the real case projects linked to each concept are presented. The resulting classification addresses the generative design concept development and divides it into ten key periods of thought structured under four groups: Analog Design, Digitalization, Computation and Data-Driven Design (Figure 2.6.).

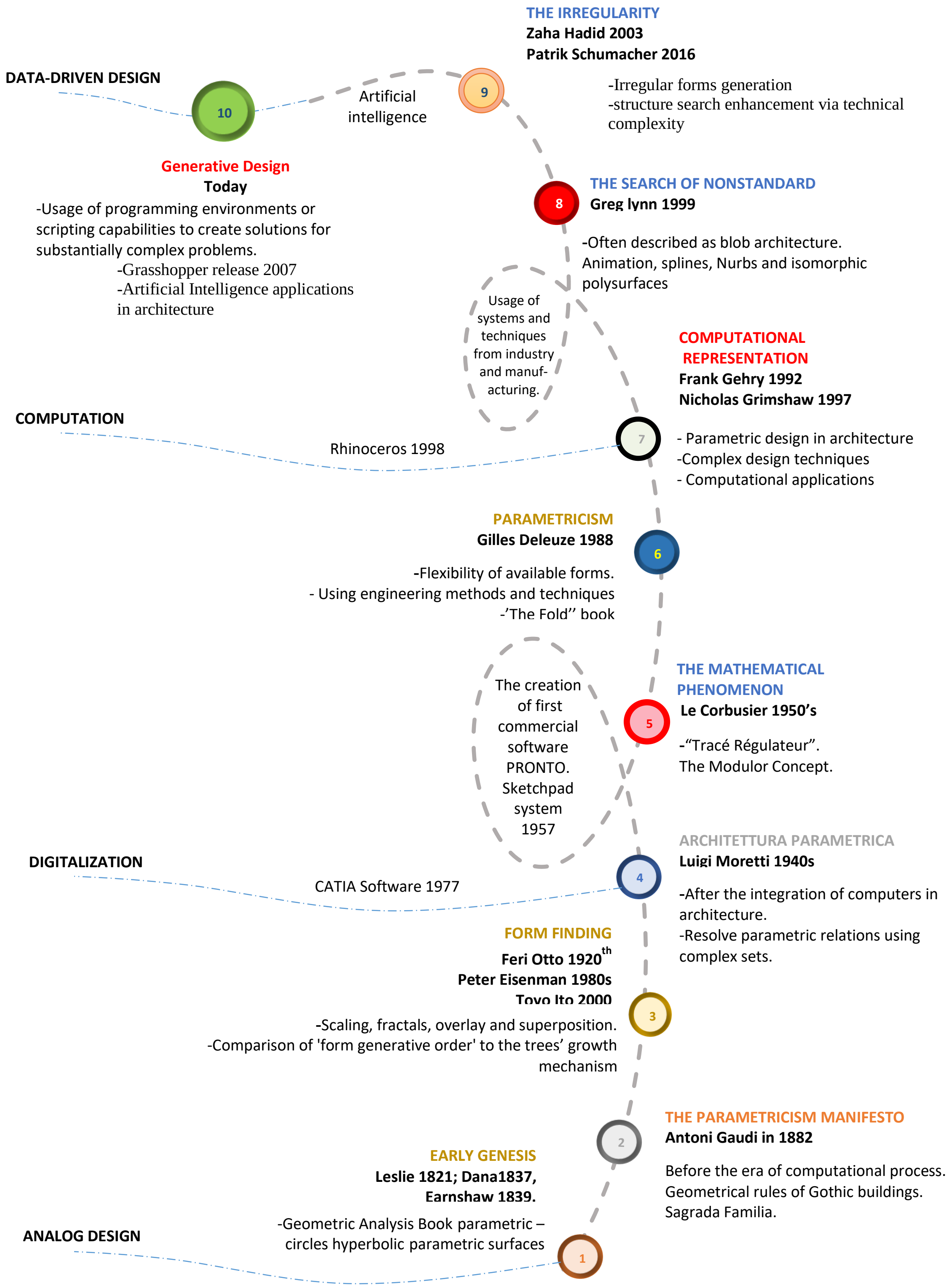


Figure 2.6. *Classification addressing the generative design concept development. (Source: by the Author).*

2.3.1. Analog design

The analog design, also spelled “analogue”, refers in this research to those techniques that examine architecture before the innovation of computers. It also refers to the behavior that architecture projects engage with the environment through connecting to the surroundings. The concept of generative design started to be theoretically and practically utilized even before the existence of computational design alternatives. The early genesis, parametric manifesto and form finding explorations are discussed as the following:

2.3.1.1. Early Genesis

The word “Generative” or “Generation” used mainly in several fields throughout history, but there is no sign about the first practical usage in architectural design. It is believed that The term has been utilized in architecture and engineering for more than a decade, and is also used in biology mathematics, engineering, geometry, and computer science (Kolarevic, 2003). In architecture and even before the use of this term, almost one hundred years we could find some relevant applications that have been used to describe three-dimensional design examples which could signify the meaning of the “Generative” term. Davis (2013) cited three references explaining some practices that could be considered as generation search. The first one is dana’s paper which explains the use of several variables on the drawing of Crystals’ figures by general steps. Besides that, sir John Leslie’s book “Geometric Analysis” is another example of the mathematic of design representations where he proved the self-similarity using Circles. Later, Samuel Earnshaw wrote about a new concept focused on the line of force named Hyperbolic Surfaces. Those are some examples before the period of Antoni Gaudi who is known in the ninetieth century as the pioneer of designing architecture employing different methods and applications. All those examples are based on essential practices that were engaged later in architectural design (Davis, 2013).

2.3.1.2. The Parametricism Manifesto

During the early stage of using this concept in architecture, many designs were based on the geometrical rules of Gothic buildings which were interpreted later as algorithms (Davis, 2013). Going back in history the work of Antoni Gaudí could be considered as the starting point of all generative ideas in architecture. His earlier work

Sagrada Familia in 1882 is an essential example. Gaudi developed the design method during the 19th century and even though it took him a lot of time to perfect his model. The design concept at that time was named Parametricism Manifesto which was used by him and some other architects later on (Burry, 1998).

Different mathematical rules like helicoids, paraboloids, and hyperboloids associated together with ruled lines, Booleans, Ratios, and Catenary arches were the basics of Gaudies' architecture which is difficult to decide whether he was influenced by the uses of parametric equations of various mathematicians (J. and M. Burry 2010, M. Burry 2011). What is sure is that Gaudi knew about the earlier examples where he used generative applications when designing architectural projects.

Antoni Gaudi started to use generative design systems without digital computation. Systems like doubly curved, ruled surfaces were applied. He also exercised complex subdivision strategies that could be applicable today with the help of computers to interpret the naturalistic geometrical complexity (Davis, 2013).

The Sagrada Familia is considered as an example from where designers may interpret algorithms for new ideas. Its Gothic design with the use of organic and inorganic geometrical rules underlies a naturally formed concept. This proposal synthesizes the architect's intentions into computational processing and geometry schematization algorithms while seeking to determine the degree of variance required to mimic the efficient organism of the initial model (Kevin Jan Mazanek, 2016).

2.3.1.3. Form Finding

The generative design concept progressed and started to be inspired by nature. In addition to Antoni Gaudi and Luigi Moretti, Feri Otto is considered one of the outstanding generative design pioneers of the 20th century. At the start of the twentieth century, Frei Otto and Frederick Kiesler were applying design methods that were very similar to today's computational approach. At that time Otto called these methods of design “form-finding” which opened doors to many generative modeling to be applied (Burry,1998). Subsequently, he sought new horizons of that concept through his experiments based on analog form-finding approaches comparative to Antoni Gaudi’s early applications in the 1950s. He was working on minimizing the level of energy to create an equilibrium state by applying the self-organization method using basic materials (Frei Otto, 1995). As De

Landa (2007) states, the processes that generate these geometrical forms may be viewed as searching a possible space until they reach singularity. In terms of form-finding techniques, the Multihalle project was a relevant success that test and develop new approaches to realize dynamic contractions. The project is a construction with a large scale prepared for the German national show as an example that makes use of analog models very early. It was realized to provide a covered space for cultural events. It created a new conceptual bridge between the concept of Parametricism manifesto and new form generating methods, construction realization and tectonic principles (Otto, 1996).

The same application logic could be seen later on within the project the Olympic Stadium of Frei Otto and Frederick Kiesler in Munich. By the integration of the tensile structure and lightweight innovations, Frei Otto presented one of Munich city's landmarks and show a different, more compassionate face of Germany within the Olympic Stadium project. As long as a tree's shape responds to its surroundings, the architect mimics the growth mechanism of trees and compared it with a generative complex order to provide a form by a repetition of basic rules. The roof in the shape of the tent that covers the surrounding of the Olympic Park is considered the most exceptional part of the whole project. Otto aimed to enhance the sustainability principles by the application of new methods minimizing the material and energy uses. Natural phenomena like birds' anatomy, bubbles and spiders' webs were concerning Frei Otto and led him to do many experiments to understand the different processes of form-finding using physical, biological and technical methods (Agkathidis, 2015).

During the early nineties, just before the boom of computational architecture, Eisenman started as well applying a set of design techniques to find new design forms, such as scaling, fractals, overlay and superposition, which could be seen in his projects like Biocentrum in Frankfurt and the Nunotani Corporation headquarters in Tokyo. Creating a mystery between architecture and biology was the clue of Eisenman with the design of Biocentrum that combines structure and ornament in an analogical generative process. The symbolic idea of the project engages biological contractions transported to architectural forms in such a way that produces analogical discipline of the final parts. By applying replication, transcription, and translation which are known as the physical basics of biological growth, a simple representation is used to progressively articulate and transform the projects. A final complex project was presented, naturally expanded as an addition to science neither simply architectural nor simply biological (Eisenman 2004). Following this, Toyo Ito compares 'form generative order' to the trees' growth mechanism, whose form derives from the repetition of simple rules, creating a very complex order (Turnbull 2012). A tree's shape responds to its surroundings, blurring the boundaries of interior and exterior spaces qualities that are easy to recognize in Ito's Serpentine Gallery Pavilion in London (Agkathidis, 2015).

2.3.2. Digitalization

The innovation of computers and their integration into architectural design lead to an important shift of the generative design concept from analog to digitalization. The generative design concept throughout this period was discovered through different design techniques and applications discussed as the following:

2.3.2.1. Architettura Parametrica

Parametric architecture or "Architettura Parametrica" is defined by Moretti (1971) as a relationship between geometric parameters and mechanisms during the study of architecture generative systems. He started to work with this concept even before the era of the computational process. However, after the integration of computers in architecture, Moretti was probably the first to practice digital computation and to resolve geometric relations using complex sets and create three-dimensional forms (Schumacher, 2009). Many technological innovations have made the concept of generative design one step forward in architecture. For example, the creation of the first commercial software Pronto in 1957, provides parametric algorithms for shifting data from computers to manufacturing machines by the idea of Patrick Hanratty. In addition to that, the pioneers of digital design such as Ivan Sutherland with his Sketchpad developed an essentially parametric system for architectural design to fast the application of any equation (Schumacher, 2016). Nevertheless, Stiles (2006) believe that the commencement of parametric concept in architecture happened a few decades earlier of digital design improvements within the writings of architect Luigi Moretti in the 1940s. As a formulation of many parameters, in 1960 Moretti generated a concept for the architecture exhibition at Milan Triennial (Bucci and Mulazzani 2000). The project of Gehry for the Olympic village in Barcelona is also one of the generative design's significant examples which used both conditions and angle of the sun to make an abstract object that reflects rays and changes colors. The project reflects a futuristic memorial as a golden steel-mesh fish sculpture involving three-dimensional aeronautical-design software CATIA to generate the idea (computer-aided three-dimensional interactive application) (Yoo, Boland & Lyytinen, 2006). Besides that, the International Terminal at Waterloo Station in 1993 was considered among earlier works to digitally incorporate parametric design techniques by Nicholas Grimshaw and Partners. The ceiling structure was made up of several structurally diverse but reasonably similar arches that were arranged along with the platforms. Instead of calculating each arch separately, the architects designed a parametric approach based on the project's fundamental design criteria, proving the feasibility of a parametric approach in a practical setting and demonstrating its benefits for architectural practice (Kolarevic 2003). The site constraints forced the building curves and variables to gradually expand and creates a train shed. The roof structure follows the configuration of curves with a series of different dimensions' arches. Many problems concerning the span size and curves of the structure were solved by creating a parametric model that encodes the rules of the arches together as a whole (Szalapaj, 2001). The design process provides the ability to reproduce the dimensional changes of the whole model, mass and elements' positions via an innovative system of parameters (Kolarevic, 2003).

2.3.2.2. The mathematical Phenomenon

Numbers has a long history in architectural design, from the era of geometry ideas to the regulating lines and modular grids presented by Vitruve, le Corbusier and Mies (Prousalidou, 2006). Many architectural applications demand various mathematical definitions and bases in the calculation. Different architects established methods of mathematics as a language of their architecture, which might be confirmed by numerous hypotheses developed throughout history. Le Corbusier is one of those architects that started to use mathematics early in the 1920s. He is the one that predominantly matched generative design and architecture in his career by different mathematical methods. He was obsessed with the geometric schema called "Tracé Régulateur" to express art projects from several historical periods. He started to use mathematics as a tool of an architectural generation when he started to work on the Modulor, which become one of the important academic topics of all time. After that many other architects started to express interest in the combination of mathematics and architecture such as Peter Smithson who expressed it as a parallel to the renaissance (Judi Loach, 1998). Nowadays, with the development of digital design, striking operations of logic and mathematical complex applications are directly integrated into numerous generation programs to help architects display different projects and examples. This is what makes this phenomenon getting interesting in generative design by building a relationship between architecture and mathematics (Jane Burry and Mark Burry, 2010).

According to Prousalidou (2006), the earliest project brought to life engaged the use of mathematical definitions as generative systems are believed to be the Philips Pavilion. During the occurrence of new architectural style Hyperbolic Parabola Le Corbusier and Iannis designed the Philip pavilion for the Brussels World's fair with an approach that was explored in a known music composer "clouds of sound". A primitive model was originated by an application of the hyperbolic paraboloids, relocated later using computational graphics to create technological modern artwork. The project was an artistic technological self-supporting project of that time, with curved walls and irregular contour on the ground. The interior contained visual components and music that could be experienced by entering the pavilion from only one side (Felciano, 1996). Later on, the Wildlife Health Centre was developed by using the Cellular Automation method of generative design as a potential model for biological systems. The practice of Minifie Nixon came with a novel design technique from abstract mathematical ideas. Imitating the heart valve a central space was emblematic of the building. Using a form-finding process to determine the final design which could combine the programmatic parameters and the formal intentions of the designer and engage the geometry and typological definition of the surface with its constraints (Kwinter, 2005). To design a simple gradual curves geometry that gives the sense of calm, Norman Foster created the Beijing International Airport. The success of the project's design is hidden behind its transmissibility. Using simple techniques from mathematics the plans of the projects are projected by providing different curves. Concerning the roof arcs and lines are the basic elements of the shape generation. (Tavernor, 1995).

2.3.2.3. Parametricism

Years later, some of the best uses of generative design have occurred in collaboration with structural designers using engineering methods and techniques (Beesley et al., 2006). Parametricism is the concept where designers could explore a variety of designs, numerically represent the outcomes and automatically drive the shape

(Teresko, 1993). Parametric design as it is known today is merely a contemporary digital condition that was initially described in the book of Gilles Deleuze ’The Fold’ (Schumacher 2016). The possibilities of digital design’s parametric features in architecture were first stated by Gross (1985), who exposed that they were useful to elaborate typical variable forms. In his PhD thesis, he suggested modeling buildings with formal and economic restrictions. Parametric design has also found its way into architecture through different software programming environments. To optimize components of the system, coding interfaces enable designers to store data. That the architect may respond to exceptional circumstances (Alvarado and Munoz, 2012).

The use of parametric methods could be seen in different projects applications. An example where the parametric system was used is the Zentrum Paul Klee building in Berne, Switzerland designed by Renzo Piano. The design idea combined some curvature applications within the structure of the roof. By the use of some parametric techniques different modifications applied the incline angle of the roof structure and the curvature of the supporting beams. Every curved panel in a double looped wall has been constructed parametrically to be prototyped or produced later on (Stacy, 2013). The design of Melbourne's Rectangular Stadium is another illustration of a parametrically solved architectural optimization issue. The project's primary goal was to design a dome structure that was as light and rigid as possible while still being easily assembled into parts. To maintain uniformity across flexible areas and structural planes of force, certain methods were implemented (Jane and mark burry 2010). For this purpose, generative parametric models were developed where the focus was on finding an optimal roof’s curve shape with a structure performance without affecting aesthetics as well as allowing for light to easily enter through its fabricated units. The design process assigned the individual domes and their curved profile to be harmonized through all shape components (French, 2008).

2.3.3. Computation

Computation in generative design concept is focusing more on different methods and techniques integration through the implementation of mathematics and computational strategies. It is aimed at improving the applicability of design and seeking a better representation of architectural design productivity. Computational representation, the irregularity and the search of the non-standard in relation to generative design system are the main concepts discussed within this part.

2.3.3.1. Computational Representation

In some other references, a discussion about the progress and development of the concept is held by giving some examples and points of view. Shelden (2002) claimed that, the fish-shaped roofing installed by Frank Gehry in the Olympic Village in Barcelona in 1992, is one of the great representations of generative design techniques. Szalapaj (2001) and Gane (2004), believe that the Waterloo Terminal by Nicholas Grimshaw in 1997, is also a good example of the concept in architecture. Instead of focusing on the geometric elements of the design representation, computation pays more attention to its application process. This notion opens up new design and production opportunities by converting computational design representations into physical implementations. Computational representation as a fundamental milestone in digital design is expanding the capabilities of traditional techniques. Architectural computational design technology performed a significant influence in this case.

Among many generative design methods recommended by Foster, subdivision surface techniques were applied to create the glazed roof of the great court at the British Museum that has proved later as highly influential. Despite the boundaries and constraints faced to designing both rectangular and circular roofs, many other techniques such as NURB surfaces were used to generate the grid on the surface and the curvatures at the corners. (Jane and mark burry 2010). Drafting grids and optimizations for the structural performance and simulation are been developed to generate the roof mesh applying the subdivision technique. From the original mesh, several grids of varying density may be created rapidly, symbolizing multiple levels of segmentation. The generative process of the Smithsonian Institution Courtyard's roof which is also based on structural optimization allowed us to explore hundreds of form propositions through simple performance control of the used panels. With the help of a computer program designed by Brady Peters of Foster and partners the constraints and decisions through the design process were encoded into control geometries (Jane and mark burry 2010). The results were established with the involvement of computational representation where the combination of mathematics and computers play the key role in the application process. Arata Isozaki designed the Qatar Education City Convention Centre with the inspiration of the Sidra tree. The nature of the “Voluptuous Structure” design is not a kind of randomness by using the extended evolutionary structural optimization method which was evolved. This method helped to attain using as little as material possible with the most efficient shape performance according to the design criteria and site requirements (Jane and mark burry 2010).

2.3.3.2. The search of the non-standard

The use of scripting in architecture opens on to a nonstandard phenomenon that is associated with digital environments. At the same time, we could find Greg Lynn, which applied new tools such as animation, splines, NURBS (non-uniform rational basis splines) and isomorphic polysurfaces, influencing a whole wave of architectural production, often described as ‘blob architecture’ (Lynn 1999). These new possibilities have led to new movements in architecture and defined the field of non-standard architecture (Eisenman 2004). The use of those generative tools is based on the logic of computers and digital-based design to define the technical object and fabrication (Oxman, 2017). Nowadays, we could find many research engage these concepts to explain different phenomena concerning three-dimension applications and form generation. It became the concept where all non-defined practices were gathered to define the process of design and generation. Qatar Education City Convention Center is a prime illustration of structural topology optimization that shows a nonstandard generation. The structural optimization challenge was computationally addressed using evolutionary structural optimization (Pohlheim, 2006). To get the patterns of the Sidra trees that compose the building's exterior, an evolutionary structural optimization was performed. The trees were grown using an optimization solution by eliminating the least degree of the pressured component from a block progressively until the remaining structure required the least amount of material. The mass of the structure to be decreased becomes the ultimate variable of the numerical structural optimization process (Rian et al., 2014). Eisenman applied as well a set of mathematical techniques to design the Nunotani Corporation. Those techniques have led to the appearance of the nonstandard movement in architecture which brings new possibilities to design. At the same time, the influence of deconstruction theory could be easily seen within the project. As long as Eisenman was engaged in using biological-architecture analogies, the Nunotani project was an example that break the boundaries between the conceptual character of the design, even if it was one of his recent design approaches, he searched new generative frameworks that illustrated his works (Eisenman 2004).

Furthermore, by using an algorithmic system Toyo Ito and Balmond designed a genesis example with an irregular façade pattern named the Serpentine Pavilion. The tectonic pattern of the façade was developed specifically for the project is designed by using a geometric algorithm. It was used both for the façade and building's roof by a pattern traversing, scaling and rotating the edge of a square around a central axis (Jodidio et al., 2011). The effective expression of the complex tectonic pattern resulted from the use of different panels' materials like steel flat, glass and white aluminum (Deuling, 2001). After that some adaptations were directed to create entrances and openings. The final design is a complex and nonstandard-looking building where is difficult to distinguish between skin and structure which was created using a well-defined generative algorithm (Jodidio et al., 2011). Although the different constraints, fabricating a complex geometry of the dome is naturally emerged within the project by involving several performance criteria and component standardization within the project Louvre Abu Dhabi. Taking into consideration the natural environment and especially the light performance the building results in a complex aesthetic expression and economic support (Jane and mark burry 2010).

2.3.3.3. The Irregularity

The irregularity is not a result of coincidence, but an original idea of combining digital technologies, design and an intention of saving the architectural values with each form generation. The concept of irregularity signifies a predominance of many elements such as curves, movements and fluidity to provide futuristic designs characterized by form plasticity or unpredictable patterns. This does not mean that the generated designs are not responding to the social and environmental context. However, thanks to computational innovations that allow the architecture of Zaha Hadid to consider all design factors from form generation to function representation. The irregularity applications that Zaha Hadid tested through her works focused more on the belief that design generation could reach proportion without the need for symmetries. A big number of her projects are based on a significant complexity with given importance to construction materials by the application of technology for a better generative process implementation (Abdullah, Said, Ossen, 2016). She creates the future cities' building with a focus on structure usage (Kosinski, 2010).

In one of her important projects, Zaha Hadid aimed to express the future vision of Azerbaijan and show the optimism of its people by designing the Heydar Aliyev Centre which is named after the country's former president (Schumacher, 2012). The symbolism of the project that reflects contrast with the Soviet-era architecture of Baku, makes it the primary cultural building of the country containing many functions such as museum, gallery and conference auditorium. The structure form of the project was achieved by using a generative space frame system which is constructed with glass fiber reinforced concrete panels (Schumacher, 2010). Moreover, the idea of designing The Spanish Pavilion started with developing attractive facades and interior environments within standard boxes to be presented at the Expo 2005 in Japan. Inspired by the history of Spanish architecture the project tends to express the incorporation of the Jewish-Christian cultures and the Islamic influence. As applied in Islamic and Gothic designs, the hexagonal grid with various shades continually differs to build parts with a mathematical process. Glazed pottery is a technique common along the Mediterranean coast used for the blocks and associated with colors that reflect the national flag of Spain (Jane and mark burry 2010). Taking advantage of the same application, the conceptual idea of the Island City Central Park and its surroundings was applied by Toyo Ito based on the complexity and fluid dynamics studies which could be seen in his sketches and waveforms (Turnbull 2012). A generative process of evolutionary nonstandard shape design was created to search for the final shapes of the concrete shells that covered the interior areas using sensitivity analysis. It tends to minimize the strain energy by designing a shape that transmitted load by axial forces and bending movements supported with structural dynamics evaluation (Jane and mark burry 2010).

2.3.4. Data-Driven Design

As a crucial application to clarify design information on any range of fields, data-driven design starts to provide the ability to positively represent different impacts on current architectural projects. With the easy acquisition of enormous data, decisions on design production can be addressed relatively faster, buildings can be designed more efficiently, and users can be made more comfortable. Accordingly, data-driven design acts for different approaches and techniques that rely on data collection and users' related decision-making. Recently we could find the generative design as a wide used data-driven system that engages the same methods to understand the target design objectives and reveals exceptional generation possibilities and alternatives.

The generative design concept is well-defined by the phrase saying “shift the emphasis from “form making” to “form finding” (Kolarevic 2003) based on techniques and methods widely used in industrial design and manufacturing. Nowadays many authors like Oxman, Jabi, Nagy and Agkathidis are using the word generative design to mark out their works and researches. In 1998, Robert McNeel & Associates launched Rhinoceros 3D, a commercial 3D CAD tool based on the NURBS (non-uniform rational basis spline) mathematical model (Rogers, 2004) that focused on producing a mathematically precise representation of curves and free-form surfaces. The generative design concept is theoretically and practically present in many kinds of research and most contemporary architecture projects. Its rapid expansion based on the data-driven design application has understandably led to some mystification over its meaning. Generative design has a set of quantities that could be expressed as numbers and parameters for the aim of exploring the modeling and design possibilities. The digital era simplified applications that were not possible with Gaudi, Otto and Le Corbusier’s parametric models. During the early stage of computational design, no one had realized the impact generative design would have on architecture. Only in the last decade parametric modeling has gone from being a mathematical method employed by some engineers, to being a regular part of architectural practice. After that many techniques systems and approaches started to be developed and highlighted the potential of integrating generative design approaches in architecture design (Zhang and Xu, 2018). Furthermore, because of their various physical interpretability, they became an urban landmark, signifying major architectural underlying trends that not only influenced contemporary designs but also fostered a shift in architectural practice.

Simultaneously, the design area has progressively embraced methodologies and concepts from other disciplines, such as biology, mathematics, mechanics, physics, and, more significantly, computer science, improving both design practice and theory. To encourage a more comprehensive viewpoint on the history of generative design in architecture, its evolution over the previous decades was described, classifying it into four major perspectives: analog, digitalization, computation and data-driven design. In addition to that, several chronological timelines, one for concepts and main used applications (Table 2.2.) and the other for relevant examples also provided (Figure 2.7.), (Table 2.3.). Finally, conclusions about the development of generative design concepts in the architectural area based on the examination of these classifications are presented in the last chapter of the research.

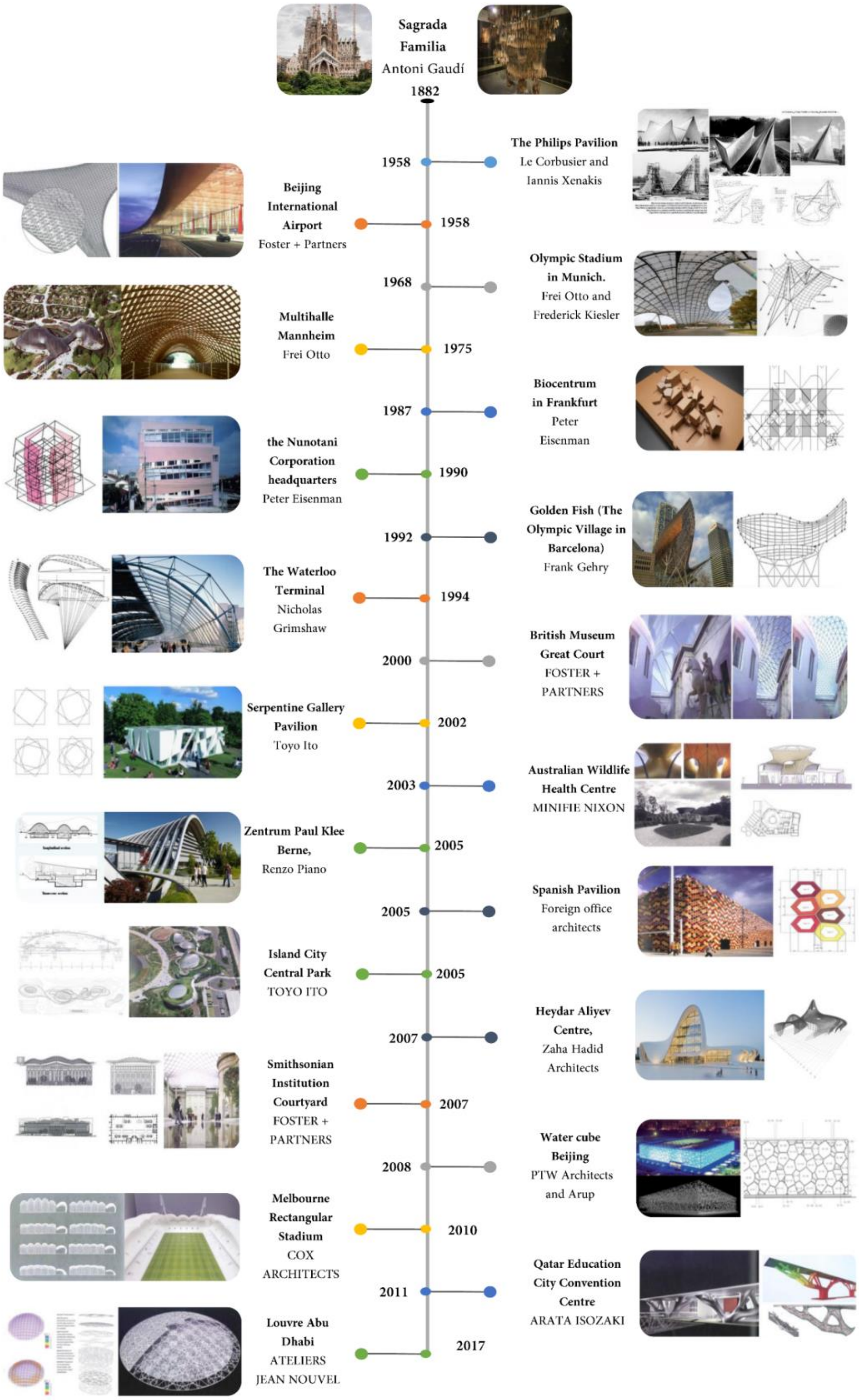


Figure 2.7. *Relevant examples of generative design concept application in architecture. (Source: by the author).*

Table 2.2. *Chronological timelines of the generative design concepts and main used applications. (Source: by the author).*

Chronological Timelines of The Generative Design Concepts				
	ANALOG DESIGN			
EARLY Genesis	Geometric Analysis book (1821, 390)	-Mathematics applications - Describe three-dimensional parametric examples	-1821; Leslie, -1837, Dana, - 1839 Earnshaw.	"Parametric circles". "Hyperbolic parametric surfaces".
THE PARAMETRICISM MANIFESTO	Before the era of the computational process	Geometrical rules of Gothic buildings	- In 1882 Antoni Gaudí	-Sagrada Familia (Antoni Gaudí)
FORM FINDING	Influenced by Jacques Derrida's Deconstruction theory (1976)	Scaling, fractals, overlay and superposition. Comparison of 'form generative order' to the trees' growth mechanism	-1920th, Feri Otto -1980s, Peter Eisenman -2000 Toyo Ito	-Beijing International Airport (Norman Foster) - Olympic Stadium Munich (Frei Otto and Frederick Kiesler) -The Nunotani Corporation headquarters in Tokyo (Peter Eisenman)
	DIGITALIZATION			
ARCHITETTURA PARAMETRICA	After the integration of computers in architecture The creation of the first commercial software PRONTO CATIA Software 1977 Sketchpad system	-Resolve parametric relations using complex sets	- During the 1940s - 1957 Luigi Moretti --1963 Patrick J. Hanratty -Ivan Sutherland	- Golden Fish (The Olympic Village in Barcelona, Frank Gehry) - The Waterloo Terminal in London (Nicholas Grimshaw)
THE MATHEMATICAL PHENOMENON	-Era of geometry ideas -Presented consecutively by Vitruve, le Corbusier and Mies	"Tracé Régulateur". The Modulor Concept	-1950's Le Corbusier	-The Philips Pavilion for the Brussels World´s Fair (Le Corbusier and Iannis Xenakis) - Australian Wildlife Health Centre Healesville Sanctuary (Minifie Nixon)
PARAMETRICISM	-Flexibility of available forms. -Using engineering methods and techniques	-'The Fold'' book	-1988Gilles Deleuze	-Zentrum Paul Klee Berne, Switzerland (Renzo Piano) - Melbourne Rectangular Stadium (Cox Architects)
	COMPUTATION			
COMPUTATIONAL REPRESENTATION	-Usage of systems and techniques from industry and manufacturing. -Rhinoceros 1998	- Parametric design in architecture -Complex design techniques - Computational applications	-1992 Frank Gehry -1997Nicholas Grimshaw	-British Museum Great Court London (Foster + Partners) - Smithsonian Institution Courtyard Washington (Foster + Partners) - Qatar Education City Convention Centre Doha (Arata Isozaki)
THE BIRTH OF NONSTANDARD	Often described as blob architecture	Animation, splines, NURBS and isomorphic polysurfaces	-1999 Greg Lynn	-Serpentine Gallery Pavilion in London (Toyo Ito) - Island City Central Park Fukuoka, Japan (Toyo Ito) -Louvre Abu Dhabi Abu Dhabi (Ateliers Jean Nouvel)
THE IRREGULARITY	-Irregular forms generation -structure search enhancement via technical complexity	-Parametricism book	-2003 Zaha Hadid -2016 Patrik Schumacher	-Heydar Aliyev Centre, Azerbaijan (Zaha Hadid Architects) -Spanish Pavilion Expo 2005 (Foreign Office Architects)
	DATA-DRIVEN DESIGN			
GENERATIVE DESIGN	-Usage of programming environments or scripting capabilities to create solutions for substantially complex problems.	- Grasshopper release 2007 -Artificial Intelligence applications in architecture	-Today Many Architects and designers	/

Table 2.3. *Summary of the generative process and design genesis of relevant architectural projects. (Source: by the author).*

Projects	*Realization*	*Description*	*Generative Process*	*Design Genesis*
Sagrada Familia Barcelona, Spain	ANTONI Gaudi, 1882	Example from where designers may interpret parametric algorithms for new ideas	Mathematical sequencing and algorithms of the geometry schematization	Mathematics, algorithms
The Philips Pavilion For The Brussels World's Fair	Le Corbusier and Iannis Xenakis, 1958	An artistic technological self-supporting project (music composer "clouds of sound".)	Application of the computational graphics to create a technological modern work (hyperbolic paraboloids).	Computation and technology integration
Beijing International Airport, China	Foster and Partners, 1958	a simple gradual curves geometry that gives the sense of calm	Using simple techniques from mathematics arcs and lines are the basic elements of the shape generation	-Mathematics, Geometry-based Generation process
Olympic Stadium, Munich	Frei Otto and Frederick Kiesler, 1968	One of Munich city's landmarks that shows a more compassionate face of Germany.	Mimics the growth mechanism of trees and compared it with a generative complex order	Nature-based generation process
Multihalle Mannheim	Frei Otto, 1975	An example that makes use of analog models, designed for the aim of providing a covered space for cultural events.	Application of self-organization method using basic materials searching a possibility space and generate geometrical forms	Algorithms, Interdisciplinary generation process
Biocentrum In Frankfurt	Peter Eisenman, 1987	Simple design that presents a mystery between architecture and biology	An analogical generative process applying replication, transcription, and translation which known as the physical basics of biological growth.	Biology-based generation process
The Nunotani Corporation Headquarters, Tokyo	Peter Eisenman, 1990	An example that breaks the boundaries between the polemical and provocative character of the design. Influenced by deconstruction theory	Application of a set of mathematical techniques such as scaling, overlay, fractals and superposition	Mathematics, algorithms
Golden Fish (The Olympic Village in Barcelona)	Frank Gehry, 1992	One of the generative design significant examples based on nature applications and Interdisciplinary computing	Used three-dimensional aeronautical-design software to generate the idea (CATIA). Employing conditions and angle of the sun to make an abstract object that reflects rays and changes colors.	Nature-based data integration. Interdisciplinary generation process
The Waterloo Terminal, London	Nicholas Grimshaw, 1994	Important examples of parametric design system application.	Creating a parametric model that encodes the rules of the arches together as a whole process provides the ability to reproduce the dimensional changes	Parametric application, Geometry-based Generation process
British Museum Great Court, London	Foster partners, 2000	The project is a highly influential glazed roof design that is both rectangular and circular.	Besides the subdivision surface techniques applied many other techniques such as NURB surfaces were used to generate the grid on the surface and the curvatures at the corners	Parametric application, Interdisciplinary generation process
Serpentine Gallery Pavilion, London	Toyo Ito, 2002	An example of form genesis generation with an irregular and tectonic façade pattern	A pattern traversing, scaling and rotating the edge of a square around a central axis using an algorithmic system.	Geometry-based Generation process, Algorithms
Australian Wildlife Health Centre Healesville Sanctuary, Australia	Minifie Nixon company, 2003	A novel design technique with an abstract mathematical idea based on a biological system of generation	Using Cellular Automation method of generative design as a potential model for biological systems	Interdisciplinary generation process,
Zentrum Paul Klee Berne, Switzerland	Renzo Piano, 2005	Example represents the application of the parametric approach in architectural practice.	Uses of some parametric technics different modifications applied the incline angle of the roof structure and the curvature of the supporting beams	Parametric application, Algorithms
Spanish Pavilion Expo Aichi, Japan	Foreign office architects, 2005	Developing attractive facades and interior environments within standard boxes Inspired by the history of Spanish architecture	Designed a hexagonal grid with different colors continuously varying to generate pieces based on a mathematical process (Islamic and gothic ornamental geometries)	Geometry-based Generation process
Island City Central Park Fukuoka, Japan	Toyo Ito, 2005	A project that represents complexity and fluid dynamics studies that could be seen in his sketches and waveforms	A generative process of evolutionary shape tends to minimize the strain energy by designing a shape that transmitted load.	Interdisciplinary generation process, energy application
Heydar Aliyev Centre, Azerbaijan	Zaha Hadid Architects, 2007	This project expresses the future vision of Azerbaijan and shows the optimism of its people	Generative space frame system which is constructed with glass fiber reinforced concrete panels.	Interdisciplinary generation process, Technology integration
Smithsonian Institution Courtyard Washington,	Foster and Partners, 2007	Roof design based on structural characteristics and computation capacities	Based on structural optimization allowed to explore hundreds of form propositions through simple performance control of the used panels	Structural optimization, Algorithms
Melbourne Rectangular Stadium, Australia	Cox Architects, 2010	A project that was designed to combine esthetics and parametric design approaches.	Generative parametric models were developed to find an optimal roof's curve shape with a structure performance without affecting aesthetics	Parametric applications
Qatar Education City Convention Centre Doha, Qatar	Arata Isozaki, 2011	Designed with the inspiration of the Sidra tree by using fewer materials searching for an efficient shape.	Using the extended evolutionary structural optimization method to provide efficient shape performance according to the design criteria and site requirements.	Structural optimization, Algorithms
Louvre Abu Dhabi Abu Dhabi, UAE	Ateliers Jean Nouvel 2017	Dome designed although many geometrical and environmental requirements	Employment of several performance criteria and respecting natural requirements without affecting aesthetics.	Complexity applications, Interdisciplinary generation process.

3. GENERATIVE DESIGN APPLICATION IN ARCHITECTURE

Recently many generative design methods are widely employed in different fields. Here, it is important to understand how these applications are practically interpreted in different design processes and simplified to be easily explored. Furthermore, defining classifying and finding relationships between these different applications will help to engage them in different design problem-solving procedures. On this basis, this part of the research tends to provide a new classification of generative design systems and approaches and explore their applications in architecture. Besides that, generative design processes and optimization methods engaged in different architectural designs are also reviewed and summarized. This section compares current generative design methods and offers some insights into what may be acquired from other generative systems and design optimization.

3.1 Generative Design Approaches and Systems

The inclusive variety of generative design applications shows significance in distinguishing between a generative system and generative approaches. This misunderstanding of the association between such systems and approaches, as well as their basic functioning procedures, calls for a solid classification and discussion. Very few researches have promoted systematic classifications for the used approaches and systems. Through this research, a system is meant to express a group of combination and computational applications to provide multiple design possibilities. It is a unitary where a complex process engages different pre-collected data to respond to the design problems by providing better design alternatives. It is where a design could be performed by using one or many generative design approaches. Moreover, an approach is meant to express a tendency to make a proposal or suggestion to resolve a specific design challenge with the support of other applications and processes that must be connected with and integrated inside a given system. Approaches then could be defined as a component of the broader system. Their features must be effective at what they do for the system to function successfully.

Based on this distinctness, this section provides a more detailed holistic classification which includes the extensively used generative systems and approaches in the discipline of architectural design. Every system and approach was first defined, and then the relevant relationships and interconnections between the systems and approaches were addressed. It is believed that this classification will fulfill the research gap and make it properly explained.

This classification guides the researchers and designers towards an evident categorization of systems and approaches, each addressing solutions to different generation problems. From theoretical terms, it will help researchers in the field of generative design to understand the different approaches and systems and decide which one is needed to be theoretically improved. However, in practical terms, designers will benefit from the classification by selecting the appropriate methods for the generation of typical design and which of them is accurate to engage for such a design problem. Generative design systems and approaches have been applied to several problems and through various periods, they are all representing solutions in the search of explaining and comprehending complex forms, shapes and structures. The broadness of the subject initiates a significant need for a holistic classification that can describe and explain these approaches and systems, as well as establish underlying theoretical relationships and functional connections between them in the area of architecture (Figure 3.1.). Several methods that have evolved are classified into various groups as the following:

-Algorithmic Generation Methods: which are introduced as “Algorithmic system”, “Genetic algorithms system”, “Parametric approach”, “History-based technique”, “Algebra technique”, “Concept seeding approach”, “Epigenetic approach”, “Fractal approach”. Those applications are based on form exploration and evolutionary shape modeling, space layout, form and function composition along with formal and structural fitness. They also seek non-identified forms and shape competencies.

-Generative Grammar Methods: focus on developing the shape grammar system by merging geometric knowledge into design rules to respond to the defined goals. They allow generation without any constraints by applying repetitive patterns based on natural organic forms. They are also based on rules and systems to create complex structures and replace the initial objects. Those methods are mainly constituted of “Shape grammar system” and “L system”.

-Emergent Methods (Self-organization): aim to generate a wide range of complex diagram-based applications and grid-based designs for self-reproducing systems. Besides that, they intend to expand a mathematical representation and generation of non-simple structures and set the interconnect between parameters and interaction with their environments. “Swarm behavior system” and “Cellular Automata system” are the main systems that use similar applications.

-Behavioral Methods: principally seek an optimal shape and forms to be responsive to multiple defined constraints. The systems could be proceeded through the implementation of various applications to improve the efficiency of the design responding to the defined constraints and attributes. Among these methods “Topology optimization system” and “Packing approach” are principally involved.

-Agent-Based Methods: engaged basically in layout generation, design composition where a set of forms including generation points represented in defined shapes. Those systems generally use mathematical modulation in form exploration and parametrical modeling together with design analysis. “Voronoi system”, “Variational technique”, “Template technique”, “Grid-based technique”, “shape-based technique” are a few of these methods.

-Recursive Growth Methods: where the systems are based on a substrate algorithm and generation applications like modulation and manipulation which can be executed by repeatedly substituting parts or components of an initial design form into the new set to generate new forms. “Subdivision system”, “Combinational approach”, “Substitutional approach” are some of those methods that allow much more control and permit elements to be integrated into a series of positions or locations.

The generative design system is not meant to replace the designer ability, as it is still depending on combining the entire design phases, setting the interconnections between them, representing and integrating the different systems and approaches which solve that design component, and for the programming that may be expected to deal with explicit conditions of the design. Generative design in general is inspired by geometry, nature, algorithms and biology. It is testing several variables and functions during the representation of the algorithmic process which manages the variance of data. Furthermore, the process comprises several perspectives, solution possibilities which leads the problem of generation to complexity. The generative design methods present various answers to this problem. It treats a diversified design problem with techniques that could exactly resolve a specific side of the problem such as managing data, managing results possibilities, involving several viewpoints and so on (Singh et al., 2012).

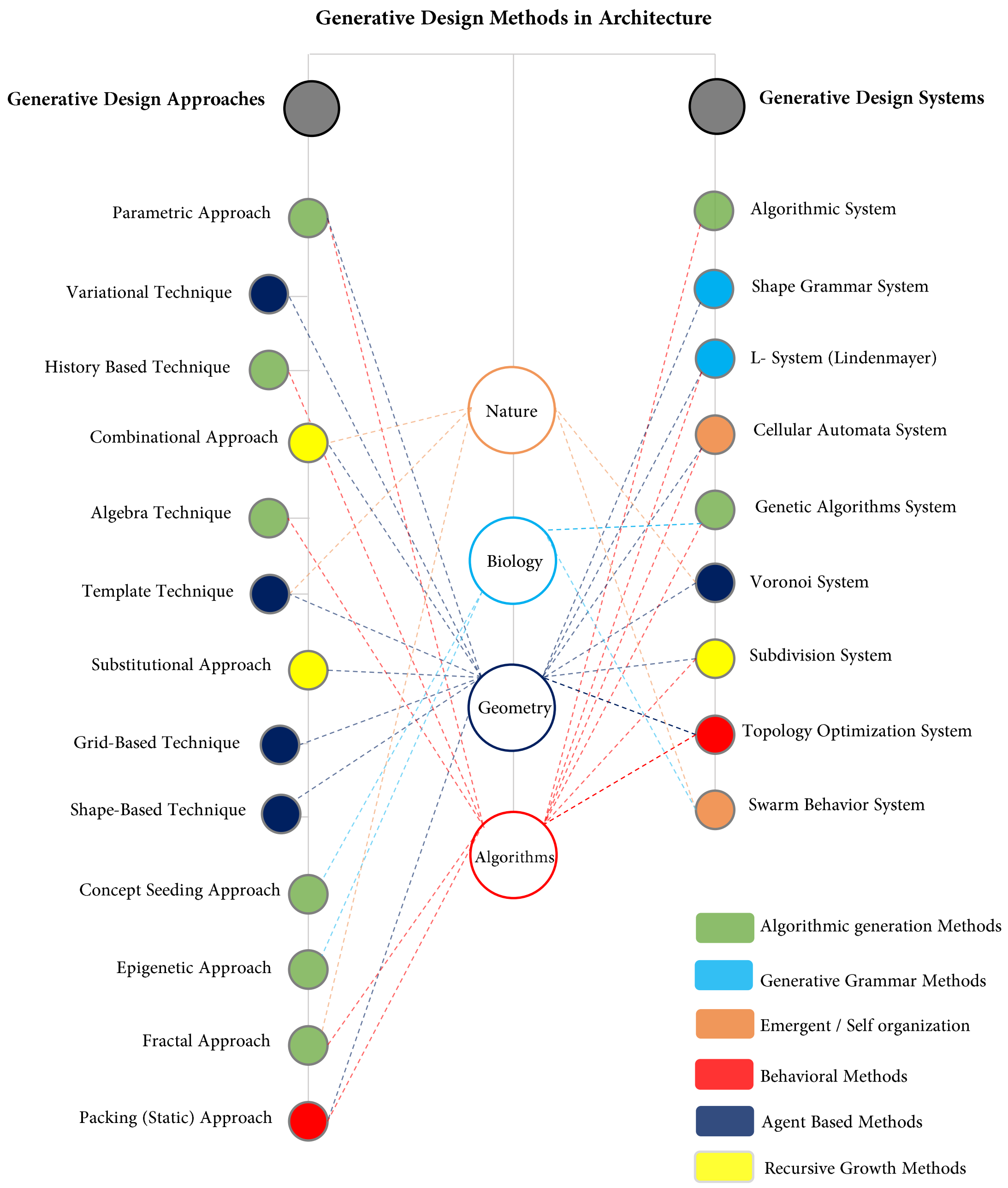


Figure 3.1. *Classification of generative design systems and approaches in architecture. (Source: by the author)*

Many examples tried to incorporate those inspirations within the design process. The application of these methods expanded across multiple areas, including mathematics, social studies, art, urban studies, design, and so on, to improve advanced formal and architectural development. The different practices that have been carried out comprise many approaches and systems, which are discussed in depth in the following pages.

3.1.1. Generative Design Approaches

In the last decade, few researchers have proposed some categorizations either for approaches or for the used systems. One of the worthwhile studies focused on the generative design approaches is the categorization of Janssen (2004) explaining the relations between their different techniques. He identified three main approaches that can be used within a generative design process to seek design possibilities, even if he knew about the existence of other approaches. He classified them into three key concepts; the "parametric approach", the "combinatorial approach" and the "substitution approach" (Bukhari,2011). According to him, the combinatorial and substitution approaches are more flexible than the parametric approach. Whereas, the integration of all the three could be used in a generative design system. Earlier, Frazer (1995) in his research about "generative evolutionary design" talked about two other approaches named "Concept seeding approach" and "Epigenetic approach" where many more techniques could be employed and involved for the same design problem. Restricted to the same context, this research explored more other essential approaches such as the "Fractal approach", "Packing approach" which are recently used in several architectural design developments and researches.

3.1.1.1. Parametric Approach

The parametric approach is the method that permits designers to generate series of forms by specifying parameters to a model or a procedure and then applying modulation on some of these parameters (Wu et al., 2021). It does not cover applications where only dimensional parameters are varied, but includes rational modeling, variational design, constraint-based design and so on (Bukhari,2011). The origin of the idea started in 1957 when Patrick Hanratty founded PRONTO, the first commercial software to provide parametric algorithms for interpreting data from computers to manufacturing instruments. After that, in 1963, Ivan Sutherland developed Sketchpad and demonstrated the first graphical representation of parametric. Kolarevic, (2003) argued that the parametric approach in the generative design domain could be considered as a system as well. After that, Janssen (2004) highlighted two techniques of parametric modeling, the "variational technique" and the "history-based technique". The variational technique is used in parametric modeling systems and must have a predefined model of the form to be generated. The history- based technique, on the other hand, generates forms incrementally through a series of operations that require certain data values. Recently, the application of the parametric approach in architectural design is widely expansive in different subfields such as from generation (Jabi et al., 2017; Bhooshan, 2017), space planning (Çalışkan, 2017; Wu et al., 2021) and structure performance (Harding et Shepherd, 2017; Cruz et al., 2021), (Figure 3.2.).

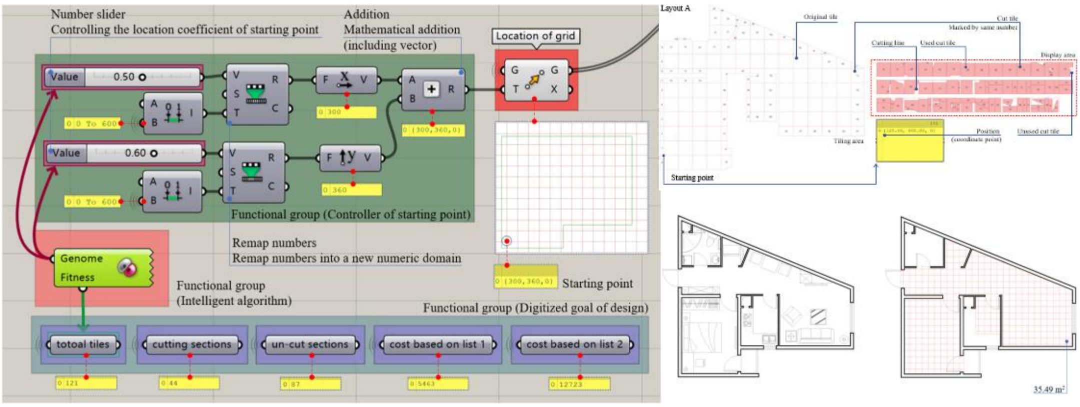


Figure 3.2. *Generating and optimizing workflow using a parametric design approach. (Source: wu et al., 2021).*

3.1.1.2. Combinatorial Approach

The combinatorial approach is the technique of generating forms by assembling and merging a predefined series of elements which is considered the most general sort of approach to attempt generation models and forms (Bukhari,2011). Janssen (2004) identifies two combinatorial techniques, the first using an algebra technique and the second using a template technique. By using an algebra technique, a collection of components or elements are predefined including not only the element types but also a set of operations for position alteration. Using the template technique allows for much more control, but the variability of the generated forms is reduced. The template technique permits elements to be integrated into a series of positions or locations in a pre-defined organizational template (Figure 3.3/3.4).

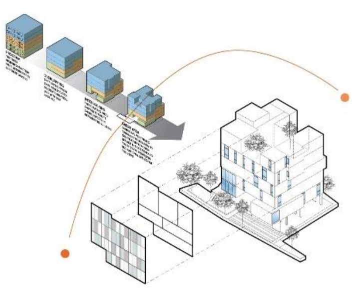


Figure 3.3. *Zonic vision office. (Source: citation award, 2014).*

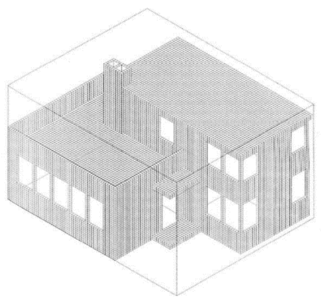


Figure 3.4. *A house represented as a collection of four-inch cubes. (Source: Mitchell, 1990).*

3.1.1.3. Substitution Approach

The substitution approach generally represents the generations of shapes starting from a basis (seed form) that is preceding provided (Singh et al., 2012). Modulation and manipulation can be executed by repeatedly substituting parts or components of that basic form into the new set to generate new forms. Janssen (2004) declared that the substitution approach to generative design can be achieved by using one of two techniques, generating forms by using a grid or generating forms by analyzing the shapes of the components. The “grid-based” substitution technique uses a pre-defined cellular grid into which the substitution of the various parts of the form can be made. Moreover, when using the “shape-based” technique, the substitutions are performed based on the geometry of the individual shapes' (Bukhari, 2011).

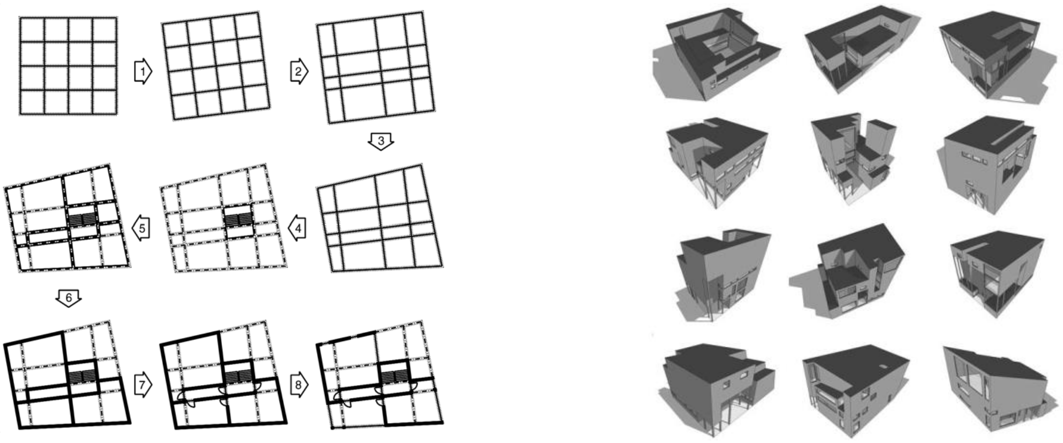


Figure 3.5. *Example of the generative process steps. (Source: Frazer and Janssen, 2004).*

3.1.1.4. The Concept-Seeding Approach

Frazer (1995) promotes a completely dissimilar approach to generative evolutionary design in relation to the designer assignment. He focused first on the generative systems’ requirements and then enhanced them with evolutionary competencies. In Frazer's approach, the designer selects and codifies his design ideas, which are then merged into a computer program that can generate various designs and still ensure the original design ideas. The origin of the concept can include any design considerations, such as the formal, structural, constructional, aesthetic or indeed any other consideration (Janssen, 2004). This may open up the opportunity for many more design concepts to be computationally explored and implemented using tools like Grasshopper and dynamo. However, there is no further application using this approach in architectural design.

3.1.1.5. The Epigenetic Design Approach

The epigenetic design approach responds more to the design environmental requirements out of the design evaluation phase which allows designs to be generated in response to them. Frazer (1995) summarizes this method saying that: "The evolutionary model requires an architectural concept to be described in a form of genetic code''. Whereas, both in the academic arena or architecture practical field, no generative design examples have been recently developed based on the goal of context requirement responsive solutions. Engaging novel innovated computational design tools and visual programming platforms may open doors for interesting applications using epigenetic design approaches or similar methods.

3.1.1.6. Fractal Approach

When Benoit Mandelbrot initially introduced the concept, fractals became a mathematics major. Fractals were counted as the obscurity of nature's design and used as symbols and decorative forms from a long time in the past, like many, describes patterns regenerated by the golden ration concept "a pentagon" (Shiffman, 2012) (Appendix-2). These are geometric elements whose fractal characteristics are major than or equal to the Euclidean dimension, according to Mandelbrot's definition (Mandelbrot 1982). The main idea that the fractal concept presents is self-similarity. The property of a form to look like itself pays little respect to which some portion of it is watched and pays little respect to how frequently it is amplified. It may be subdivided into several elements, every one of which is (at least approximately) a decreased size duplicate of the entirety.

Fractals usage as generation systems have eventually led to a major revolution in the natural and technological sciences, and subsequently in the fields of architecture and civil engineering as practical sciences (Figure 3.6.). Mathematics was always an important part of architectural design concerning the generation of order and beauty (Zlatić, S 2013). Recently many applications are done in the design process using fractals as a generation system to seek non-found forms and shapes respecting the main constraints of both architecture and mathematics.

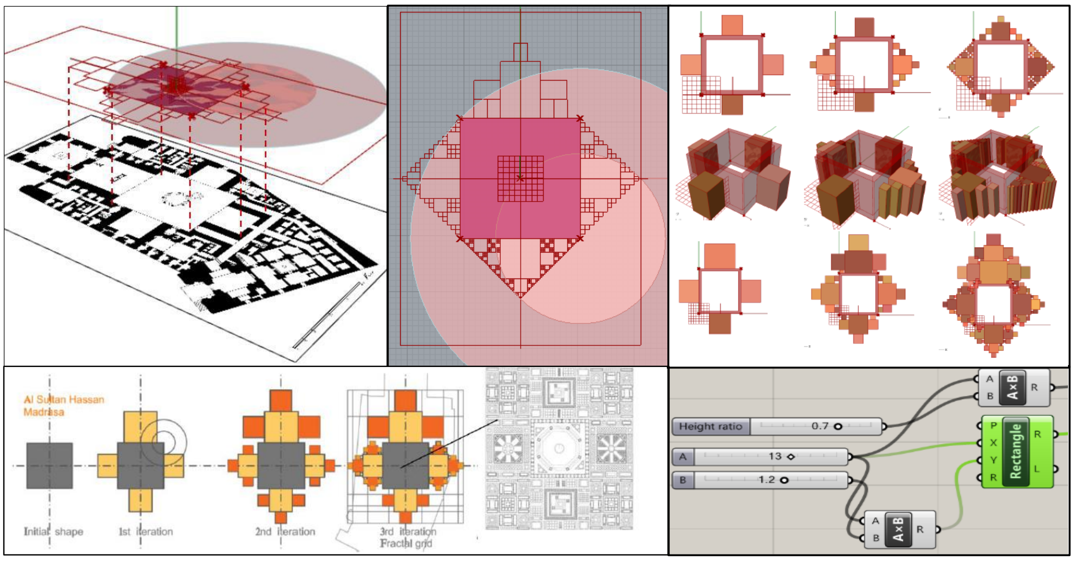


Figure 3.6. *Fractals usage as a generation system (Explanation of Koch Curve).*
(Source: Abdelsalam and Ibrahim, 2019).

3.1.1.7. Packing Approach

This approach is developed in essence for the objective of researching the historical usage of a specific material selection and its future position and integration in contemporary architectural design. For this situation, the main goal was to study the variance of transferability to improve the efficiency of the wall brick system responding to the defined constraints and attributes. Contemporary, the work of Dritsas et al. (2013) is one of the relevant examples of this generative approach (Figure 3.7.).

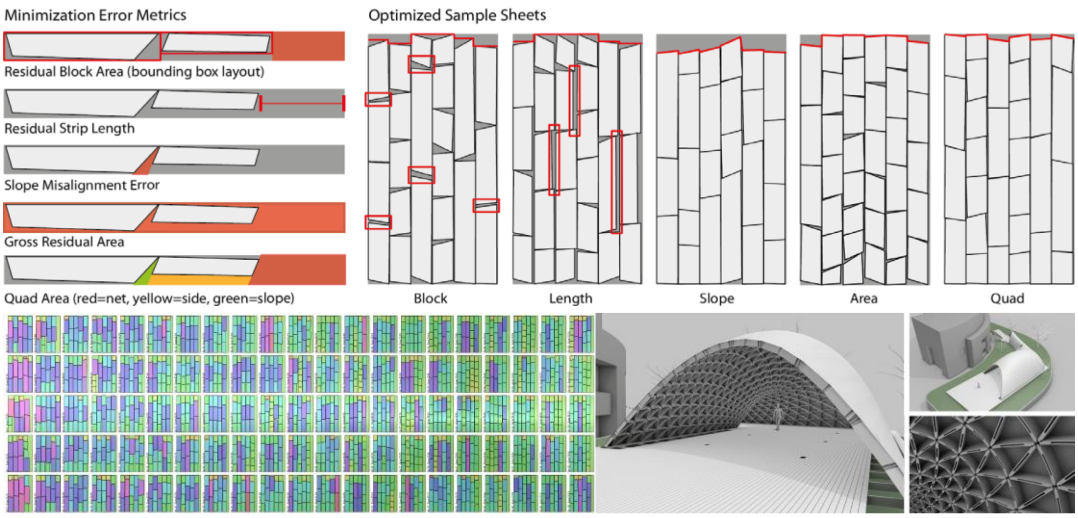


Figure 3.7. *Result of the automated layout of thousands of beam elements using the packing approach.*
(Source: Dritsas et al., 2013).

Dritsas et al. (2013) developed an algorithm that minimizes the material utilization, reduces manufacturing durations and enhances the expenses of production through the use of the packaging method. They conclude that is necessary to tackle design concerns like the simplicity of the building component, layout and path optimization, correspondingly, resulting in material and performance efficiency.

Before that, this approach has been involved in many other studies and experiments with the help of technology tools. Gramazio and Kohler (2012) also investigated the same approach in their academic research through students' works. They mentioned that *"The students defined not the geometry of the wall, but the constructive logic according to which the material was organized in a particular temporal order, and which thus produced an architectonic form".* During the research, they avoided the typical form-finding by working on mathematical algorithms which manage every single part of the brick structure. However, each phase of the system is interpreted in the digital environment, then the process information is transmitted to a robot arm which works accurately to place each module. The used technology lays on a connecting agent up of each brick that gives the possibility for the next block to be precisely placed to the one before (Gramazio and Kohler, 2012). Some other version of the same generative design approach was applied using the wood material. The outcome is a similar formal expression with an ability of horizontal relationship structure leads the researchers to discover new research interest in analyzing complex forms and their material efficiency and structural economy. Various alterations arise from the same tectonic expression where the generative system transfers its inconstancy (Figure 3.8.).

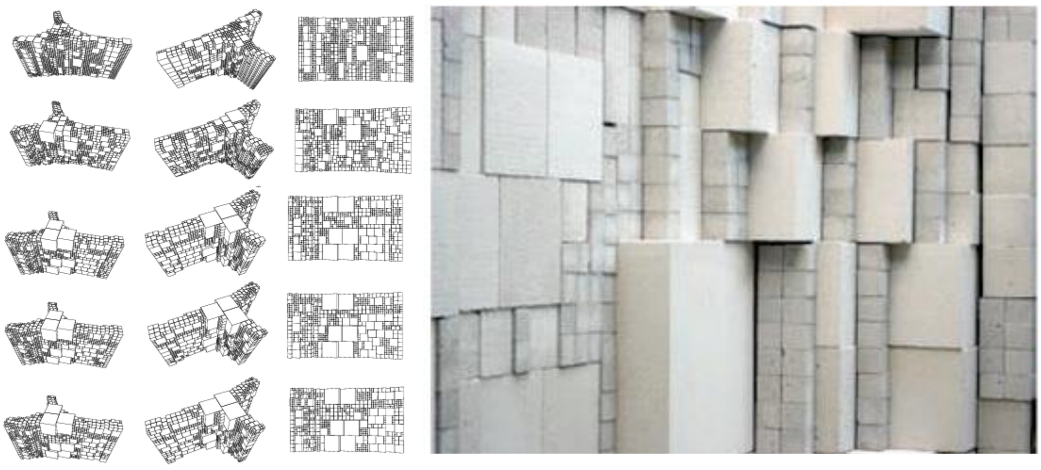


Figure 3.8. *Digitally fabricating non- standardized brick walls. (Source: Bonwetsc et al., 2007).*

In any case, given the remaining burden toward the front of the structure procedure (creating complex calculations, custom displaying programming, and machine code), the speed of generation might be an illusion just made conceivable by incalculable hours in the studio shop manufactured boards are embedded into solid frames, transported to the site, and raised into place on the last building combination (Bonwetsc et al., 2007). This effective structure testing experience provides an important potential for future constructions.

Another example based on the packing approach to construct a structural form is the Hy-Fi mushroom brick technology designed by David Benjamin of New York architects company “The Living”. The main intent of this example is the use of innovative building material organic, biodegradable bricks depending on the structural language that is grown to assist a brick-formed model (Figure 3.9.). Some steel supports are used to grow the bricks on the top of the structure which was read functional enhancing the light entrance to the interior. The architect Benjamin gave more details about the brick structure saying "we wanted to acknowledge the red brick structures and glass towers of New York City, but then turn them inside out," (Living, Hy-fi, 2014).

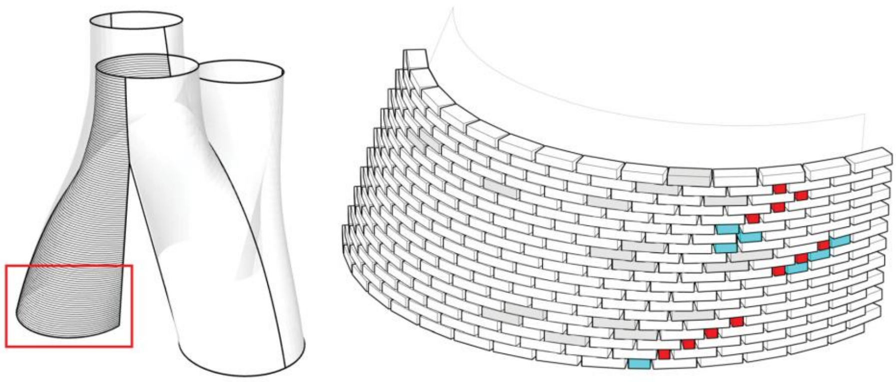


Figure 3.9. *Packing generative system' working process by "the living". (source: Hy-fi, 2014)*

The discussed generative design approaches are those offered dependencies to the conceptualization of the research objectives and limitations. Many other approaches engaged in architectural design application can be existing, this may open doors for extra investigation in the same topic. As a result of this section, various generative design approaches are explored and examined on a scope basis. The following table is an overview of the most important characteristics, limitations, and application purposes of the generative design approaches that might be valuable for future architecture researches and design applications (Table 3.1.).

Table 3.1. *Overview of the most important generative design approaches. (Source: by the author).*

	Parametric Approach	Combinatorial Approach	Substitution Approach	Concept-Seeding Approach	Epigenetic Design Approach	Fractals Approach	Packing (Static)
Literature	Patrick J. Hanratty (1957), Ivan Sutherland (1963)	Mitchell (1990), Janssen (2004)	Janssen (2004).	John Frazer (1995), Janssen (2004).	Frazer (1995)	Benoit Mandelbrot (1975)	Eladio Dieste (1958)
Definition	-Generate a series of forms by specifying parameters	- Generating forms by assembling and merging a predefined series of elements	- Generates forms starting with a provided radix form (seed form)	- A generative evolutionary approach that enhances generative systems' requirements	-Concept described in a form of genetic code that respond to environmental requirements	-Obscurity of nature's design - Generation of order and beauty	-Usage of a specific material selection and position and integration in architectural design
Techniques	-The variational technique, -The history-based technique	- Generation by an algebra technique - Generation by a template technique	- Generation based on a specific grid - Generating forms by analyzing the shapes of the components	- All evolutionary design techniques	- Generation techniques that mimic biology evolution	- Concept presented is self-similarity - Subdivided into several elements - Decrease entirety size during duplication	-Define the constructive logic according to which the material organization and order
Components	-Specific parameters to a model or a procedure	- Predefined series of elements	- Pre-defined cellular grid -Geometry of individual shapes	- Codified design ideas	- Parameters specified according to the context (respect environment)	-Geometric elements major than equal to the Euclidean dimension	-Process information transmitted to a robot arm that works accurately to place each module
Features	-Cover many parameters variation: *Dimensional parameters *Rational modeling, *Variational design, *Constraint-based design	- include a set of operations for position alteration - allows for much more control - Permits elements to be integrated into a series of positions or locations	- Generation applications like modulation and manipulation can be executed by repeatedly substituting parts or components of that radix form into the new set to generate new forms	- Concept can include any design considerations - Generation allows for any other consideration - Generation of several forms that similar to the original ideas	- Responds more to the design environmental requirements - Freedom of the parameters identification	-Pattern generation (Golden ratio) - Paying respect to the form amplification	-Integration in contemporary architectural design -Responding to the defined constraints and attributes -Creating complex calculations, custom displaying programming, and machine code
Constraints	-Limitation of generation during modulation on some of the defined parameters	- Attached to the predefined elements which limit possibilities -The variability of the generated forms is reduced	- Constraints performed by grid fitness - Limitation of the resulting forms - Restricted employment of the component's shapes	- Limitation linked to the used computational programs	- Based on theories may not have a scientific explanation	- Mathematical Constraints during generation - Symmetrical results and lack of variation	- Incalculable hours of the generation speed -Burden toward the front of the structure procedure
Application Purpose	Design generation: Form exploration and parametrical shapes modeling	Design efficiency: space layout, form and function composition	-Design variation: form composition and shape analysis	Evolutionary Design: formal and structural fitness, shape competencies	Environmental responding: form limitations and codes integration	- Used as symbols and decorative forms. - Generation system to seek non-found forms and shapes	-Study the variance of light and air transmission - Improve the efficiency of the wall brick system responding to the defined constraints and attributes

3.1.2. Generative design systems

Generative design systems essentially engage computational methods like algorithms and mathematical rules to encode the conversion of the design form. These generative systems can be considered as methods that explicitly simplify design processing and assess variation in from finding or space generation by providing multiple alternatives (Dino, 2012, Krish, 2011). Soddu (2006) emphasizes that generative design systems mimic different phenomena to create and imitate the rules and limitations with several unrefined design variations. The use of actual computation and digital technologies helps to enhance the designer's capabilities to construct novel and efficient design processes (Shea et al., 2005). Kalay (2004) defines generative design systems as mechanisms and processes that provide possibilities to generate undiscovered forms and artifacts.

According to a specific framework in many fields and, consequently, generative design processes fundamentally follow and repeat four steps which are; Representation, Generation, Evaluation and Feedback. These operations are based on the input-output relationship. Cagan et al. (2005) explained that the representation phase is the identification of the design problem which helps to set the convenient techniques generation. Generation is the performance of the whole mechanism with its parts. Where evaluation represents the testing phase of the system and how well it associates the aims and limitations. Moreover, feedback is the last step where design improvements are provided for the next generation process. During all steps of iteration, the role of design is focused on the beginning of the process by cognitively concept the design problem, its procedures, limitations and conditions (Cagan et al., 2005).

Contemporary generative design systems have challenged architectural theories and practices addressing novel digital technology and computational design applications. Many of them started to engage in practices influenced by natural and biological exploration. This led the domain of research to impose the analysis of various computational generative theories for the aim of treating data constraints with the help of computers' potential. Oxman (2006) has declared that the fast evolution of generative design takes various ways while seeking design systems and approaches. The future of computational design research raises the necessity to reconsider the practices and techniques used in the generation processes. Agkathidis (2015) defined generative design system saying *"It can be described as a design method where generation of form is based on rules or algorithms, often deriving from computational tools, such as Processing, Rhinoceros, Grasshopper and other scripting platforms". Fischer in his paper "Teaching Generative Design"* (2002) provided a fundamental classification presenting the emerging areas for the generative computer aided designing methods for better comprehension of the systems. However, each of the stated areas is not particularly functioning, most of them engage attributes and proprieties with others. This is what makes a new holistic classification of the generative design systems essential for the architectural design field.

In the same way, the generative design systems were first structured by Fischer and Herr (2001) and after by Janssen (2004) where they gave a very brief explanation about their applications and processes. With each passing day, the provided information is becoming limited to be benefited from in today's architectural design application. Fischer and Herr (2001) believed that generative design systems should be introduced according to specific projects which contain mathematical techniques. Their categorization is divided into four groups; "Emergent systems or self-organization" such as cellular automata and swarm modeling; Generative grammar" which signify L-system, shape grammars systems; "Algorithmic and growth systems" like fractals, parametric design and "Evolutionary systems" expressed in genetic algorithms and selective procedures. In architectural design theory, there are some other worth mentioning generative design systems which are discussed by Oxman and Oxman (2013). In their book "Theories of the Digital in Architecture" they theoretically considered two periods of the system application "First generation period 1990-200; and second generation period 2000-today". The first one is characterized by its relationship with philosophy and mathematics and the second set apart no precedents in defining the paradigm shift of the design formulation. Singh and Gu (2012) have also investigated generative design methods in considerable depth information. However, they focused just on a few major systems of generative design methods, namely, Cellular Automata, Shape Grammars, L-Systems, Swarm Intelligence, and Genetic Algorithms. Thus, it does not include the most recent methods. This categorization is providing a concept-based more than an application-based classification which is the main objective of this research section (conceptualization part).

3.1.2.1. Algorithmic systems

Among all the generative practices the algorithmic systems may be the most flexible and conventional. They do not follow specific organization or relationship conditions. They extend a generation setting where the designer has the ease of implementing their design intent and methods (El-Khaldi, 2007). The word algorithms could be found in many different works of literature named as methods, processes, techniques which intend to comprise parameters of the same idea for solving a specific problem. They are a series of commands presented in a step-by-step particular language designed to resolve a problem that requires abilities to execute it and come to an end (Berlinski, 1999).

Algorithms demand diversified data such as location, dimensions, form properties and many more to process the generation system by using different components connected beyond several functions and rules. An architectural example based on the algorithmic system is the pavilion by Toyo Ito and Cecil Belmond designed for the 2002 Serpentine Gallery. The algorithm specifically designed for this building involves the rotation and scaling of a series of squares around a central axis (Figure 3.10.). The resulting form is a well-defined algorithmic system that looks complex and random where is no visual disparity between exterior skin and building structure (Deuling, 2001).

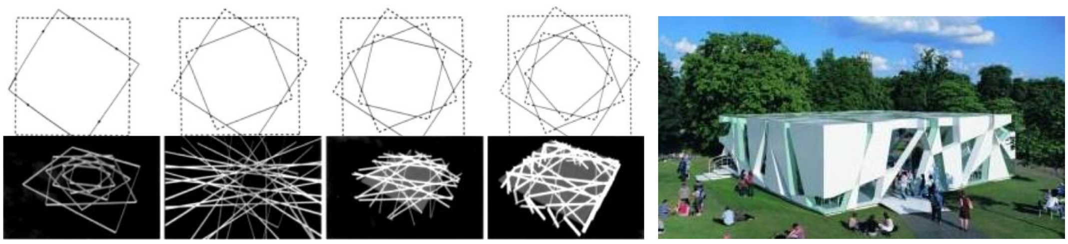


Figure 3.10. *Schematic representation of the application of the algorithm system. The 2002 Serpentine Gallery. (Source: http://www.serpentinegallery.org/architecture/.)*

3.1.2.2. Shape Grammars

A shape grammar is a set of shape rules that are applied in a step-by-step problem-solving procedure to represent a process of designs. Shape grammars are spatial, rather than textual or symbolic algorithms (Knight, 1999). They are especially useful in designing forms that are differentiated primarily on the basis of form yet driven by function (Shea and Cagan,1999). These generative systems were invented by Stiny and

Gips in 1972 and were named "design-oriented" generative systems (Appendix-2). They extend the foundations for research into algorithmic design systems in the context of design analysis and design synthesis (Alfaris, 2009).

Grobman et al. (2009) declared that shape grammar has techniques that apply to initial shape taking into consideration the replacement of forms and symbols for the generation. During the design process, this system has always a tendency to the sake of its first design stage based on using computers' potential such as speed and extrusion. He mentioned that the resulting geometric forms are easy to understand, modify and manage because of the designed rules and principles. However, this system cannot solve any problems when varying the initial forms. Knight (1998) defined a shape grammar system as a series of forms that can be modulated to generate several design alternatives where shape rules are the attributes of the design mechanism. It is used as a method to seek new design languages or test existing ones. The critical challenge that confronts the improvement of a shape grammar system is to design forms and shapes that respond to design purposes and limitations. Knight (1999) proposed two approaches, the first approach entails appropriate design cognition while developing the shape grammar system by merging geometric knowledge into design rules to respond to the defined goals. This approach decreases the shape forecasting and controls the application of design rules which constraint the system. The second approach does not need any design knowledge to start the development of a shape grammar system and allow the generation without any constraints. During the design development, several applications of testing and selection are performed by an automated appliance to reach the targeted solutions.

Stiny (1980) proposed the initial components of a shape grammar as a finite set of shapes, a finite set of symbols, a finite set of shape rules with an initial shape. He said that any design generated by this system is considered as "elements in relations" (Stiny, 1990). It is formed via shape rules that define and alter connections between specific elements through applying addition, subtraction and replacement techniques. The most known examples of the shape grammar application are the Palladian grammar (Stiny & Mitchell, 1978), Mughul Gardens grammar (Stiny & Mitchell, 1980), Prairie Houses grammar (Koning & Eizenberg, 1981) and Siza Houses grammar (Duarte, 2005) (Figure 20). Other effective experiments have recently been performed by Duarte et al. (2007) and Paio et al. (2011). Both intended to consider optimization into the generative procedure, which is a method of merging design optimization with generative approaches. Until the present, form grammar has appreciated the most effective and applicable system in functional architectural and urban design (Figure 3.11.). Progressively, many applications of procedural modeling methods using shape grammar systems are discussed in both urban planning and architectural design to demonstrate solutions to specific spatial and contextual challenges (Halatsch et al., 2008).

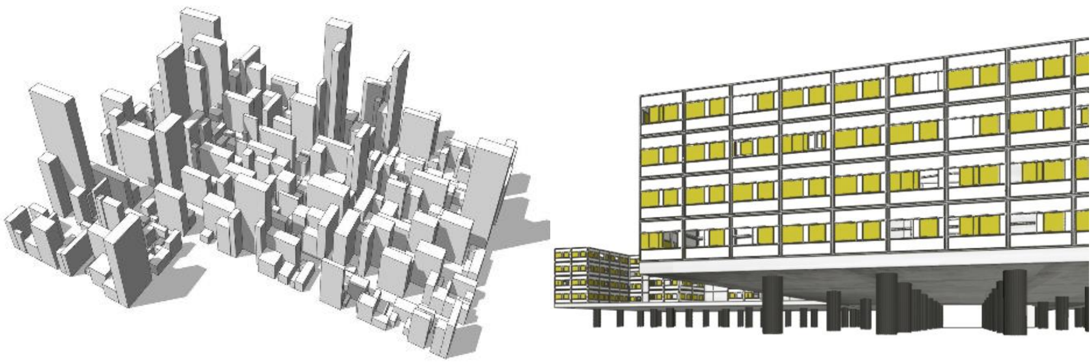


Figure 3.11. *Shape placed building masses and a Detail of the modeled facade using Shape grammar system.*
(Source: Halatsch et al., 2008).

3.1.2.3. L-systems

Rocker (2006) declared that architects were inspired by the geometrical forms existing in nature since ancient times. Many of them strive to engage natural geometric shapes in their designs, the Lindenmayer system was one of them (Lindenmayer, 1968). In 1968, the biologist Aristid Lindenmayer proposed a mathematical theory of plant growth based on the central concept of string-rewriting inspired by nature which is known for short as L-systems (Appendix-2). They are considered a powerful tool for designers (Fasoulaki, 2008) particularly, because of their ability to produce highly complex designs from extremely small inputs (Hansmeyer, 2014). Kolarevic (2003) wrote in his book "Architecture in the Digital Age" that the L-systems are based on rules and systems, through which, designers can create complex structures and replace the objects, which were created before. These systems are mathematical algorithms applied for generating forms with shape-similarity. They have been used to solve different design problems in urban planning (Kelly & McCabe, 2006), simulation and computer graphic patterns (Palubicki et al., 2009). Prusinkiewicz (1996) stated that, the L-system is based on a set of rules and symbols that assist a process to find new forms' characteristics.

Later on, models and frameworks with a visualizing graphic, and from on the L-system became known and applied. Many experts begin to do researches on plants, their leaves and their branches to learn from them. Applying processes including plant development with constants and modification parameters using varying starting points. Digital morphogenesis for “Proto-bionic” is one of the relevant L-system examples in architecture which was represented as a generative logic using plant development’s processes (Kolarevic, 2003). After that, Smith worked on one of the important ideas of L-system functions “data amplification”, which focuses on the combination of multiple data to design complex structures in the domain of synthesizing images (Prusinkiewicz et al., 1996). Fundamental biological theories contributed to the development of an efficient generative computational framework, which was later employed as a component of several design generation and computational methods (Figure 3.12.). However, there is one limitation that stems from the constraints of these methods in general (Duarte et al., 2007). Rather than being influenced by existing designs, the created designs are generally independent of the urban configuration. They are more appropriate for application in a broader range of circumstances than those with significant specific attributes (Paio et al., 2011). In essence, the effective and revolutionary application of these architectural design systems relies significantly on the designer's capability to formulate an innovative set of rules that meet the desired objectives. This makes the L-system an excellent alternative as requirement-based methods for generative design exploration. (Cruz, 2018).

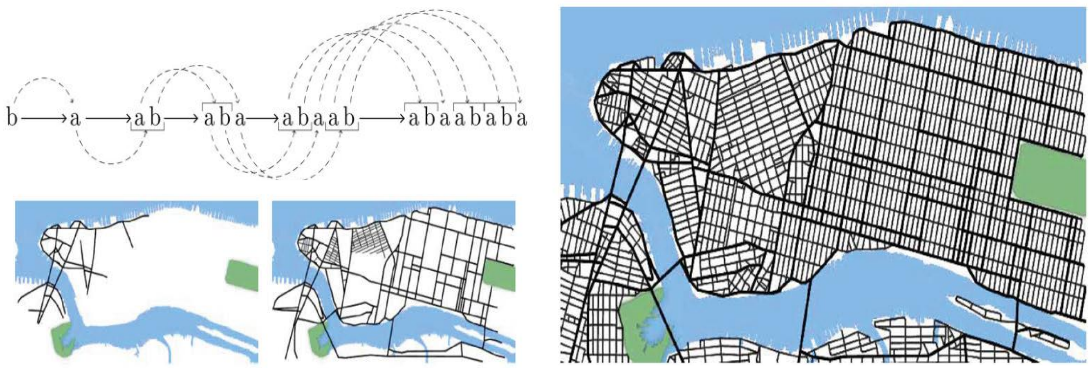


Figure 3.12. *Procedural generation of the street pattern using geographic information from manhattan and an l-system. (Source: Cruz 2018).*

3.1.2.4. Cellular Automata

Cellular Automata are generative systems and many researchers considered them as models described of self-reproducing systems (Dinçer, 2014). A cellular automaton is a combination of cells arranged in orthogonal grids, each with a finite number of states that are designated as colors or numbers. The generation of each cell consists first of its actual state and the state of the adjoining cells (Alfaris, 2009). According to Grobman et al. (2009), Cellular Automata were most probably the evolutionary generative systems that were influenced by the biological connotations. Besides that, Wolfram (2002) believed that cellular automaton is based on simple mathematical and analytical methods for generating a wide range of complex diagrams. They are holistic models, which encompassed systems about physics, chemistry, biology, and other sciences. Fundamental rules to design 2D patterns started to be generated by many designers applying a package called "Conway's Game of Life" which was founded in the 1970s (Appendix-2). Applying several similar rules leads to having various degrees of ramification with complex pattern's generation which are not enough predictable (Wolfram, 1984). Although these processes tend to transform cells during execution, their potential procedures are often restricted by the grid type selected. Thereafter, Rocker (2006) declared that the emergence of algorithm simulation and design software is determined by 2D technology.

Cellular Automata was also effectively integrated into architectural and urban planning in a variety of ways (Herr et al., 2005). However, because it is bottom-up, the results are frequently challenging and difficult to anticipate (Dinçer, 2014). Furthermore, design professionals are unaware of the process of defining constraints that are necessary to steer the generative process. Practical motivation in this approach has already decreased in recent experimental researches (Krawczyk, 2002b). Many comparable applications are being used for different aspects of architecture and urban design (Zandavali, 2019) based on the same generative system characteristics (Krawczyk, 2002a). The applications are expected to create a broad range of generations via the integration of the cellular automata as a generative system combined with various digital tools to create environment model connectivity and performative urban measures as building responsiveness (Figure 3.13.).

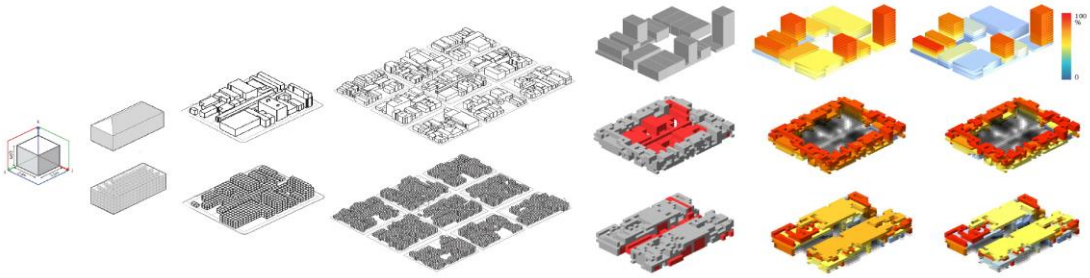


Figure 3.13. *Building forms and results the redesigned buildings of court and street morpho-typologies using cellular automata generative system. (Source: Zandavali, 2019).*

3.1.2.5. Genetic Algorithm

Genetic algorithm (GA) is a computational procedure, inspired by natural evolution, which was first introduced in the 1970s by Holland (Kalay, 2004). It is also considered as a search method for design problem-solving (Caldas, 2008). Fasoulaki (2008) believes that this system has been used basically as a method of solving optimization problems of biological evolution. These concepts are used in architecture for handling complicated language of projects. It helps solve fully defined issues including structural or performance applications. The generative algorithms system proposes the model of nature as the generative force for architectural form (Frazer, 1995). The genetic algorithm system includes two genetic concepts that make the difference between the schema and the observed characteristics, which are phenotype and genotype (Holland, 1992). Genotype means the genetic structure of an organism where the information is included in the genome. It can be considered as a schema that includes the individuals' traits inherited during the generation process. However, the Phenotype demonstrates the observed characteristics of an organism determined genetically and environmentally (Haupt & Haupt,2004) regarding the functions assorted by the genotype (Appendix-2). Consequently, the genotypes extend orders and functions to designate the phenotypes which are the outcomes of the generation process (Sastry et al., 2005).

On the other hand, we can find the Genetic Algorithm for Design Optimization (GADO) developed by Khaled Rasheed which engages a genetic algorithm for continuous design space optimization that uses new GA operators and strategies adjusted to the structure and properties of engineering design domains (Rasheed, 1998). During the optimization phase, the fitness solution with a higher score is the critical aim of the system where a pursuit for the optimum solution is determined by the functions' fitness (Kalay, 2004). To reach this the used individuals are paired off and compete (Jones, 2002). Genetic algorithms or evolutionary systems as they are titles in many other pieces of literature by Bentley, can be used for a variety of design types following the general synchronous evolutionary architecture, but uses specifically developed rules and representations' (Janssen, 2004).

The genetic algorithm systems consist of four main phases including creation, selection, crossovers, and mutations of a defined population. In all the generative design systems, representation sets between the design problem and generation process. In genetic algorithms, representation is the phase constructed according to the genome's symbolic characteristics (Mitchell, 2009). It is known that the representations are mathematical and they performed via symbols, whereas in the genetic algorithm systems representations are not visual. The phase after representation is the generative process itself, where the system engages individuals in a generation mechanism searching for the optimal solution of the design problem presented in the beginning. The initial step within the process sets an individuals' random generation.

After that three other operations are repetitively applied to procure generation, which are selection, crossover and mutation (Abraham et al., 2006). Selection is an operation based on a fitness function that assesses the convenience of the final solution after choosing a parent for regeneration (Abraham et al., 2006). It aims to avoid some individuals such that the stronger genotypes survive and progressively improve the fitness level of the population (Sober, 2006). This phase focuses on mating the surviving individuals during each generation with the aim of modulating the population's fitness. Crossover is the mechanism where the genotype of individuals is randomly mated to generate new ones by the distribution of genes from parents' genotype. (Hensel et al., 2004). The mutation is the operation of regeneration that randomly changes genes in the parent chromosome (Haupt & Haupt, 2004). Weinstock (2010) said that, changes emerge in the genome by "duplicate errors" and mutations that mix the sequence of genes or iterate a few fragments, which thus produce changes to the physical form. Mutation builds a decent variety in a population by expanding the genotype diversity, subsequently phenotypic variation. The evaluation operation is the last phase of the genetic algorithm generation system where the fitness value of each genotype is evaluated and a feedback process (guidance as it is also named) is maintained for better individuals' contribution in the future generation of genetic composition (Cagan et al., 2005). Thus, the evaluation phase guides the generation mechanism and leads the process for a preferable design solution. Goldberg and Holland (1988) declared that there is somehow complication even in the simple genetic algorithm system when it is compared to design.

In architectural design, genetic algorithm system has been applied for various objectives such as optimization (Caldas & Norford, 2001; Salge et al., 2008), space layout planning (Coates & Hazarika, 1999; Gero & Kazakov, 1998;), the evolution of representation patterns (Ding & Gero, 2001) and architectural form-finding. The example of Caldas and Norford (2001) also engaged genetic algorithm system to optimize different other solutions such as façade designs, study the energy consumption and optimize the results. Villaggi and Nagy, (2017) believe that using a genetic algorithm as a generative design system for architecture enables the discovery of unpredicted innovative layouts, manage exchange between high-performing design features, illustration restrictions and objectives rather than spatial patterns, and also effectively collaborate between computers and humans in the design process. This embraces new aspects of thinking, generation, and controlling architectural design while taking spatial requirements and contextual conditions into account (Figure 3.14.).

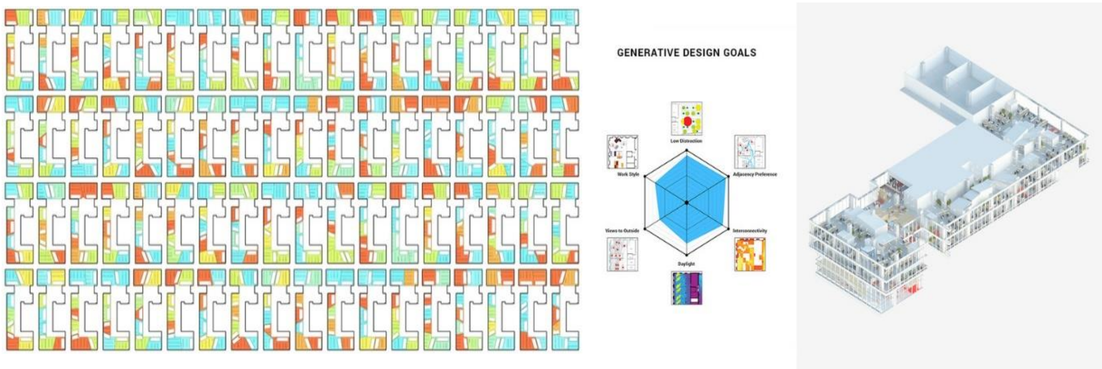


Figure 3.14. *Generative design options and generative design goals of Autodesk research group's the living. (Source: Danil Nagy, 2017).*

3.1.2.6. Voronoi Diagrams

The Voronoi Diagram is a generative design system that respects the biological structures in nature and self-organization constraints by using mathematical modulation (Nowak, 2015). It is a set of forms including generation points or zones represented in defined shapes (Fasoulaki, 2008). It is formed from cells, nodes and angles made up of elements with lines in different lengths. Each one of the cells is a series of points with almost the same site closeness. It is believed that the introduction of the Voronoi concept is provided by the mathematicians Dirichlet and Voronoi when they used it for the analysis of quadratic forms. It is measured by the Euclidean distance in sites integer lattice points. It is also created by a set of forms with proximate regions joining all the same points together to search for the result variation (Figure 3.15.). The outcomes were called Dirichlet tessellation or Voronoi diagram as it is used in the generative design systems today (Davis 2013). Recently many sciences started to utilize this independently emerged concept which was proven useful later. for example, in biology and physiology, this system has been engaged to study Medial axis transformation, besides that it was used in chemistry to test the Wigner-Seitz zones, and later to discover the Thiessen polygons in meteorology and geography (Nowak, 2015).

The application of Voronoi diagram features in modern architecture, planning, and engineering is becoming more widespread. In todays' concepts, it comes to be one of the most dominant projections in the search for new forms of interpretation in architectural design and urban planning along with the creation of architectural and structural shapes. The use of computational configuration in the design of buildings and forms in architecture and urban planning opens up new possibilities for architectural and urban ideas, as shown in the creative design of various works such as London's Aldgate Aerial Park and Vertical Village (Nowak, 2015). Currently, many architects are using the same principles with the inspiration of nature to seek structural forms.

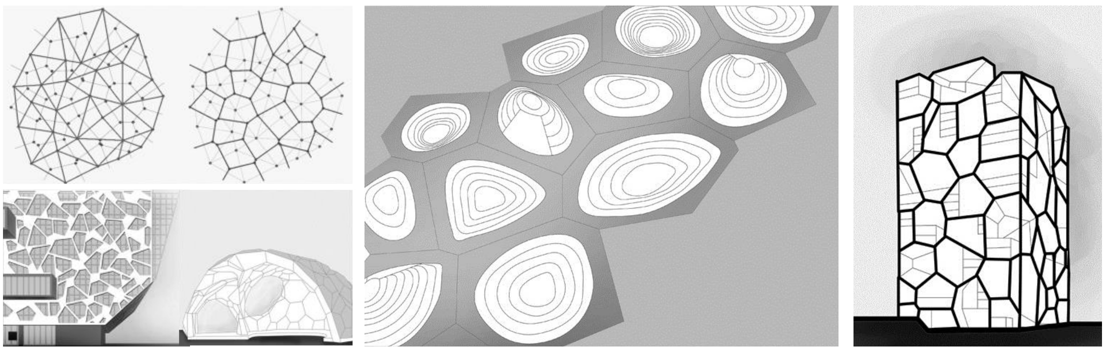


Figure 3.15. *Examples of Voronoi diagrams application in urban spaces, exterior structure and façade design. (Source: Nowak, 2015).*

3.1.2.7. Subdivision System

Compared to other generative design systems, the subdivision is a novel system based on a substrate algorithm presented by Trabell (2003). It consists of countless lines oriented in many senses through a computational design process influenced by crystals grow mechanism and employs simpler algorithmic procedures to provide more sophisticated outcomes (Figure 00). Tarbell generated images from known computational methods and developed his algorithms that mimic urban patterns, such as his substrates concept (Reas et al., 2006). The subdivision was also known in computer aided geometric design as a technique for the approximation of a smooth surface by a sequence of increasingly faceted polyhedral (Warren, 1995). These algorithms find their main application in industrial design and computer animations, for instance, to model the skin of a human character. Dynamic city-like grids emerge from basic algorithms in the gist of substrate ideas (Swart, 2020). Trabel (2003) explained the system saying *"A single line (known internally as a "crack") begins drawing itself from some random point in some random direction. The line continues to draw itself until it either (a) hits the edge of the screen or (b) hits another line, at which point it stops and two more lines begin. The one simple rule used in the creation of new lines is that they begin at tangents to existing lines. This process is repeated until there are too many lines to keep track of or the program is stopped"* (Figure 3.16.).

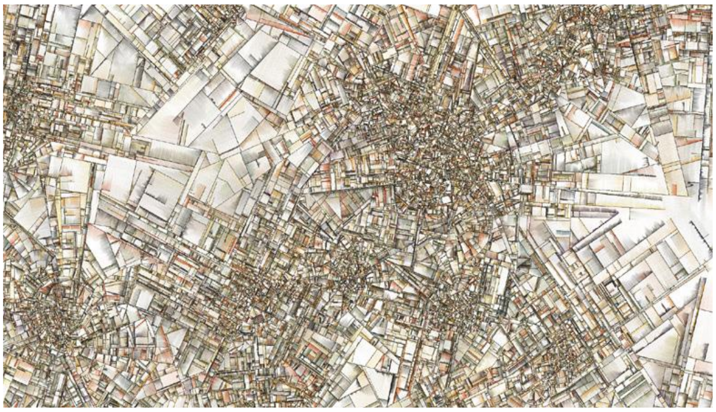


Figure 3.16. *Dynamic city-like grids emerge from basic algorithms. (Source: Tarbell, Substrate Algorithm, 2003)*

Up till now, there are no relevant examples involving the same generative system in architecture or urban design, but it is believed that this system will lead to pioneer designs in urban planning and spatial organization. A basic vertical growth formula enables the creation of complex urban structures. Understanding programming basics demonstrates how initializing or "looping" a straightforward function to produce points may enable us to mimic the complicated and attractive patterns observed in nature.

3.1.2.8. Topology optimization

The topology optimization algorithm started first to be used in the industrial sector where the efficiency and materiality of the designed parts are decisive such as automotive and aerospace (Guest and Moen 2010). It is also known as “Structural Optimization”, one of the systems employed in generative design practices within different fields. Topology optimization is defined as a mathematical technique that optimizes layout in a determined design space for a set of limitations and loads for the aim of the outcome responding to a predefined series of performance purposes (Dapogny et al., 2017). For the analysis and variance of the optimization approaches, the system could proceed through the implementation of various methods such as the *Method of Moving Asymptotes, Genetic Algorithms, the Optimality Criteria method, Level Sets or Topological Derivatives*. Because of the complication and long process time required to produce appropriate results, discussion of this system application in architectural discourse and study is quite limited (Guest and Moen 2010). Nevertheless, there are some examples in the architectural design practices that might be mentioned. Perhaps the foremost known example of shape and topology optimization in architecture is the Eiffel Tower of the French architect Gustave Eiffel. This example focused more on the optimization of the optimal shape and loads to be responsive to gravity and wind upon its typology which is inspired by nature patterns (Yamada et al., 2010).

Concerning the application of typology optimization systems in modern architecture, the Florence station in 2002 example presented by Sasaki may be the one to be pointed (Grobman et al., 2009). Sasaki employed Bi-directional “Evolutionary Structural Optimization” method in an international competition to design the station with the intent to search for more tectonic efficiency and less material usage. The final product was an optimal design that attains an iso-stress distribution in the general form and avoids curvature forces and either effect of tension or compression (Shea, 2004). The same system was used to design the Qatar National Convention Centre’s entrance. The resulted design shows a controlling structure of steel bars representing the initial objectives of shape and topology optimization (Jane and mark burry 2010). Later on, Sasaki has engaged in other works exploring geometric optimization systems focused more on shape and structure, generating forms according to an initial design without impacting the main typology. His examples in City Central Park Grin-Grin and the Crematorium in Kakamigahara in Japan achieved the tectonic efficiency of the typology optimization as a generative design system (Richardson et al., 2014).

Figure 3.17. *Florence station. (Source: Grobman, 2008)*

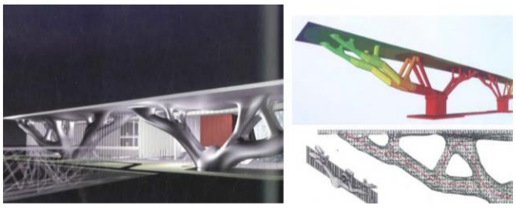


Figure 3.18. *Qatar National Convention Centre. (Source: Jane and mark burry, 2010)*

3.1.2.9. Swarm behavior system

A swarm behavior system is one of the generative design systems that allow the simulation, consideration and generation of forms and complex shapes according to evolutionary processes (Kolarevic, 2000). This system going also by the name of Self-organization expands a mathematical representation and generation of non-simple structures and interconnections between agents and interaction with their environments for the design process (Hensel, Menges & Weinstock, 2004). The term Swarm was first used for insects regrouping mechanisms after that is spread to any group of animals presents an organized behavior. Some other terms like flocking, shoaling or schooling are used to refer to the swarm behavior of birds, quadrupeds and fish (Kennedy & Eberhart, 2001). Reynolds (1987) says that, the early swarm behavior experiments used mathematical representation to mimic behavior and understand it. In particular, the simplest mathematical models of animal swarms represent individual animals according to those rules including separation, alignment, and cohesion. A swarm behavior system operates according to those rules by assisting the communication between agents and their behaviors (Coates & Carranza, 2000). These simple rules result in complex and systemic behavior. A Swarm system is generally employed in optimization problems' practices seeking optimal solutions (Brownlee, 2011).

In architectural design, many interconnection patterns can be designed and simulated with a swarm behavior system for emergency building and visibility planning.

In addition, it can create and simulate urban planning strategies (Guest et al., 2013). Although swarm intelligence has achieved remarkable relevance in the fields of mathematics and technology, it is still effectively unemployed, particularly in professional practice like space planning and design performance. Thus far swarm behavior system also offers high potential for durability, materials' efficiency, and function arrangement solutions in architectural applications (Tan et al., 2016). One of the significant examples involving swarm behavior systems in architectural practices is the "Evolutionary Cellular Design Engine" study. It explores the potential application to the architectural design of agent-based modules. The aim is to look for design solutions using the evolving qualities of self-organized structures. Therefore, Wiesenhuetter et al. (2016) establish an experimental set-up for architectural design approaches that are developed in an evolutionary process (Figure 3.19.). The system is only a computer model set up in a plugin for CAD software to provide an interpretation from evolutionary processes to architectural design approaches. Architects might come up with innovative strategies to realize their architectural concepts. Swarm intelligence can be applied in architectural form finding, urban design, planning and spatial arrangement (Magdy and Eldaly, 2020).

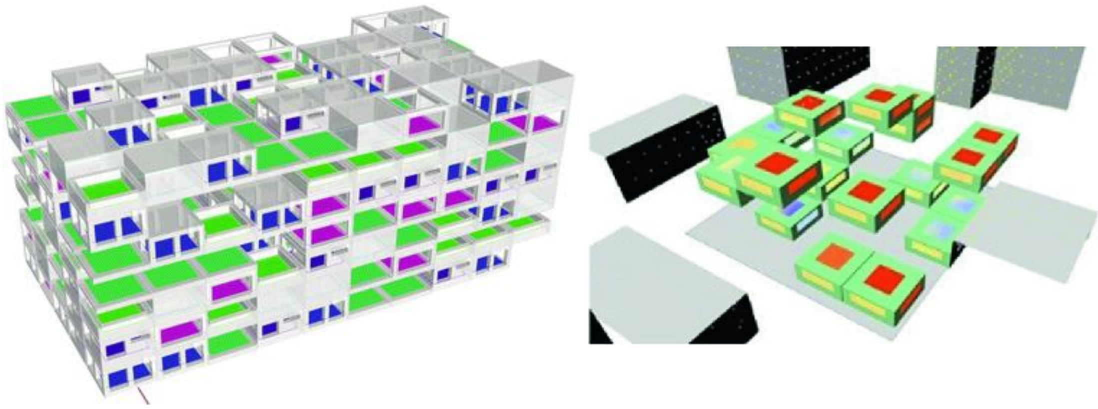


Figure 3.19. *Simulation engine for evolutionary optimized cellular housing design (Left). Representation of the voxel in the urban environment (Right). (Source: Magdy and Eldaly, 2020)*

Another example where the elements of particles are used to reflect the movement pattern of nature or events is the "The Seed Cathedral" designed by focusing on texture generation. The designers wanted to make the façade of the building behave like the grass in a windy environment. It also seemed that if you enlarge the building's surface enough, it would eventually become its form. Seeds seemed to be the conclusive symbol of generation and opportunity for the future-oriented expo (Mashhadi, 2014).

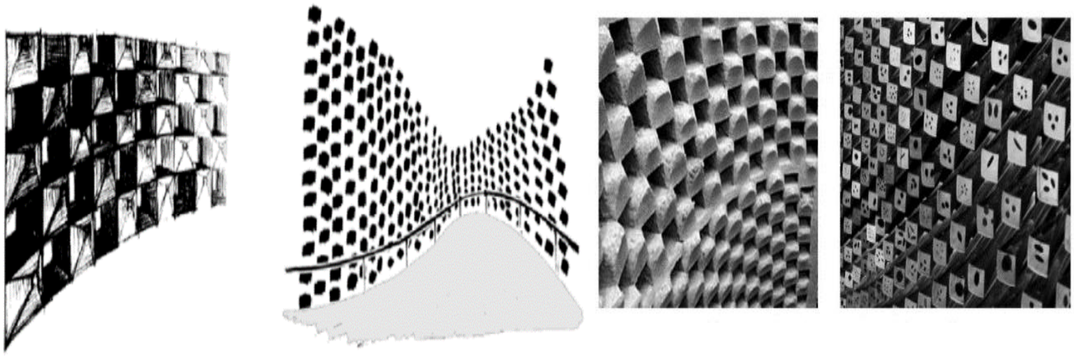


Figure 3.20. *The conceptualization and exterior/interior space of the Seed Cathedral. (Source: Mashhadi, 2014).*

Swarm behavior systems can have a major impact on architecture, but these examples are very general and do not alter the architectural main structure development. Even so, in the construction process itself, swarm intelligent technologies can change the way buildings evolve. Some processes could be self-generative, happening in a materialistic environment, maximizing in ways of work repetition efficiency and a very short-term cycle of reaction to possible improvements in building characteristics and physical structure. Robots, such as distributed 3D printing, are occupying many of these future design areas. (Parker, Zhang, Kube, 2003). It is also possible to engage swarm behavior generative system in an architectural design process where data limitation and artificial selection will be two of the main parameters. Swarm behaviors should improve the effectiveness and credibility of the architectural design. Information on data may establish a digital environment as a limitation on swarm architectural activity. Architects develop a method to produce the form by swarm system rather than designing a shape.

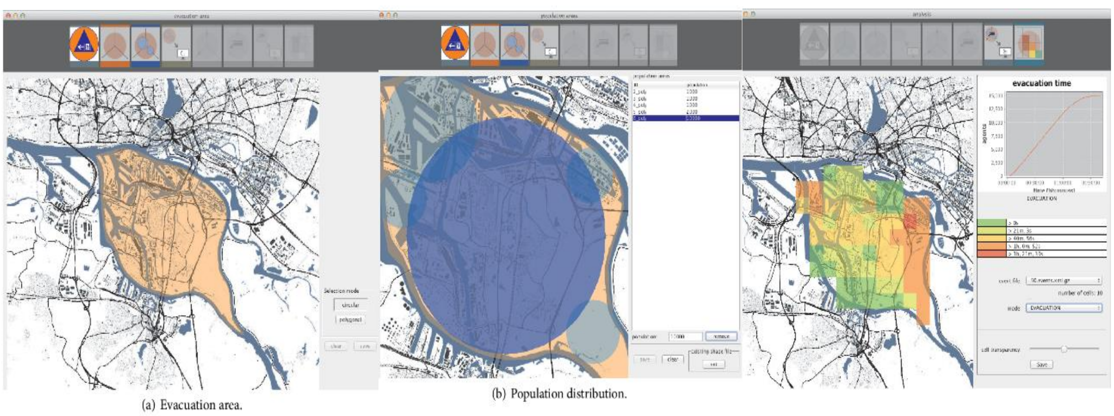


Figure 3.21. Urban *design evaluation and simulations representations. (Source: Axhausen et al., (2016).*

For instance, swarm intelligence is being used in space planning and urban design digital purposes. Horni et al. (2016) presented one of the well-known illustrations of a successful system for transportation planning. This may be considered as one component of the urban design challenge, but it should not be the only aspect (Figure 3.21.). The type of generative design systems may be used for design evaluation and simulations representation, which can enable a designer to properly comprehend the future tendencies and progressions of inhabitants in the destined environment.

Table 3.2. *Overview of the most important generative design systems. (Source: by the author).*

	Application Purpose	Generation System	Architectural Problems	Features	Limitations
Algorithmic Systems	-Comprise parameters of the same idea for solving a specific problem.	-Extend a generation setting where the designer has the ease of implementing his design intent and methods	-Shape flexibility, 2D forms and 3D models' generation. -Space variation and shape representation.	-The most flexible and conventional systems.	-Demand data (positions, shape, form properties). - Using different components connected through constraints and rules.
Shape Grammars	-Design analysis and design synthesis. -Spatial exploration and form compositions.	-Developing the shape grammar system by merging geometric knowledge into design rules to respond to the defined goals. - Allow the generation without any constraints.	- 2D spatial problems and few 3D examples. - Architectural patterns and objects' style. - Initial shape taking into consideration the replacement of forms and alphabetic symbols	-The results are easy to understand, modify and manage because of the designed rules and principles.	- Form is yet driven by function. - Limited techniques to be used for 3D models.
L-Systems (Lindenmayer System)	- Mathematical algorithms with a set of rules and symbols that assist a process to find new forms' characteristics.	- Application of repetitive patterns based on natural organic forms. -Based on rules and systems to create complex structures and replace the initial objects	-Design complex structures in the domain of synthesizing images. - Design problems in urban planning (Roads, networks and textures) simulation and computer graphic patterns -Organic forms based on natural evolution	-Ability to produce highly complex designs from extremely small inputs.	- Systems applied for shape-similarity. - Outcomes usually require validation.
Cellular Automata System	- The evolutionary generative systems employed to architectural interpretation (building density, spatial tectonics etc.)	-Generating a wide range of complex diagrams. -Orthogonal grid-based system for self-reproducing systems	-Design 2D patterns. - Design aspects of spatial architecture (planning, zoning) and urban design. - Growth patterns' problems	-Simple mathematical and analytical methods for generating a wide range of complex diagrams. - Influenced by the biological connotations.	- Related to context limitations and constraints -Generation patterns are not enough predictable.
Genetic Algorithms System	- Solving optimization problems of biological evolution. - Handling complicated language of projects.	- Proposes the model of nature as the generative force for architectural form. -Consist of four main phases including creation, selection, crossovers, and mutations of a defined population.	-Space optimization problems. - Project enhancement and improvements. -Space layout planning	-Used for a variety of design types follows the general synchronous evolutionary architecture -Fitness of the results criteria.	-Similar design alternatives in most cases. - Uses specifically developed rules and representations.
Voronoi System	- Generate forms, seek structural compositions with the inspiration of nature. - analysis of quadratic forms	-Using mathematical modulation. - It is a set of forms including generation points represented in defined shapes.	- structural properties, both in 2d and 3d. - Urban expansion and spatial growth mechanisms. - Models and shapes that mimic natural evolution.	-Respects the biological structures in nature and self-organization constraints.	-Restricted by the definition of generation points. -Use of the same principles in all the generations.
Subdivision System	-Generate high-density building form - Architectural interpretation	-Design system based on a substrate algorithm - Consists of several lines oriented in many senses by a computational design	- Urban space representation. - Space analysis (Visibility, accessibility ..etc)	- Influenced by a crystals' grow mechanism - Algorithmic parameters used.	- Randomly generated pathway. - This process is repeated until there are too many lines
Topology Optimization System	-Mathematical technique that optimizes form layout in a determined design space.	-Optimization of the optimal shape and loads to be responsive to defined constraints. -The system could proceed through the implementation of various methods.	-The application of this system in architectural discourse and research is unusual. -Shape, topology and structure optimization (Eiffel tower).	-The outcome layout responds to a predefined series of performance purposes. -Inspired by nature patterns.	-Complexity and long process time of generation to achieve satisfying results.
Swarm Behavior System	-Allows the simulation, consideration and generation of forms and complex shapes according to natures' evolutionary processes.	-Expands a mathematical representation and generation of non-simple structures. -Interconnect between agents and interact with their environments.	-Employed in optimization problems' practices seeking optimal solutions. - Design and simulate human flow paths and interconnection patterns. -Emergency building visibility planning	-Assist the communication between agents and their behaviors. -Adapt and control system actions according to environmental defined conditions.	-Unemployed in the professional practice of architectural contexts. - Lack of "Function fitness" and the resulting insufficiency

The previous discussions focused on how different applications usage of knowledge in different fields have enhanced the possibilities in architectural generative design. Therefore, the inclusion of different approaches and systems in the design process permit designers to manage more data complications and parameters manipulations. Evolutions that happened in digital design does not disconnect from architectural design practices, but it may be improved by generative systems. Generative design cannot eliminate the designer's crucial role, however preferable design results and advanced execution are conceivable with its practical support. Different generative design applications are based on natural, biological or mathematical applications and methods of optimization with the help of different software and tools. Therefore, we came to a conclusion that when highly interconnection emerges among architectural design and algorithmic practices, generative designs outcomes reach effective results.

3.2. Generative Design Exploration

Digital design capabilities, particularly generative ones, have significantly shaped architectural practice development. By this development, technical and procedural changes at the scale of architectural practices are taking place, causing a change in how designers deal with computer-aided design tools and geometrical complexity. Generative processes have the capability to support the innovation while also revealing how these capabilities might resolve some of the existing complexities and a total absence of common traits with the same flexibility of use along with the creation of components used for effectiveness assessments (Reinhart, 2013). It appears that the potential benefits of new generative software, as perceived and observed by many professionals, may help to overcome some of the complications identified throughout architectural practice. As mentioned in the previous research sections, the practical procedures introduced difficulty in regards to the design computational definition, which was not yet comprehended at the time. This complexity may be now resolved by the generative design methods, which allow for modeling flexibility as well as adaptability. Digital platforms in principle seek a broader range of design alternatives, however, this initially created difficulties between conceptualization and technological practicality. Over time, applications prove that generative software and tools contributed to the integration of numerous computational aspects from the early design beginning.

3.2.1. Generative Software and Tools

Generative design essentially investigates a wide variety of outcomes depending on pre-specified requirements and conditions. It provides a collection of possibilities that have been correctly evaluated for different important variables. Instead of a particular outcome, it gives the chance to acquire a wide range of variations, many of which seem to be completely unattainable. It also connects with many other design options to help with transformation processes. It is a fact to claim that architecture significantly evolved in response to the effects of developing technology where architects are increasingly applying these creative approaches to ensure a variety of objectives. Yet another possibility is the generative design that uses cutting-edge technologies to elevate architecture to new limits. Visual programming platforms have got to be a necessary tool in architectural design and urban planning. Grasshopper is a significant application that is used in connection with Rhinoceros software. Recently, the constricting interaction with Rhino and a wide community of independent programmers that give support and innovative components may have contributed to Grasshopper's extensive utilization.

3.2.1.1. Rhinoceros Software (Rhino)

Throughout the nineties, many companies launched 3D parametric solid modeling software as a three-dimensional modeling program for many domains such as architecture, urban planning and mechanical design simulation (Caetano et al., 2020). Rhinoceros was one of these platforms where the selection was decided to construct a different 3D modeling program (Figure 3.22.). This 3D modeling tool's application and personalization contributed to its initial recognition (Donley, 2011). Rhinoceros 3D is a professional Computer-Aided Design software pioneered by Robert McNeel & Associates that aims to create a design on mathematical NURBS representations (Non-uniform rational basis spline). This signifies that the modeling of freeform shapes is mathematically accurate (Fink and Koenig, 2019b). Its feature is that NURBS surfaces are twisted and do not approach curved surfaces with barely visible shaped edges. Besides that, it provides a visual programming platform to develop different generative design applications. As a result, it is highly effective in the generation of evolutionary forms (Pottman et al., 2007).

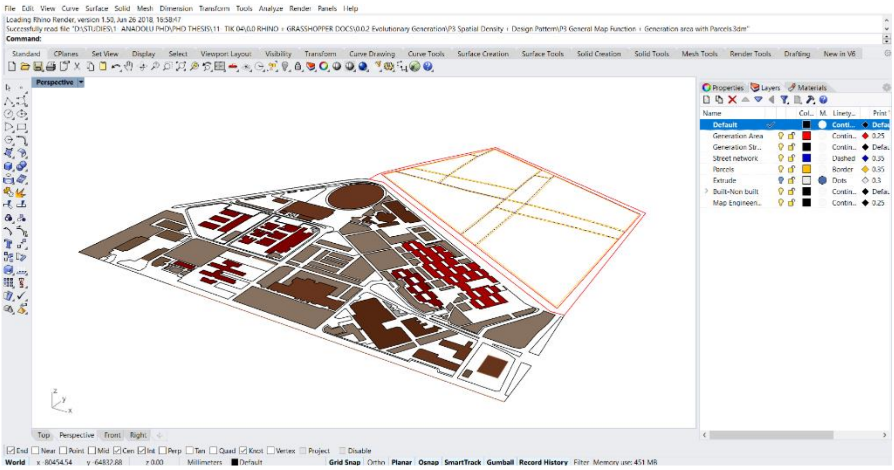


Figure 3.22. *The working environment inside Rhinoceros software. (Source: by the author).*

3.2.1.2. Grasshopper Plugin

Grasshopper is a commercial visual programming software, that has been released to improve the use of parametric and generative modeling. It is among various plugins that may be integrated into Rhino as a visual scripting platform that allows a generative design technique to illustrate the development and performance instantly. In Grasshopper, numerous components may be attached one to another on a sophisticated canvas, and each of them has various programmatic functions (Decoding, Anemone, Galapagos, Octopus, Wallacei …etc) (Figure 3.23.). It provides adaptive modeling without the requirement for considerable scripting expertise (Stals et al., 2018).

Grasshopper has become the more frequently used parametric platform in the world, thanks to its visual programming interface (Cichocka et al., 2017). The program in this context depends on implied multi-operation recursion, which is very efficient with an ability to operate with data structures and conduct more complicated data matches (Eltaweel et al., 2017). It is the automatic creation of solution parts depending on parameters. predictive algorithm function regulates the synthesis and alteration of the components inside a definition (Stals et al., 2017). Grasshopper has many constraints that necessitate the use of extra plugins and avant-garde components to build visual scripts, which makes the processing relatively slow. Some mathematical operations need a large amount of processing capability (Leach, 2014). When this is the case, Grasshopper can then be employed to develop scripts. In addition to C# which is used as a key scripting language in this research, Grasshopper supports many other computer languages such as Visual Basic and Python (Fink and Koenig, 2019a).

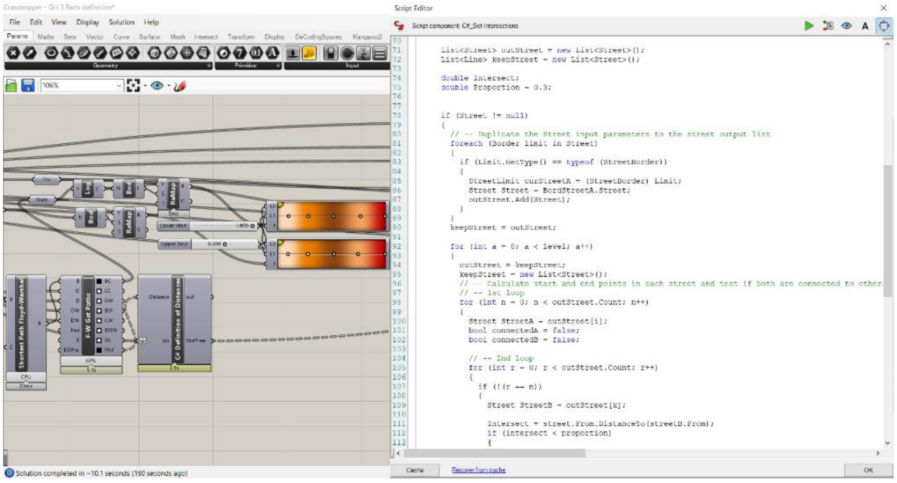


Figure 3.23. *Grasshopper canvas with different integrated components (such as C# scripting). (Source: by the author).*

3.2.1.3. Dynamo Plugin

While building information models (BIM) are frequently employed in the architecture and construction sectors, having a visual programming platform for popular software packages like Autodesk Revit would be quite beneficial. Dynamo is a programming platform that is continuously undergoing development (Figure 3.24.). It is a generative graphic design engine inspired by Grasshopper for Rhino's generative components. Using a visual scripting platform, Dynamo Studio in Revit helps also to discover similar adaptive creative models and automate operations. Dynamo has visual components known as nodes combined in a visual development environment for customizing the building information process (Kron, 2013). Many plugins exist inside Dynamo studio to integrate algorithmic design strength with a solid modeling environment, improving computational performance and generating complicated structures using basic columns and slabs (Stals et al., 2018). It is intended to expand Revit's parametric modeling features by introducing a level of associativity not accessible in the off-the-shelf program, such as controlling parameters depending on external inputs (Leach, 2014) as an illustration of sensors or data from analysis. Variables can be transferred and flexibly switched based on the data source (Keough, 2011). mechanisms (Scheer, 2013); analyzing solar energy statistics and controlling descriptive geometric features by adjusting several practical parameters (Jezyk, 2013).

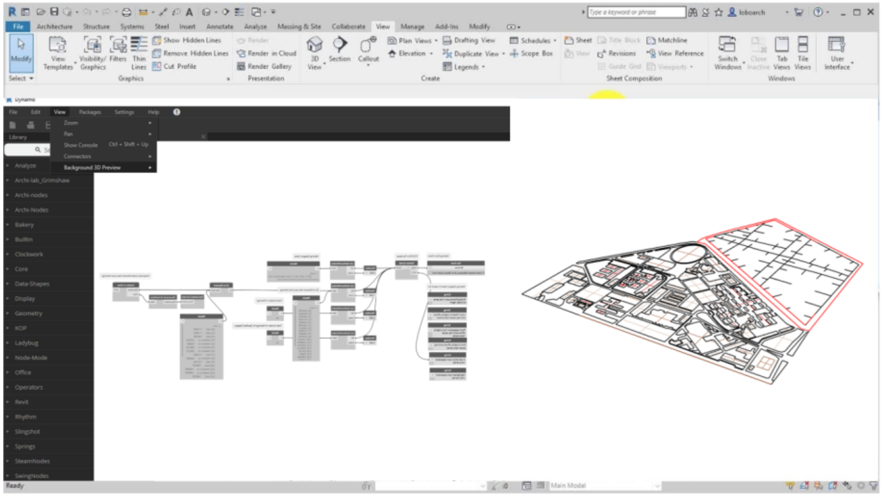


Figure 3.24. *Dynamo working environment in Revit software. (Source: by the author).*

Even if it is not at the same developmental extent as Grasshopper, Dynamo has been applied for a variety of systems, including the creation of information models. As a particular platform for Revit, it has been applied in multiple functionalities such as producing views and sheet patterns, which may be implemented for the creation of architectural attributes (Kron, 2013); building virtual adaptive shading. However, the model connectivity duration in Dynamo is significantly slower than Grasshopper. Dynamo does not have the possibility of a responsive design setup, in contrast to Grasshopper, that gives the chance to show any change after every manipulation (but not devoted to the database- if "baked" by the designer). This is advantageous for Grasshopper in regards to the efficiency with which a process may be assessed. Process assessment efficiency is usually related to database interaction performance in Dynamo. Furthermore, any design produced out of a Dynamo process is “Real-time”, having already been recorded, creating an underlying instability because a user may then edit, or in the poorest scenario, remove shape immediately in the Revit interface, therefore destroying the processing (Keough, 2011).

3.2.2. Generative Design Processes and Optimization

Much before the digital era, many design processes were used in architecture. Nowadays these procedures in which form generation is focused on standards or techniques, often generated from computational software such as Rhinoceros, Grasshopper, and other programming platforms, which define high-level targets and strategies and use simulation to instantly examine a significant design environment and define the best design alternatives. Frequently, this entails researching previously presented examples. In addition to that, optimization methods increasingly dominate generative design systems and approaches as computations and programming become more practical to architects and designers. Not long ago, design optimization has been investigated among the fundamental generative design systems. Later than, in the context of urban planning, it is still in the investigation and exploratory stage, and it is rarely implemented in realistic designs. The purpose of this part of the research is to highlight the generative design process and optimization methods through a comprehensive review of evolution, application performance, and future developments. It also offers a framework for combining computational thinking into existing methods for generative design in architecture and urban planning.

3.2.2.1. Generative Design Processes

In their book, *Generative Design*, Lazzeroni et al., (2009) recognize the generative design process as a repetitive procedure focused on a fundamental simplified concept which is assigned to a system or algorithmic model (figure 3.25.). It is subsequently transformed into a codebase, which generates digital outcomes through a computer. The outcomes are forwarded again into a feedback loop, permitting the architect to re-inform the process and source code. It is an evolutionary procedure that depends on feedback from both the architect and the design system.

Soddu (1994) stated that, generative design is a *"morphogenetic process"* involving methods built as asymmetric frameworks for indefinite specific and unpredictable outcomes performed by an idea-code, like in nature. Indeed, the concepts of digital morphogenesis and generative design are theoretically interconnected. According to Branko Kolarevic (2003), the generative process is defined as the abandonment of predictable connections between design and representation in support of computationally developed systems and approaches. The predefined standards of traditional processes are being replaced with design models capable of sustained, persistent, and adaptive evolution. Hensel et al. (2006) believe that the generative process is a "self-organization mechanism enabling the evolution of natural creatures from which designers may take lessons" (Hensel, Menges and Weinstock 2006). Rivka and Robert Oxman (2013) classify design process formation into six major approaches based on their main motivator;

mathematical, tectonic, material, natural, fabrication, and performative. However, this classification has not seen any update in recent research and application.

Agkathidis (2015) provided an integrative assortment of design processes in architecture which make the interconnection of relevant concepts understandable and logical for application. He mentioned that design processes driven by nature are the ones where consideration was directed to patterns from natural evolution and scientifically proven techniques. Those types of processes are generally evolved with many interpretations using various adaptive-based methods (Oxman, 2013). They all attempted to imitate the developmental mechanisms of natural organisms, transferring them into the design rather than essentially inspiring ideas from them. After that, Agkathidis (2015) believe that design processes driven by geometry adopting geometric principles and compositions have been the principal determinants for several outstanding architects. Both are considered the most geometrically developed designs, illustrating that the Modulor proportion principles may be used as a toolbox with unexpected outcomes. Other proposed design processes are those driven by context which take advantage of structural and morphological aspects as their design strategy. No matter what the functionality or dimension, the forms are incredibly smooth (Agkathidis, 2015). In these types of processes, material and color combinations are influenced by the local environment (Eltaweel et al., 2017). Design processes driven by performance are also extensive frameworks centered on the most basic shape possible, generated from structural efficiency and materials characteristics. Just a minimal influence is performed by the building's interaction with its environment (Agkathidis, 2015).

Simultaneously, Villaggi and Nagy (2017) believe that the generative design process is the step by step method followed to apply different generative design approaches and systems responding to the context requirements and spatial problems. They believe that recent generative methods incorporate artificial intelligence into the design process by employing evolutionary algorithms software tools to explore innovative and high-performing outcomes within a particular design system. Its system is structured on three key subsystems; a generative geometry model providing a design space of potential layout possibilities; a combination of variables or indicators that define the design problem's purposes or intentions; an evolutionary computation method, such as a genetic algorithm, that can investigate the design environment for several high design options according to the specified requirements. The field of generative design is part of a larger system (Figure 3.25.). It is introduced by a process known as pre-generative design and accompanied by a phase known as post-generative design (Villaggi and Nagy, 2017). This simplified representation of the generative design process could be taken as a basis for new propositions in similar contexts and different design problem-solving applications (Figure 3.26.).

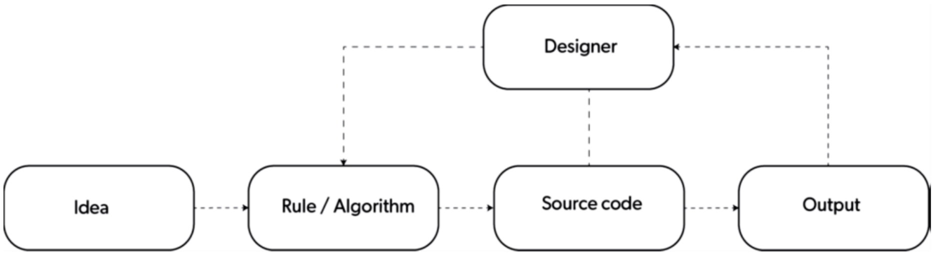


Figure 3.25. *Generative design process diagram / General application. (Source: by Lazzeroni et al., 2018).*

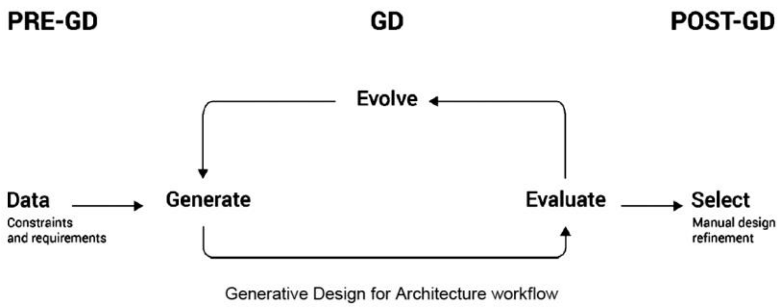


Figure 3.26. *Generative Design for Architecture workflow / Case study application. (Source: by Danil Nagy, 2018).*

3.2.2.2. Generative Design Optimization

Optimization is the process of developing a design or consideration as functional or efficient as necessary (Merriam, 2020). Analytically, optimization is the procedure of identifying the minimum or maximum valuation of a framework by selecting the optimal value of parameters. Although optimization allows for the effective analysis of a significant number of design possibilities, converting a building design challenge into a mathematical expression is not simple work (Simon, 2019). Architecture performance optimization has been possible with the progress of generative design, building efficiency modeling, and optimization technology in the past few years. Although mathematical optimization methods have been there since the 1990s, the major of research in architecture performance optimization involving buildings performance modeling and an algorithmic optimization engine were reported in the late 2000s (Nguyen et al., 2014). Many serious design issues involve several inconsistent purposes, both in terms of technical and architectural features. These are frequently to some degree contradicting, resulting in a variety of possible solutions that are not optimum for all applications. An optimization challenge with various criteria can be solved in a range of methods. One successful strategy used by architects to find the optimal design alternative is the exploration of different designs and evaluation where several layout factors are associated to create several design possibilities, and the best design is identified by comparing their characteristics. Since that strategy is simple and adaptable, it is frequently employed in practice and research. The process of applying optimal solution approaches to discover the best design alternatives that meet the proposal's objectives is known as design optimization. This section of the research intends to give a coherent overview of optimization methods in architecture and spatial planning from the viewpoint of chronological evolution, existing challenges, and future perspectives. Furthermore, different optimization techniques and methods are discussed under two different titles "Objective-based optimization methods" and "Multiple data-driven optimizations".

3.2.2.3. Objective-Based Optimization Methods

The development of optimization techniques in design issues may be traced back to 1969, with Simon's pioneering book "The Sciences of the Artificial" and his outstanding paper the "Science of Design" (Simon, 2019). Later, it was used in architecture as a particular type of generative design system (Gero, 1975). Nevertheless, most conventional and simplified optimization methods only work with one of the criteria at a time. Contemporary CAAD applications are supposed to address this gap by providing a comprehensive, domain-oriented, and knowledge-based framework. When the design requirements can be defined and represented mathematically, the design task may be effectively implemented as an optimization problem (Simon, 2019), allowing for the integration of design evaluation and synthesis. Gero and Radford (1987) carried innovating research in the field of architecture and building design, ensuing in an exceptional explanation and analysis of various processes and methodologies used in the initial phases of the use of optimization in architectural design, demonstrated with explanations and comprehensive case studies. According to them, optimization is not regarding mathematics or computational systems, but specific procedures and techniques. It is about seeking the best, about finding responses to human requirements, and about pursuing the unattainable ideal problem solving alternatives to our issues.

There are several techniques for doing such analyses and addressing such design issues (Simon, 2019). Differential calculus, linear programming, and dynamic programming are some of these alternative optimization techniques (Radford & Gero, 1987). Each technique has strengths and weaknesses, and architects must be attentive to pick the proper way based on the combinations of challenges encountered and the information available. Differential calculus can offer fast, quantitative responses to mathematically stated design issues (Radford & Gero, 1987). In other words, the association between design parameters and design principles is described as a set of sustained and differentiable equations (Gero, 1975). It is believed that linear programming is a subfield of mathematical programming (Radford & Gero, 1987). When the aim of an optimization method can be represented as linear functions with specific limitations, the problems can be resolved mathematically using linear programming. Since the theory's inception in 1948, linear programming techniques have been widely implemented in various fields (including the physical and social sciences) due to their efficiency and adaptability (Spivey, 1962). Typically, architectural design challenges require descriptive, complex, and unpredictable selection parameters; classical calculus and linear programming are ineffective in these scenarios. Considering these characteristics, dynamic programming may resolve design difficulties by dividing the main issue down into many sub-problems that can be approached progressively (Simon, 2019). Arranging the simplest alternatives to these sub-problems results in the ideal option to the initial issue. When two conditions are met, dynamic programming can be used to an issue. In beginning, the original design issue must be subdivided into a collection of small issues. Next, the primary issue must be structured so that “subsequent decisions do not contradict previous ones” (Radford & Gero, 1987).

Gero (1975) investigated other variations of optimization methods' implementations in architecture and urban design. He emphasized that a lack of mathematics in architectural education, as well as a lack of computational methods, restricted the use of this technique in design. Mitchell et al. (1976) made contributions as well, suggesting an optimization approach for generating tiny symmetrical layouts. For decades, efforts have been made to create optimization-based methodologies for design in the field of CAAD. Balachandran and Gero, (1987) published various papers that developed "multi-objective optimization" in design. Throughout this stage, design optimization recognizes a number of architectural design sub-problems. Moreover, only when design challenges could not be numerically constructed, the analytical optimization methods used commonly fail.

Additional logic-based approaches were developed in the 1990s to decrease the requirements of mathematical interpretation, while discussions over the relevance of such approaches for design continued. Pohl et al., (1990) designed a method of an intelligent computer-aided design framework that highlighted human-computer collaboration. Schmitt (1992) stated that the study limits of CAAD were shifting from design automating to design guidance, and he advocated for supplemental perspectives from human cognition. Malkawi (1994) suggested a design-oriented approach for evaluating, analyzing, and optimizing energy consumption and architectural design. Many initiatives were performed throughout this era, although concerns and criticisms from outside the CAAD discipline were common. Since the majority of optimization challenges in generative design and architecture design are multi-objective, and the primary aim of optimization in a development procedure should extend above the generation of realistic data, various approaches, technologies, and algorithms must be used (Radford & Gero, 1987). These methodologies are discussed under two common practices for the same intention of research; "Multi-objective Optimization" and "Evolutionary Optimization".

Multi-Objective Optimization

An architect generally struggles with diverse, frequently opposing, criteria during any design process. Identifying the optimal option or solution for any of these criteria, or just all of them, is a challenging process. The efficiency of a solution in multi-objective challenges is described by its performance regarding many, sometimes competing, objectives (Eiben and Smith, 2007). It is the practice of optimizing two or more opposing criteria at the same time. This method is particularly effective in architectural design challenges where the design criteria are varied, interconnected, and restricted. The challenge thus is not just that there are multiple purposes and that they interact with one another, but they are also, to some extent, inconsistent since they symbolize distinct components. Applying this method to the generative design system would be very compelling. The method may create a variety of design layouts that give alternative between the contradictory features, rather than only one optimal structure framework. In this case, the generative design system would perform as a generator of possibilities present in a distinctive design framework (e.g., what can be realized at what cost). There is no particular effective approach in multi-objective optimization applications, but rather a collection of options (Caldas, 2008). This variety of possibilities may be expressed visually by a Pareto frontier (Appendix-3) of optimum solutions demonstrating distinct trade-offs between contradictory parameters (Ciftcioglu & Bittermann, 2009). The Pareto front is a graphical technique for examining trade-offs involving many opposing objectives, in which alternatives are evaluated by their level of dominance rather than their effectiveness in the objective functions (Fontes & Gaspar-Cunha, 2010).

Generally, multi-objective optimization problems can be addressed in two different manners: 1) use a measured combination of the purpose equations, typically with variable strengths, to transform the multi-objective optimization into a direct specific optimization, and 2) identify the Pareto optimum collection, which is more commonly recognized for functional, multi-objective optimization since there is generally a collection of efficient alternatives (design alternatives) rather than a single answer for multi-objective optimization (Mackenzie & Gero, 1987).

In architectural design challenges, architects frequently must balance various competing criteria, such as optimum thermal comfort vs minimal energy consumption, or greatest technology performance against minimum cost. There are two typical techniques to resolve this issue. The first technique is the “Measured Sum Approach”, in which different values are assigned to distinct purposes and the balanced criteria are added together to form a single optimization problem. Then the challenge is limited to a single fundamental problem. The balanced present value approach is simple to implement, but the outcome is largely dependent on the effects that have been associated with each target, which necessitates competent expertise and practice. The second technique is “Pareto optimization” (Appendix-3), which involves determining the trade-off front, or Pareto front, between each objective. The possibility of influence supports the definition of the Pareto front (Evins, 2013).

Evolutionary Optimization

Evolutionary algorithms are heuristic exploration approaches that have been used to solve optimization issues in a variety of areas. They were originally established with the intention of displaying a group of optimal solutions rather than just one particular side (Marler & Arora, 2004). They are remarkably flexible techniques that can deal with any form of performance component or variables (Andersson, 2001). Caldas (2005) performed a considerable investigation in the field of architectural design including the application of genetic and evolutionary algorithms to optimize multi-criteria challenges integrating the increase of environmental efficiency in building design. She describes the Generative Design System as a way for incorporating adaptive processes and transformation concepts into the architectural design workflow. Her Generative System is designed around Evolutionary Algorithms, which function as a search and optimization accelerator. Gaspar-Cunha (2009) also invented and adjusted Multi-objective evolutionary algorithms for architectural and design studies. The technique employs the grouping approach to minimize the number of alternatives on the Pareto front, leading to a more productive optimization process and making this type of multi-objective evolutionary algorithm a potentially important component of collaborative optimization.

3.2.2.4. Multiple Data-Driven Optimization

Multiple data-driven optimizations provide benefits such as the combination of design evaluation and generation, a wide approach environment, and innovative development, all of which are required for architectural and urban design challenges (Singh et al., 2012). Coates et al. (2001) introduced so many experiments at the beginning of the twenty-first century, including the use of generative algorithms to generate shapes for architectural design. Michalek et al. (2002) suggested a methodology for optimizing floorplan layout design that includes both simulated annealing and a genetic algorithm. They also introduced an innovative approach for optimizing architectural planning. Caldas and Norford (2002) developed a design optimization technique based on evolutionary algorithms to improve building environmental efficiency. Besides that, Shea (2005) proposed a generative approach for efficiently oriented investigation of nonlinear structural forms that merge grammatical parametric shape formation, structural analysis processes, performance assessment, and randomized optimization. She has employed this technique to develop many design suggestions for rectangular structural elements (Shea & Cagan, 1999), distribution tower design (Shea & Smith, 2006), and umbrella structures constructed at the Hylo-Morphic Project.

Design optimization originated in architectural design before expanding to urban planning. In the domain of urban planning, optimization is currently in the research and experimental stage, and it is infrequently integrated into standard CAD software (Walmsley et al., 2019). Regardless of the sophistication of urban planning challenges, Evolutionary Multi-Objective Optimization (EMO) techniques are frequently applied (Nagy et al., 2018). However, efficiency in terms of performance and consistency is frequently questioned (Wortmann et al., 2019). To construct street networks, Derix (2009) employed “Ant Colony Optimization”, while Quantum Annealing was applied to determine desirable connections between multiple space usage areas in urban development. Consequently, significant perspectives concerning the implementation of optimization approaches emerge. In their study, Bleiberg & Shaviv (2007) explored optimization to improve interactive design explorations. Furthermore, advances in Multi-Objective optimization investigation provided notable algorithms for different fields usage. However, even though CAAD was used to develop more and more tangible dynamics, such as Science City Zurich, architectural support technologies struggled to make a considerable important contribution to design practice (Schmitt, 2004).

Many studies in this area are based on design space development. Janssen (2009) developed an evolutionary method for design exploration. Turrin et al. (2011) proposed a tool for the design development of performance-driven geometries that combines geometrical modeling and evolutionary algorithms. Stouffs (2015) suggested strategies for combining generative and evolutionary research. Similarly, when the challenge is or can be re-formulated like a singular accurate optimization problem, framework optimization has been proven to be a more practical option to evolutionary algorithms in terms of performance and feasibility (Wortmann, 2017). Hybrid techniques integrating metaheuristic and model-based optimization could be appropriate for Multi-Objective Optimization challenges, as indicated in other engineering design areas (Sindhya et al., 2012). With the expansion of spatial evaluation approaches such as space syntax (Hillier, 2007), a growing collection of statistical evaluation methods for urban design has been developed, which enhance the design criteria that design optimization may satisfy. Celani et al. (2011) suggested integrating shape grammars with evolutionary algorithms to produce city structures for urban planning by employing several optimization techniques. Koenig (2015) provided a synthesis methodology for street network and building design. Unlike previous design optimization tendency, their approach aims not only to construct urban structures but also to identify a significant criticism of computational innovation, such as the lack of humanity (Colton et al., 2014), by supporting the importance of human intelligence through designers' interrelationships with the created urban planning.

User-specified parameter values make it convenient to evaluate design optimization outcomes. However, gathering design data to enhance the search strategy in future optimization is challenging. As a result, a combination of cutting-edge artificial intelligence and optimization approaches is predicted to enhance one another. Nevertheless, it could not be ignored that the proposed methods' application is still quite restricted. Yet, critical reviews from the area were addressed within, encouraging the development program to continue forward. Although great work throughout academic boundaries, there is still a long way to go before applications reach the intended objectives. The absence of measurable design analysis methods and assessments remains a significant problem. Furthermore, computer-generated design alternatives are typically basic and only appropriate for visualization and representations. The optimization composition necessitates very complex processing, even for elementary generation, which underperforms behind real-time. A combined strategy is expected to be used to tackle these challenges (Figure 3.27.).

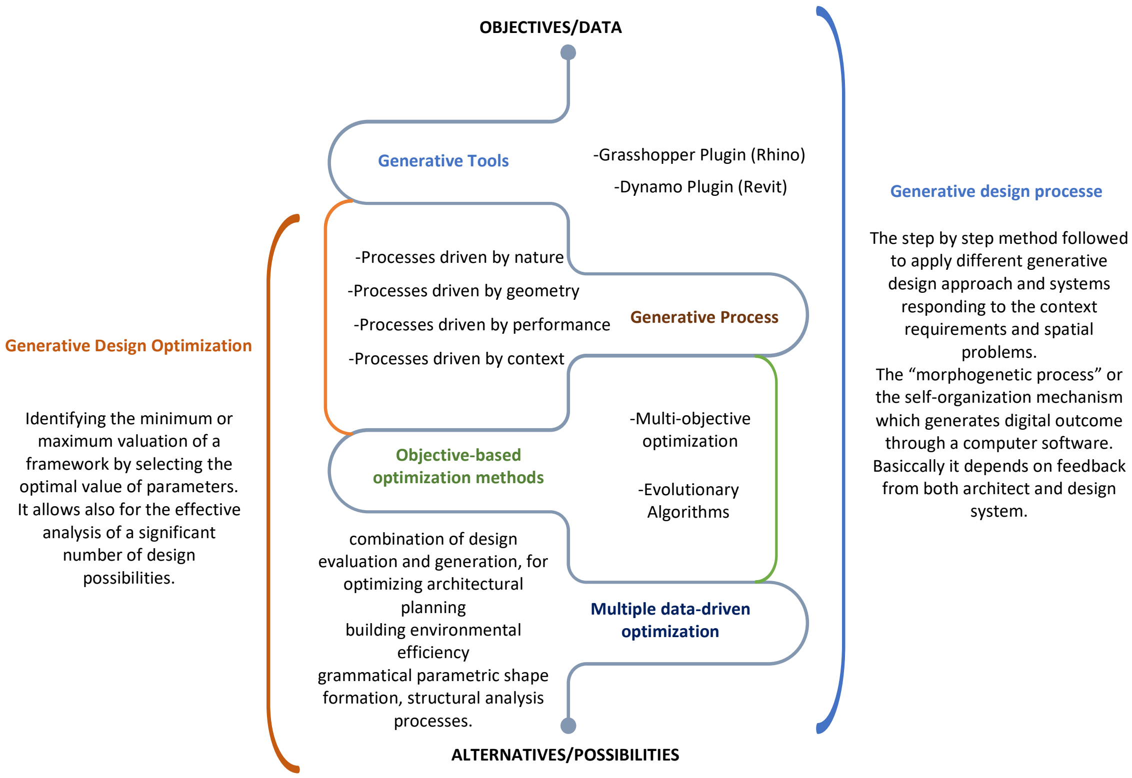


Figure 3.27. *Simplification of generative design optimization in architecture. (Source: by the author).*

Design optimization techniques require exceedingly complicated and computationally challenging procedures, making them inappropriate for immediate and large-scale design conception with limited computer capacity. The benefit of design optimization is presented in the design processes as an imitation of human intelligence. However, it is still controversial if such understanding is essential and how the responsibilities of humans and computers should be determined in the design process. To be efficient, design optimization must at the minimum approach the performance and complexity of process grammar-based software. This is also why hybrid techniques based on computer intelligence are required, as discussed in the previous section. Generally, several criteria are mathematically integrated into a single objective issue for multi-objective optimization challenges. The conversion itself is a hard process that typically involves the use of knowledgeable understanding. Even though the objectives in urban planning and architectural design might be diverse, reducing multi-objective challenges into single criteria can be problematic, especially when they are connected.

3.3. Generative Design Application Fields

Generative design is a strategy that enables human designers to investigate a wide range of design alternatives for a broad scope of challenges by strengthening designer creativity and guiding them through feasible design spaces within set performance requirements (Krish, 2011). It may be considered as a framework that enables interactivity with the end-product without necessitating direct participation with the outcomes. Moreover, it uses abstract concepts to investigate various design possibilities while displaying and producing the components of the final design output. (Fischer and Herr, 2002). One of the main focuses of this study is to support architects and designers in recognizing how to maximize the effectiveness of the system without having to go through the difficult procedures of comprehending computational and mathematical methods. This required establishing a systematic approach for creating numerous designs based on predetermined parameters and procedures, but without taking into account building regulations. Structural analysis, energy simulation, skinning performance, form generation, and space planning are among the disciplines where the generative design may be implemented in architecture. Each of these domains involves separate factors and necessitates a variety of data collection and analysis procedures according to the study's scope (Figure 3.28.).

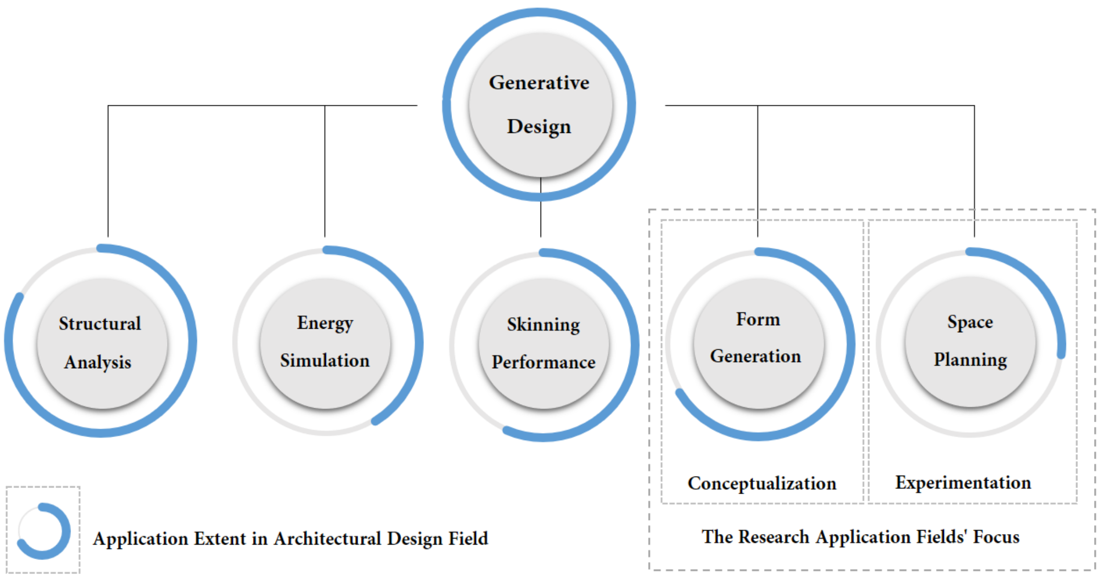


Figure 3.28. *Generative design system application's fields and extent in architecture. (Source: by the author).*

Elnimeiri and Nicknam (2011) established a building's design optimization method, utilizing a genetic algorithm and multi-objective optimization for the structural analysis discipline. The experiment focused on using an architectural form generation process to incorporate a building's structural performance. Similar to that, Touloupaki and Theodosiou (2017) suggested a novel design workflow system that combines evolutionary algorithms with energy modeling to successfully design almost zero energy buildings, and its potential and current challenges are investigated. The system addresses challenges like automation and interoperability to simplify operations, minimize modeling time, and promote multidisciplinary cooperation. The effectiveness of generative design illustrates that by making methods and operating systems more user-friendly, this methodology has the potential to reshape the way architects design. The need to manage numerous, conflicting objectives at the same time, at all phases of the design system, is becoming increasingly important, making the development of a holistic mechanism for sustainable building design an urgent requirement.

Roudsari et al. (2013) used generative systems for energy simulation to produce an ecologically friendly design. In a unique parametric platform, the generative system provides the whole scope of environmental study. This also offers energy and daylighting simulation through the use of verified modeling engines. The employed system approach generates interactive 2D and 3D visualizations for weather data representation to facilitate decision making during the early phases of design, and the components examine initial design possibilities for implications to the design based on the findings of radiation and sunlight-hours findings. Berquist et al. (2017) introduced a generative design method for HVAC, which is a particular script built to produce optimized zone-level mechanical systems for enhanced energy efficiency. Experiments are used to investigate GD approaches and assess their feasibility and impact on building HVAC design. The technique generated new design possibilities for consideration, allowing the end-user to achieve a meaningful interpretation of the design space. Many more alternative designs may be simply developed and assessed by adjusting data collection methods and taking into account the shift in design goals according to new economic difficulties, enhancing design outcomes.

Aksamija and al., (2012) provided a skinning performance generating system that investigated a building using several methodologies. It is fundamentally a design and production of building façade elements based on performance. The system relied on the representation and manufacturing processes, to produce an outcome as a scaled model for physically embodying intangible form, as well as a material and form-driven innovation procedure. This strategy resulted in the creation of a design paradigm for flexible building skin components that may respond to daily or periodic environmental changes. Tang et al. (2019) have suggested a strategy for collecting information and building the database that first incorporated innovative data acquisition and analysis approaches. The qualities of historical characteristics were then quantified and evaluated using cognitive investigation and morphological analysis. The information extraction technologies were then utilized to abstract the conventional facade's principles. The suggested technique was able to develop the referable facades statistically and establish widely recognized conservation plans and recommendations using several processes (Figure 3.29.).

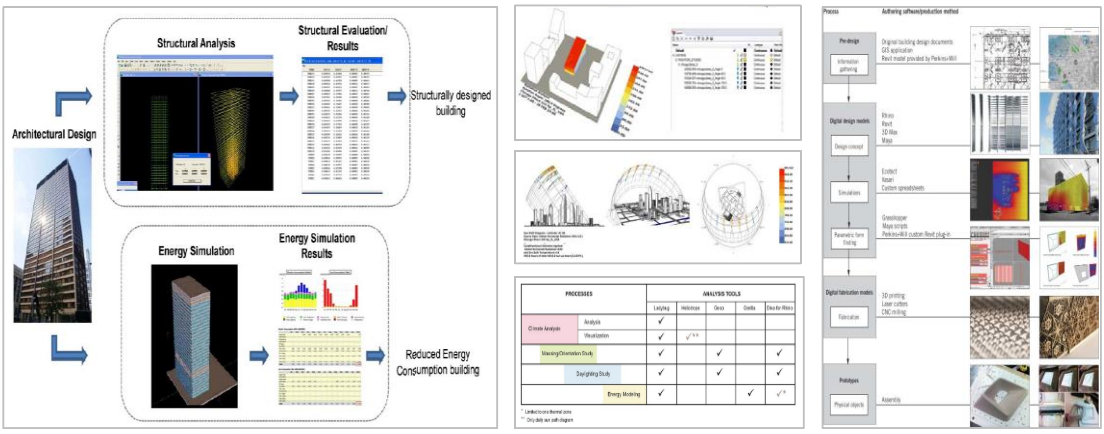


Figure 3.29. *Generative Design Systems Application Fields in Architecture. (Left) Structural analysis (source: Elnimeiri,2011), (Center) energy simulation. (Source: Nicknam, 2011), (Right) skin performance. (Source: Aksamija and al., 2012).*

In these fields, the usage of generative design systems may be employed as a relatively universal method in guideline formulation, acceptability evaluation, and compensation decision-making. The processes discussed were designed to ameliorate the profound position of architectural design and urban structure. Form generation (conceptualization portion) and spatial planning (application component) as generative design systems will be explored more extensively in the following sections. Both of them have presented significant contributions to the research literature and experiment parts, particularly on the use of generative design systems in architectural design fields.

3.3.1. Form Generation

Form generation as a domain of application is often defined as a repetitive process based on an underlying abstracted notion that is applied to a rule or algorithm. Several restrictions, such as environmental considerations, abstract form standardization, and efficient action of presenting the algorithmic design process, play a role in the overall system. The outputs of several processes traditionally return through a feedback loop, allowing the designer to re-inform the algorithm and programming language. It is an adaptive process that depends on feedback from the designer and the design system.

The Philips Pavilion project designed with an approach that was geometrically examined in a known music composer is an explicit example of the generative exploration extent. A primitive model was originated by an application of the hyperbolic paraboloids, relocated later using computational graphics to create technological modern artwork (Felciano, 1996). The project of Gehry for the Olympic village in Barcelona is also a significant example that reflects a futuristic form generation involving sophisticated design software to generate the idea genesis (Yoo et al., 2006). Its fish-shaped roofing installed is one of the great representations of form generative design techniques (Shelden, 2002).

Furthermore, Toyo Ito and Balmond designed another example of genesis form by using an algorithmic system with an irregular façade pattern named the Serpentine Pavilion. The tectonic pattern developed specifically for the project was designed by using a geometric approach. It was used both for the envelope and other parts of the building by mathematical pattern manipulation (Pirela, 2011). Some adaptations were engaged using a well-defined generative algorithm to create a complex final design and a nonstandard-looking building where is difficult to distinguish between envelope and structure (Pirela, 2011).

The use of generative methods as an improvement form generation could also be seen in different projects applications (Figure 3.30.). Zentrum Paul Klee building is an example where the computational system was used. The generation process idea combined some curvature applications within the structure of the roof. By the use of multiple technics different modifications were applied to the building’s different parts which were parametrically designed to be prototyped or produced later on (Stacy, 2013). In one of her important projects, Zaha Hadid aimed as well to express a future vision by designing the Heydar Aliyev Centre (Schumacher, 2012). The structure form of the project which could be seen from the envelope was achieved by using a generative form manipulation system constructed later with glass fiber reinforced concrete panels (Schumacher, 2010).

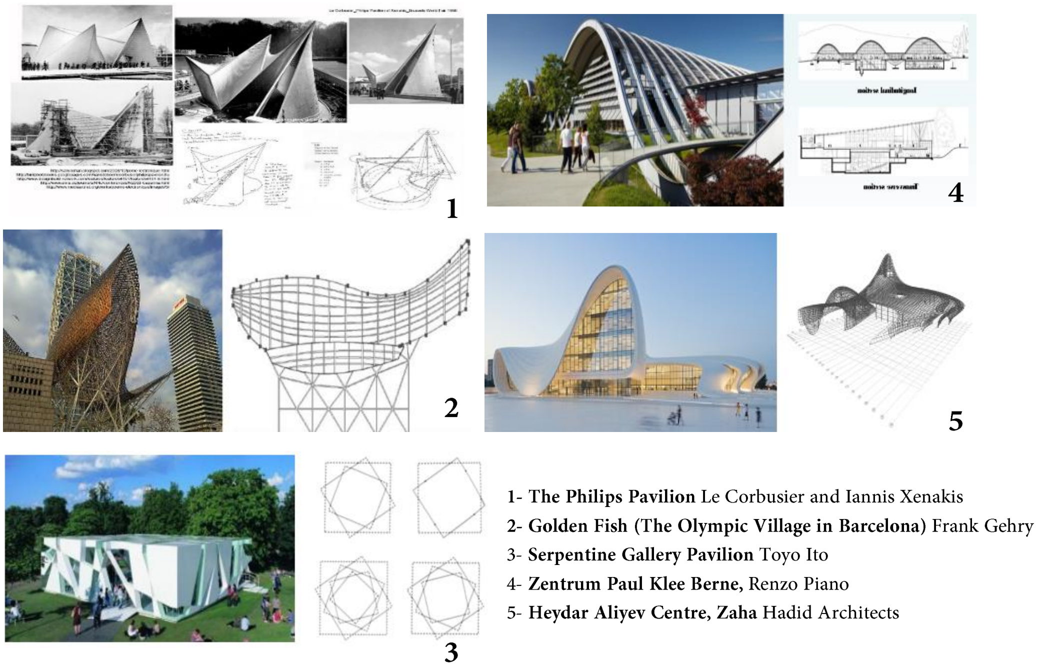


Figure 3.30. *Form generation examples in generative design systems application. (Source: See Appendix-1).*

Countless fundamental issues in architectural design are raised by form generation inquiries. Architectural knowledge and experience are frequently accompanied by controversies about the integrity of their design approaches, raising concerns about the correlation between function and form, aesthetics and construction frameworks, context and structure, user needs and site conditions in all possible implementations. The examples discussed are only a few applications for application systems that practice and interact with a designer to enhance what people or machines can achieve on their own. Different design projects are comprehensively investigated and analyzed in Chapter 02 out of the same perspective of form generation in architectural design applications (see page 37). Further examinations are expected to understand how to establish a system that permits a designer to exploit options offered in other disciplines to orient the optimization process in a new direction without examining whether constraints or fitness values need to be reconfigured.

3.3.2. Spatial Planning

The use of generative design in spatial planning is a revolutionary method that focuses on optimizing design possibilities in terms of many social qualities. Several qualities, such as mobility, accessibility, comfort, and design patterns, are taken into account as primary components throughout system formulation and implementation. Until now, the integration of approaches especially compared to computing methodology, modeling and simulation, computation theory, and computational geometry has been studied and developed.

Feng et al. (2016) present a unique way of designing layouts with human crowd dynamics in consideration. Given an input layout scope, such as the enclosure of space, the technique optimizes three metrics that quantify crowd movement properties: mobility, accessibility, and comfort. The authors suggested a unique data-driven technique in which nonlinear variables are practiced to reflect the link between agent-based measurements and geometrical and morphological layout aspects. They proved that the technique can synthesis crowd-aware layouts and modify existing layouts with higher crowd flow features by employing the trained prediction variables. This investigation may seem intuitive for architects, managers, or urban designers to specify insight into human mobility such as walking speeds and movement direction; however, how such information could be integrated into guiding the design of a layout is challenging, especially for mid-scale areas with a huge number of users, each with different cognitive and physiological features (Figure 3.31).

Nagy et al. (2017) developed a flexible approach for generative design in building space planning. They created this procedure using an application for designing a new workplace space. First, a computational design model was created that can generate a range of office configurations, including the placement of all essential programs and employees, using a limited number of input parameters. Then they offered six distinct criteria for evaluating each arrangement based on architectural effectiveness as well as employee preferences. Finally, they explained the use of a multi-objective genetic algorithm (MOGA) to explore through the high-dimensional area of all potential designs, as well as provide numerous visualization tools that may assist a designer in navigating this design space and identifying appropriate proposals. Despite significant restrictions, the outcomes of this inquiry have been significantly advanced. The procedure can be enhanced by using various forms of modeling, including machine learning, for quantifying features of the designs that are challenging or unable to compute directly. This will enable us to go much beyond the basic automation of operations seen in early CAD applications, allowing us to fully realize the potential of innovative computer-aided design (Figure 3.31).

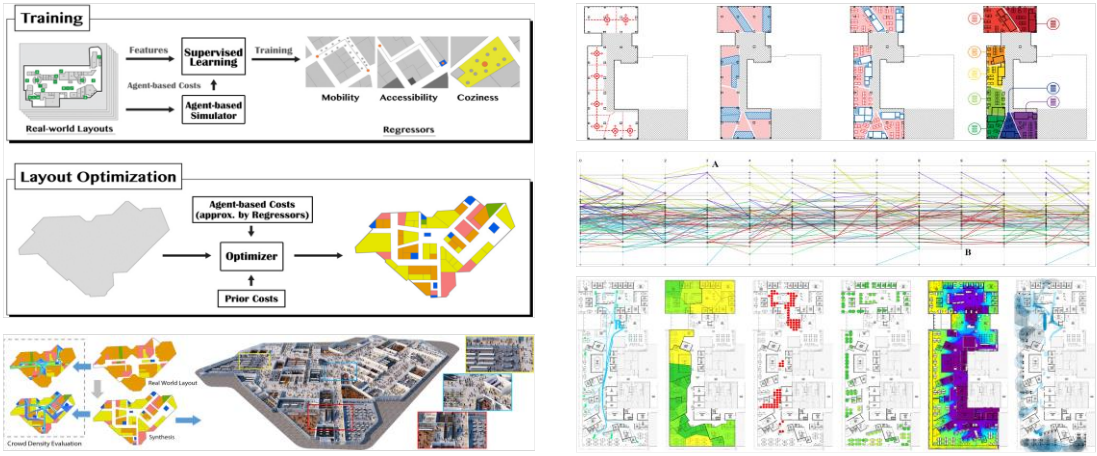


Figure 3.31. *Spatial planning Possibilities Optimization in Generative Design Systems Application. (Left) designing layouts with human crowd dynamics. (source: Feng et al., 2016). (Right) application for designing a new workplace space. (Source: Nagy et al., 2017).*

Villaggi and Nagy (2019) feel that the method of identifying high-level goals and requirements and then utilizing computation to automatically explore a large design layout and determine the best design solutions should be more investigated. Despite some early controversy, as this technique to designing a temporary display has never been performed previously, the authors have generated a design that reacts to real-world restrictions and represents identity characteristics after going through numerous generations (Figure 3.32.). Nagy, Villaggi, and Benjamin (2018) created a program of generative design to a city level through the design of a real-world housing community development project by presenting similar challenges. They highlighted this potential variability by maximizing the project's economics for the developer as well as the buildings' possibilities for energy production. The program's findings have encouraged the applicability of generative design to the appropriate scale, although further study and experimentation are needed. Future potential include the incorporation of additional design parameters crucial for spatial regeneration, such as user comfort, safety, and traffic. These measurements can uncover even more of the complexity of urban development to the generative design system, resulting in highly useful design alternatives that go beyond the perception of human designers alone (Figure 3.32.).

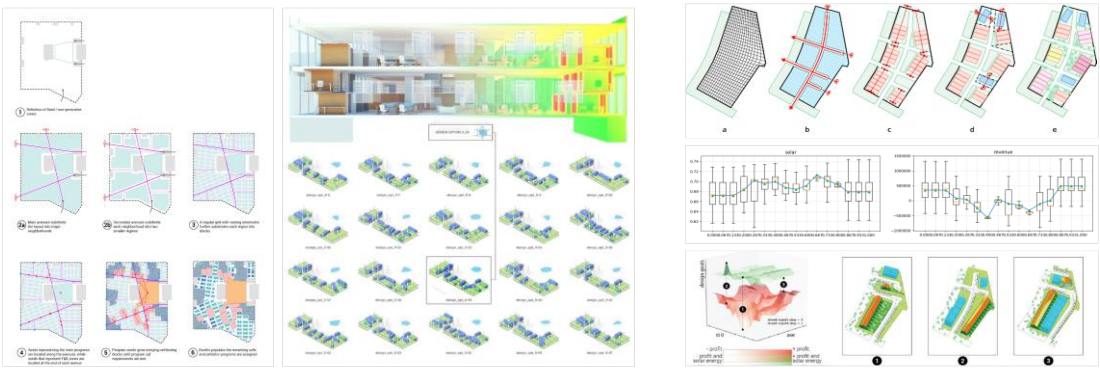


Figure 3.32. *Generative design systems application to a city level. (Left) explore a large design layout. (Source: Villaggi and Nagy, 2019). (Right) design of a real-world housing community. (Source: Nagy, Villaggi, and Benjamin, 2018).*

Makki et al. (2019) investigated the topological variation of urban tissues, which progress through the optimization of several competing purposes and improve considerably from the use of efficient metaheuristic search procedures. They employed search and optimization algorithms for design considerations with no unique optimal solution and a random search space that is too big for a human framework. The outcomes demonstrated that using generative design in spatial planning enhances the flexibility of the urban fabric to adapt and deal with changes in physical and environmental circumstances. In comparison to the conventional design methodology of optimizing a single unique design alternative, the applied model uses a process of transforming diverse populations of context-specific characteristics, allowing for a greater variance of morphological aspects throughout the urban landscape and thus shifting away from today's city to one that is effectively equipped to face prospective environmental and ecologic issues (Figure 3.33.). New approaches and technologies, however, are needed, according to Koenig et al. (2020), to better help urban designers in building sustainable, adaptable, and functional urban settings. They've presented a range of algorithmic approaches based on this, such as different types of spatial analysis to evaluate the performance of design plans or computerized development of urban design suggestions depending on specified factors. The suggested generative design methodology serves as the foundation for a flexible, adaptable, and extendable system that can accommodate various planning possibilities, processes, and capacities. The user interacts with the optimization algorithm and the proposed method guides the user by changing the

Grasshopper definition's targets, architectural specifications, and optimization parameters (Figure 3.33.).

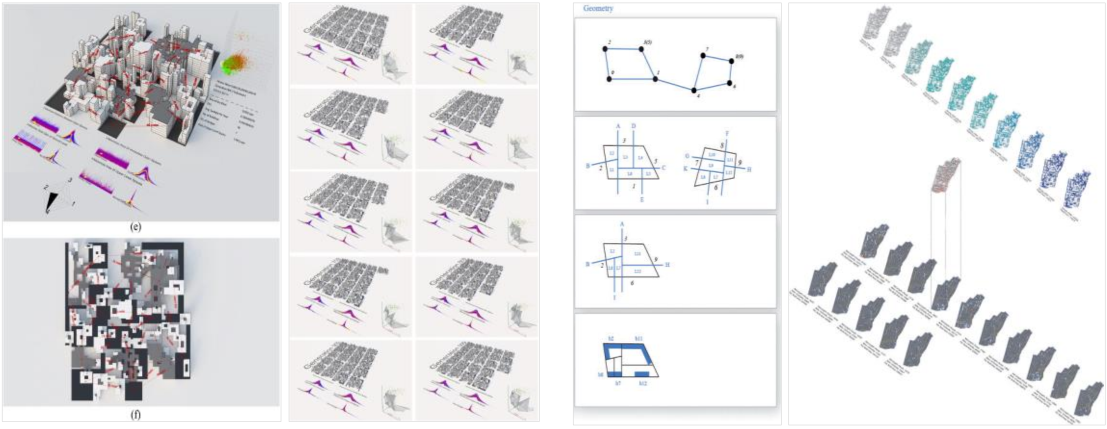


Figure 3.33. *Generative Design Systems for spatial planning. (Left) topological variation of urban tissues. (Source: Makki et al., 2019). (Right) spatial analysis to evaluate the performance of design plans. (Source: Koenig et al., 2020).*

Due to the perceived complexity of data management and interconnection of the process's separate stages, the use of generative design systems in university campus plan expansion, which is the subject of this research's experimental investigation, is exceptionally infrequent. Yang et al. (2020) compare two design methods, prediction and optimization, to create a campus-level development support system controlled by data analytics. A campus is a small-scale complex urban system made up of built environments. A simulation platform is used to manage complicated decisions and convey design decisions in the suggested data-driven campus planning support mechanism. This study contributed to the understanding of how digital data analysis influences urban design to promote efficiency and system resilience. Advanced computational technologies, such as artificial intelligence (AI), should be investigated and used further to produce a smart and resilient generative design system to support the diversity in urban planning and design. This study concluded that creating design alternatives using distinct algorithms, analyzing the options using various tools, and implementing optimized design options via the suggested web-based portal were all beneficial. Future studies might focus on combining the assessment of user satisfaction and spatial quality in a multi-objective challenge to develop the best campus master plan possibilities.

Another interesting study on generative design applications in campus master planning is the work of Liu et al. (2020), who investigated the conception and approach of applying deep learning (DL) with a limited sample size to generate campus layouts. They created two limited value sample campus plan data sets combining artificial screening and the designers' recommendations.

The experimental outcomes indicate that when the achieved particles are selected by campus layout qualities as well as value perspectives and intervention techniques of various architects, even limited amounts of reference data sets for deep learning may produce significant outputs (Figure 3.34.). The study's motivation was that although merging the fields of architectural design and algorithmic methods, researchers should focus on the particularity and novelty in the architecture, find their method, rather than just following the path of computer self-control. From this perspective, the goal is to establish a method for generative spatial planning based on reasonable amounts of collected data sets that correspond to the particularities of the architectural discipline and point to certain design concepts and design methodologies. In these types of environments, generative systems and approaches are rather uncommon; future research might be extremely valuable for better understanding system applicability in architectural design disciplines (Figure 3.34.).

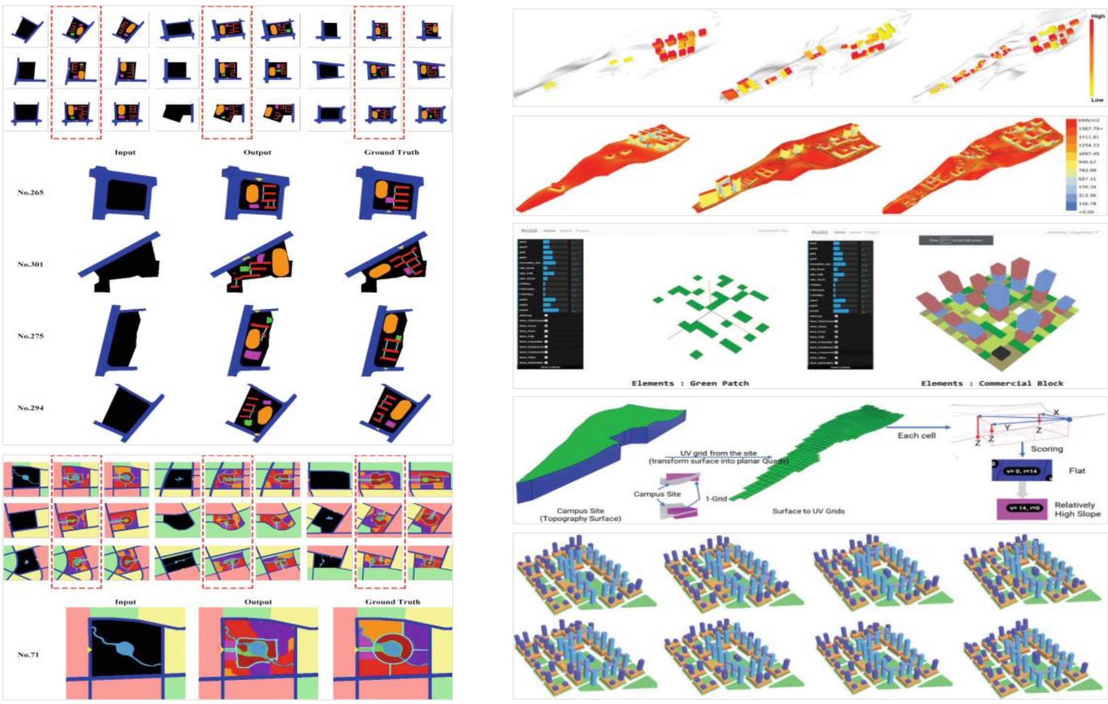


Figure 3.34. *Generative Design Systems in University Campus Plan. (Left)creating design alternatives using distinct algorithms. Source: Yang et al. (2020). (Right) campus plan data sets combination. Source: Liu et al., (2020).*

Generative design for spatial planning is a new design procedure that allows for the discovery of unexpected innovative proposals, the navigation of exchange between high-performing designs, the modeling of parameters and objectives rather than just form manipulation, and co-designing of designer and computer. In addition, generative design has managed to prepare the ground for multidisciplinary coordination of computational capabilities and human aspects in a dynamic architecture design (Ameijde, 2018). This section of the research discussed a series of studies and examples that use algorithmic approaches linked to generative design methods to create new possibilities for architectural structural analysis, energy simulation, skinning performance, form generation, and spatial planning experiments. (Table 3.3.).

Table 3.3. *Features of the generative design system application in architecture fields. (Source: by the author).*

Field of application	Problem solved/Purpose	Applied Methods	Future Explorations
Structural Analysis	-comprehend how to enhance design performance - recognize the application of computational and mathematical techniques in architecture -establish a design optimization methodology for buildings - integrate a building's structural efficiency	-Genetic algorithm -Multi-objective optimization - Evolutionary algorithms - Capabilities of energy simulation	- architectural form generation processes to design nearly zero-energy buildings -research in automated processes and connectivity to minimize modeling time and foster multidisciplinary interaction
Energy Simulation	-visualize and generate elements of final design components - facilitate a wide range of environmental analyses - allow for energy and daylighting simulation - assistance in the decision-making process throughout the early phases of design	-generative systems for energy simulation - using validated simulation engines -2D and 3D platforms for data visualization - a special web-developed scripts	-Evaluate early design possibilities for design considerations. -improve zone-level mechanical mechanisms for enhanced energy efficiency - optimizing design results in view of a shift in design requirements
Skinning Performance	-investigate a building by fostering designer innovation; -create an outcome as a scaled model for practically expressing conceptual form; -create a design environment for flexible building skin components.	-several computational strategies - processing techniques to gather information and build databases - Cognition investigation and morphology analysis	- examine the historical features of façades - set a systematic methodology for principles of the traditional façade - statistically develop the referable façade and construct extensively accepted conservation strategies and requirements
Form Generation	-allow interactivity with the end-product. - employ abstract conceptualizations to investigate numerous design alternatives -performing masterpiece works of technology contemporary art - develop a sophisticated final design and nonstandard looking building -Express a future vision by designing form or shape	-repetitive procedures depending on a basic abstracted concept -application of mathematical rules using computational graphics -using an algorithmic system -manipulation of mathematical patterns using a well-defined generative method	- employing advanced design software to generate the idea genesis -Construct methods for distinguishing between envelope and structure - use of a computational system to prototype or realize futuristic projects -integration of generative form manipulation system

Spatial Planning	- Create a systematic process for producing several designs using predefined rules. -explore an array of design possibilities - optimizing the design possibilities concerning multiple human properties - investigate a broad design environment and select the optimal design possibilities - respond to changes in environmental and climatic conditions. - assess the effectiveness of design concepts or the automated creation of urban design alternatives - Create a data-driven planning support system for campus-focus planning. - Establish an intelligent and adaptable generative design system for the expansion of the campus master plan	-computational geometry, modeling and simulation, theory of computation -A unique data-driven method for training nonlinear variables - use of a multi-objective genetic algorithm - Optimization of many competing objectives through the use of search and optimization processes - a wide range of computational techniques, including many types of spatial analysis - Employ a visualization platform to handle complicated decisions and explain design decisions.	- using various methods of modeling, specifically machine learning, for assessing design variables - Inclusion of other design criteria crucial for urban planning, such as user comfort, safety, and traffic. -using deep learning (DL) on a limited quantity of data - integrate innovative machine learning techniques, such as artificial intelligence, to the test (AI). -Utilize several aspects such as functional connectivity, responsive density, and design pattern.

Due to their complexity and the existence of numerous participants with diverse and often competing expectations, problems in architectural and urban design can benefit substantially from the generative design methodologies. However, the majority of these perspectives resulted in different tools and disconnected workflows. One of the key obstacles of incorporating generative approaches in the context of spatial planning optimization processes is a sufficient computer characterization of the urban design problem. To tackle this challenge, a comprehensive data representation for urban forms, comprising the layout of street networks, parcel division, and building extrusion, should be provided, which may be implemented efficiently with various evolutionary algorithms. Future experiments should also focus on cases to better incorporate and connect different parts of the generative system, as well as on implementing a direct feedback loop, which will permit the designer to effectively involve with generated options in the design model, for example, by guiding additional optimization and interpretation of systems through the selection of configurations or their characteristics. Designers would need to build mechanisms to explicitly parameterize these attributes and provide those characteristics to the algorithm to achieve a better and more targeted discovery. As these processes evolve in the future, we expect that they will not only enable designers to generate high-performing design alternatives, but also assist them in effectively appreciating their design challenges through a more holistic human-machine design interaction. Recommendations for a sustainable and green campus are derived from the interactions between inputted geometrical inputs and the performance requirements function. As a consequence, an algorithmic system will be developed and evaluated for many possible generations to generate master plans based on environmental requirements and identified design problems of the university campus.

4. GENERATIVE DESIGN SYSTEM FOR A UNIVERSITY CAMPUS MASTER PLAN EXPANSION

The main purpose of this thesis is to develop and describe a particular design, and to provide an extensive conceptualization of architectural generative design along with the investigation of different methodologies. The system introduced in this chapter is addressed by describing general theoretical methods and illustrating them with experimental implementation. The connection between theoretical and practical aspects may contribute to the development of systematic and applied processes to address the real practical generative challenges in architecture. The generative design system was developed and applied to a case study in Eskişehir/Turkey. It was adapted and optimized with the feedbacks of the eco-campus sustainability development plan and results from different data collection and analysis phases. The selection of computational tools and their application to the case study is discussed in detail. In addition, the algorithmic system executed is expounded with the incorporated applications and visualizations required. The most essential factors in the success of the process formulation are the accessible data that serve as a suitable foundation for application, and efficient inputs' interpretation in the proper projection and format.

Accordingly, the case study will be based on the Eskişehir Technical University campus. The existence of an eco-campus development plan provided by different university experts in the domain of architecture, urban planning and sustainability to make new spatial expansion, allows focusing more on the development of generative design systems than the design development. The same re-defined system could be applied in different case studies to provide better results.

This section of the study elaborates the methods used to create a design model capable of producing master plan possibilities with various spatial topologies at various patterns. An examination of the current application and various tools' usage are the essential elements of this chapter. The generative system is designed for the formation of many possibilities via the use of various methods. On the system, visual programming is used in conjunction with existing libraries and components to demonstrate a simple and accurate process. This enables the development of several ideas to a larger extent without devoting too much effort to any one of them. As illustrated in (Figure 4.1.) the generative design system proposed within this research can be broken up into three stages: data collection and analysis; generative design process; evaluation and design decision.

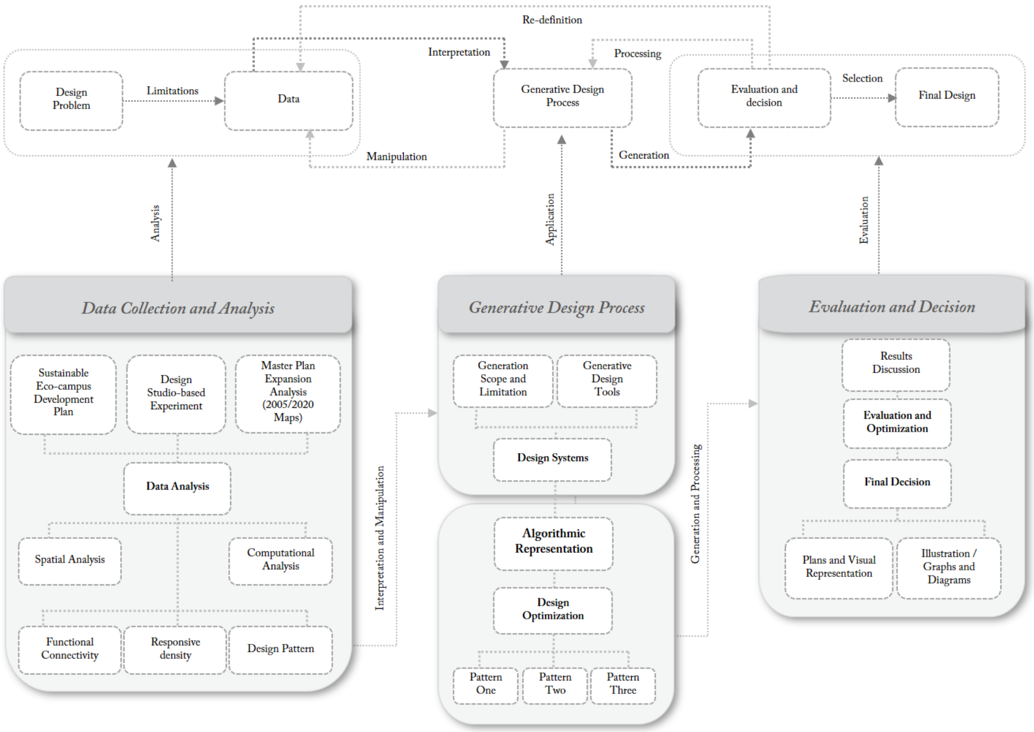


Figure 4.1. *Proposed generative design system for architecture "university campus master plan as a case study". (Source: by the author).*

4.1.Data Collection and Site Analysis

The data collection and site analysis part focused on the collection of all available information and materials needed for the execution of the generative design system. It is known that having an idea about the instant situation of the targeted study area is highly needed to decide which data information and documents are needed to perform the research (cad files, text documents, numerical data … etc.). To perform this important part of the research two different profound methodologies have occurred. The initial one is a design studio-based experiment that engages 45 architecture students (23 students during a pilot study) in analyzing the case study site and designing multiple projects during two successive semesters, at the architecture department of Eskisehir technical university. This phase is focused on accurately identifying and classifying the design problems that should be solved with the generative design system. The second methodology is a spatial analysis of two different maps in the different periods (2005/2020) of the campus area. This part of the data collection and analysis phase is implemented by involving both spatial analysis and computational analysis of the existing maps. It aimed to understand the growth mechanisms of the university campus muster plan and to collect the numerical and geometrical data that are compulsory for the formulation of the generative design system.

Many documents and technical graphics of the case study Eskisehir technical university campus are prepared using different computational and digital design tools to provide an informative base for the generative design system application. The results from this research's part give a clear vision about the main design problems, context requirements and limitations taking into consideration all the outcomes gotten from the literature review. Besides that, much other information is gotten from the sustainable eco-campus development plan which is accessible within the university website (ESTU, 2019). Since the university campus is intended to be future developed, the current situation is well documented and archived. The development plan contains general information and, student and academic staff numbers, university facilities …etc, and proposes a development master plan for the future expansion of the university.

4.1.1. Case Study Area "Eskisehir Technical University"

4.1.1.1. General Overview

The university is situated in the Anatolian region of Turkey, exactly in the city of Eskişehir. According to the Turkish Statistical Institute (2015), the city comprises a community of around 900,000 inhabitants and more than 50,000 students separated throughout three universities. Eskişehir Technical University (ESTU) is recognized as a student city in Turkey. Because of its geographical location, it is also recognized as an intersection for several cities' main routes. It is situated in the northwest of the Anatolian Region, surrounded by Afyon from the south, Konya from the southeast, Ankara from the east and north, Bolu and Bilecik from the northwest and Kütahya from the west. The foundation of ESTU was back in 2018 after its detachment from Anadolu University. The main university campus "Iki Eylül", has a total area of 4710 decares, including the land assigned as the area of expansion. It has a land area size of 4.3 million square meters and a campus area of 114,034.47 square meters. The campus is situated on a plain on the northern slopes of Boz Mountain. The city center is about 5 kilometers away, and transportation is not an issue.

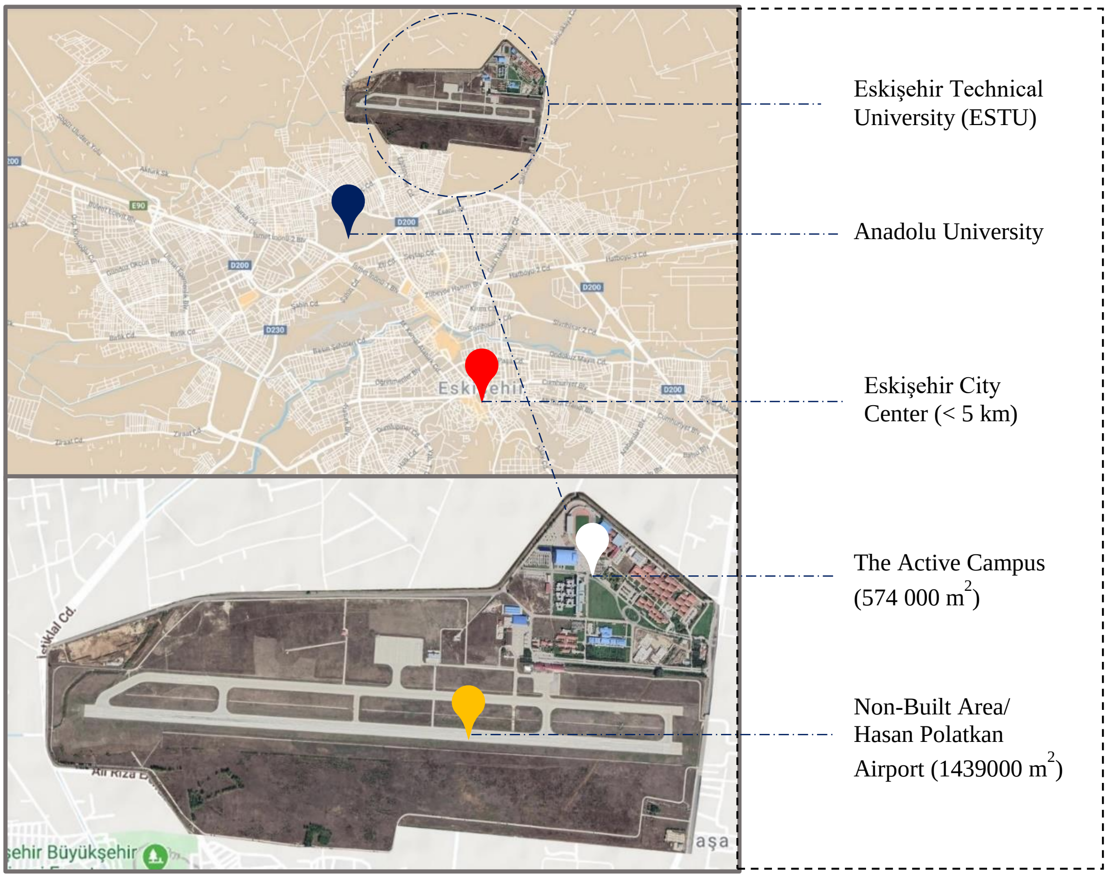


Figure 4.2. *ESTU location map in the city of Eskişehir. (Source: by the author).*

The functions, approximate sizes, and interconnections between the open-closed spaces of the spatial elements that will be built in addition to the existing buildings and amenities have been identified. Simultaneously, the active campus plan is 574 000 m2, and the campus extension area is planned to be 454000 m2 (Figure 4.3.). Based on the proposed development plan, the campus is arranged to be expanded toward the north, away from Hasan Polatkan Airport on the southern side, along with the Muttalip highway on the eastern wall, and the transportation axis that runs parallel to the western wall.

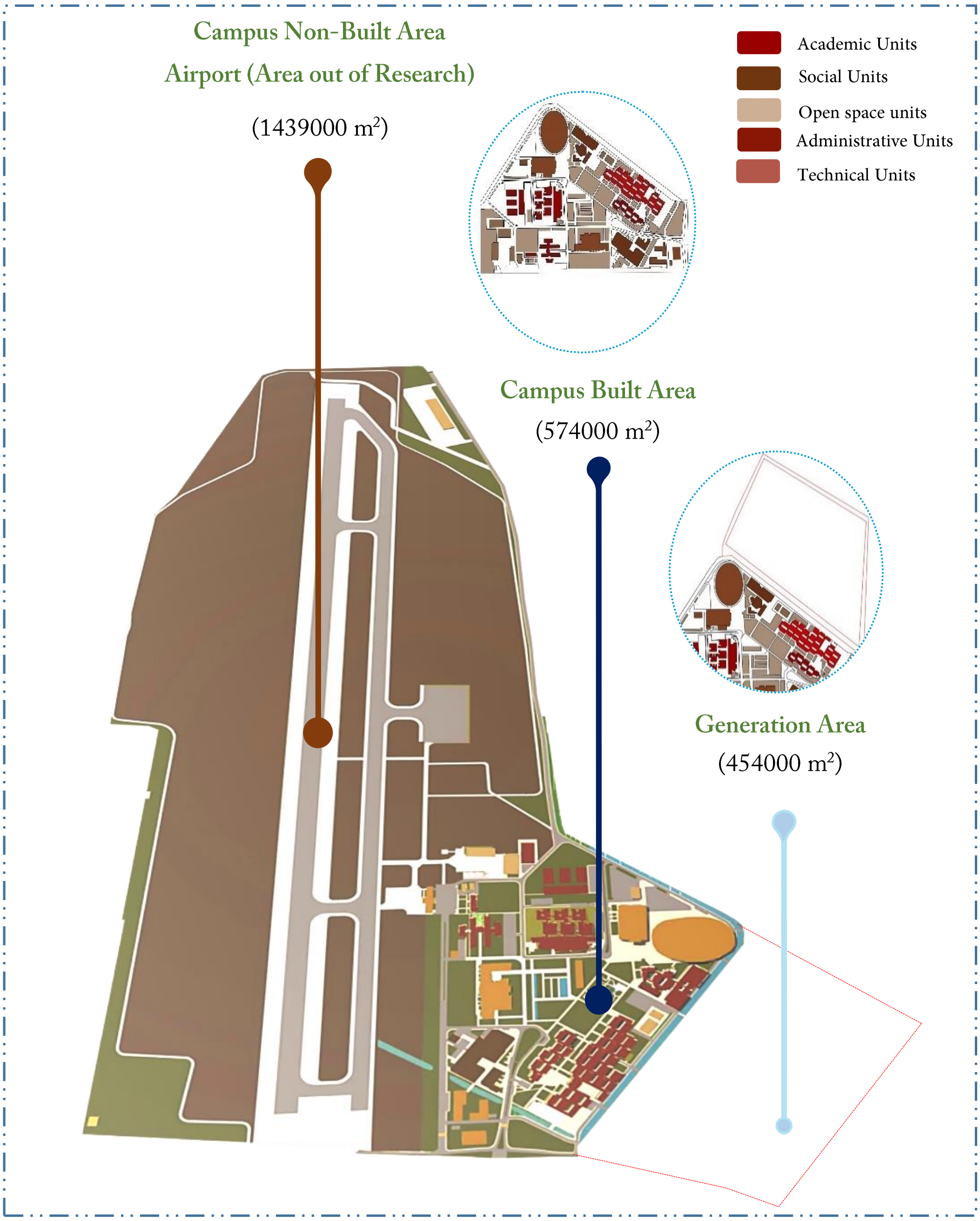


Figure 4.3. *ESTU Sustainable Eco-Campus Intended Extension Area. (Source: by the author).*

4.1.1.2. Sustainable Eco-Campus Plan Analysis

The sustainable eco-campus plan is based on the development strategy provided by the interdisciplinary commission of ESTU university. Currently, the university is trying to put in place again its spatial identity with a contextual and environmental approach. The relationship between different spatial parameters required to be well arranged such as density of land-use and build/ non-built areas should be redefined for plan expansion, and this is what the plan development proposed within the parcels organization.

Open space and the courtyard design pattern of the engineering faculty are taken into consideration aiming to improve the campus spatial quality (Figure 4.4.). Besides that, another concern should be addressed and community needs have to be indicated in long term by evaluating the campus users' experience.

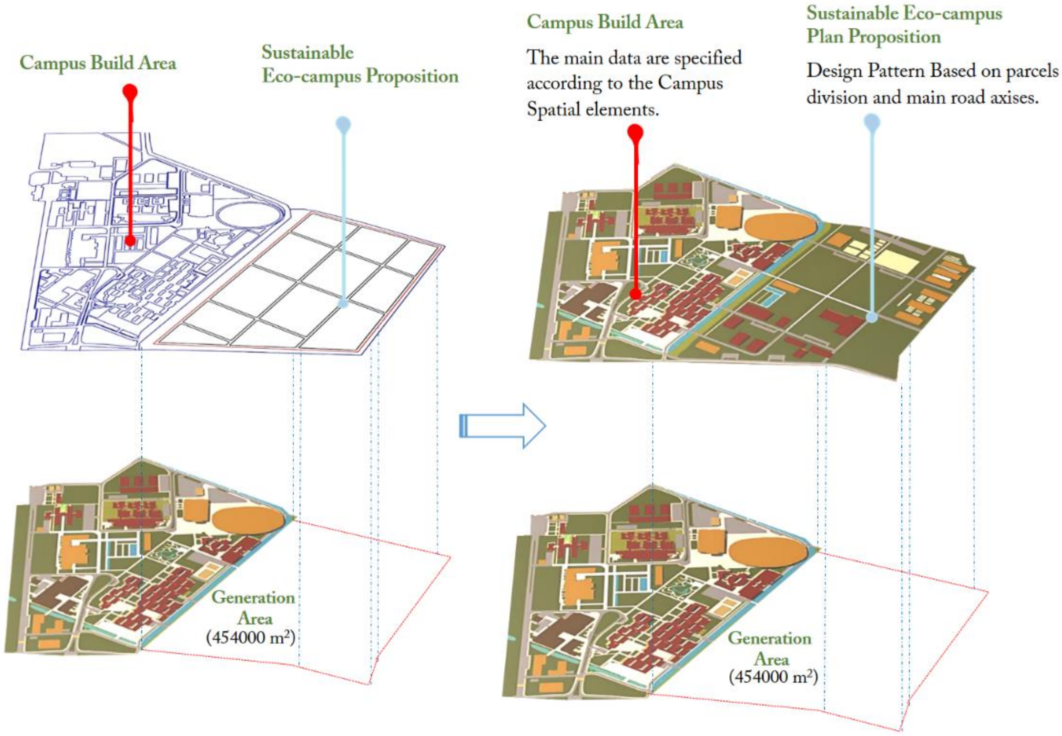


Figure 4.4. *ESTU Sustainable Eco-Campus Plan proposition: the plan in 2020 compared to 2035. (Source: by the author).*

This analysis describes the characteristics of the environmental and spatial functions, which are intended to be sustainably carried out in the "İki Eylül" Campus between 2020-2035, and the resource requirement needed for the study. It is aimed to prepare and implement the spatial limitations and context requirements within the early formulation of the generative design system. The development plan is prepared according to future spatial planning and existing design parameters of sustainable campus concept including a requisite target. This expansion development plan in İki Eylül Campus, which aims to create an environment following the principles of sustainability, is an important phase of the process. The purpose of this analysis, which will be further extended by subsequent phases, is to supervise, enhance, control, and ensure the master plan functions with all of its elements within the framework of environment and sustainability.

Getting a clear overview of the design elements of the university campus development plan makes the following analysis phases more oriented. Information about the expansion intent and the future crucial mechanisms of development comes in the first generative design system parameters. Generally, layout and spatial arrangement, connectivity and accessibility, and built area and open space are the most effective elements assigned by the plan. Those elements are more explored engaging different analyses discussed in the next sections of the research. The collection and validation of different design problems identified in the eco-campus master plan are presented in the following table:

Table 4.1. *Design problems according to ESTU university eco-campus development plan. Source: by the author. (**LS** = layout and spatial arrangement, **CA**= connectivity and accessibility, **BO**= built area and open space). (Source: by the author).*

	Design problems	***Parameter***
ESTU eco-campus plan 2020-2035	Determining the construction suitable areas and building parcels scope regarding the walking distances in the campus.	**LS**
	Arrangement of open space according to spatial density in the campus.	**BO**
	Organizing the street network for vehicles around the campus and developing other streets through an integrated and interdisciplinary perspective within the framework of accessibility.	**CA**
	Evaluating the urban context with its physical and social dimensions.	**LS**
	Adoption of approaches emphasizing pedestrian and bicycle priority in the transportation system	**CA**
	Increasing the number of pedestrian and bicycle paths according to the functional connectivity	**CA**
	Transportation connections between the campus and city, as well as the in-campus transportation network, bicycle and pedestrian paths will be planned following the sustainability targets	**CA**
	Form a basis for the improvement of the relation between the University and the close environment (Muttalip Settlement Area)	**LS**
	Assuring accessibility for all buildings and outdoor spaces on campus	**CA**
	Taking into account the existing structure scale and characteristics of campus design pattern	**LS**
	Giving importance to the interactive, continuous designs of buildings and open spaces, designed with indoor-outdoor cohesion and spatial integrity	**BO**
	Determining the spatial and structural arrangements to be made by taking into account their development potential	**BO**
	Determination of collaborative and inclusive planning processes.	**LS**
	Designs on the campus will have natural and human-oriented priorities	**BO**
	Preparing and implementing this development plan according to ecological planning and design principles of sustainable campus concept	**BO**

4.1.2. Phase 01: Design Studio-Based Experiment

Architecture design studios provide many opportunities to examine and evaluate theoretical or practical design challenges which can be later integrated and synthesized in more sophisticated experiments with the help of parametric and generative design strategies (Qureshi, 2020). Accordingly, this study engaged architecture students within design studio-based experiment to help in identifying and evaluating different design problems and spatial limitations that should be solved and interpreted as parameters in the design system of university master plan generation. The employed qualitative approach comprises the evaluation criteria of any architectural design in a universal significance. The studio-based research methodologies give instructors the chance to incorporate different capabilities with knowledge and technical skills and use the outcomes in other complex architecture design research (Crolla et al., 2019).

This study evaluates the degree to which students can perform space-generation directed explorations and to which level they manipulate various requirements and circumstances. At the same time, it assesses the degree to which varied outcomes are obtained, and the degree to which they can reach successful outcomes by applying different design processes. The author developed and applied a methodology that was presented to a group of four-year students in the architecture department with the help of three other instructors. The students were invited as volunteers to perform design assignments, and the resulting projects were evaluated in terms of spatial generations and design performance. The proposed methodology has been tested within a pilot study that engaged twenty-three third-year architecture students. Outcomes have been taken as a base to improve the methodology.

This work aimed also to analyze the performance of computational tools used by students to set efficient parameters for the generative design system explained within the following sections. Those parameters will be used in a more specific generation context to meet the criteria for specific areas of the study. Therefore, students' suggestions about the design task and the generation method used have been noted and deeply analyzed. Essentially this experiment is based on several stages to support the fundamental project evolution processes at the architecture studio and project design during '2*12 weeks' (two full semesters) (Figure 4.5.).

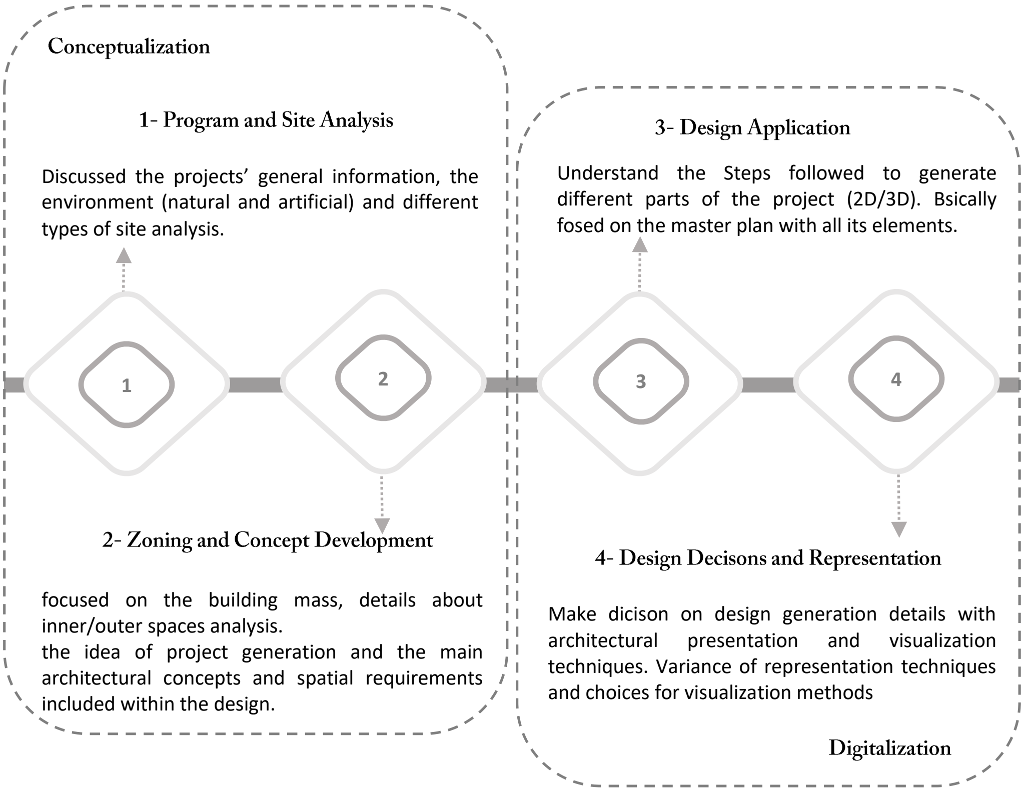


Figure 4.5. *Theoretical design Courses presented by instructors. (Source: by the author).*

The conceptualization stage focused on informative presentations provided by the instructors during 3 weeks about the architectural design process according to the following topics:

1- Project's program and site analysis: which discussed the projects' general information, the environment (natural and artificial) and different types of site analysis.
2- Zoning and Concept development: the idea of project generation and the main architectural concepts and spatial requirements included within the design. Focused on the building mass, details about inner/outer spaces analysis.
3- Design Application: Steps followed to generate different parts of the project. Focused on the master plan with all its elements.
4- Design decision and representation: design generation details with architectural presentation and visualization techniques. The variance of representation techniques and choices for visualization methods.

The digitalization stage of the methodology is based on the assessment and evaluation process of the design process which is applied sequentially during every part of the first stage. The assessment and evaluation process took nine weeks. The distribution of different steps during the semester was as the following:

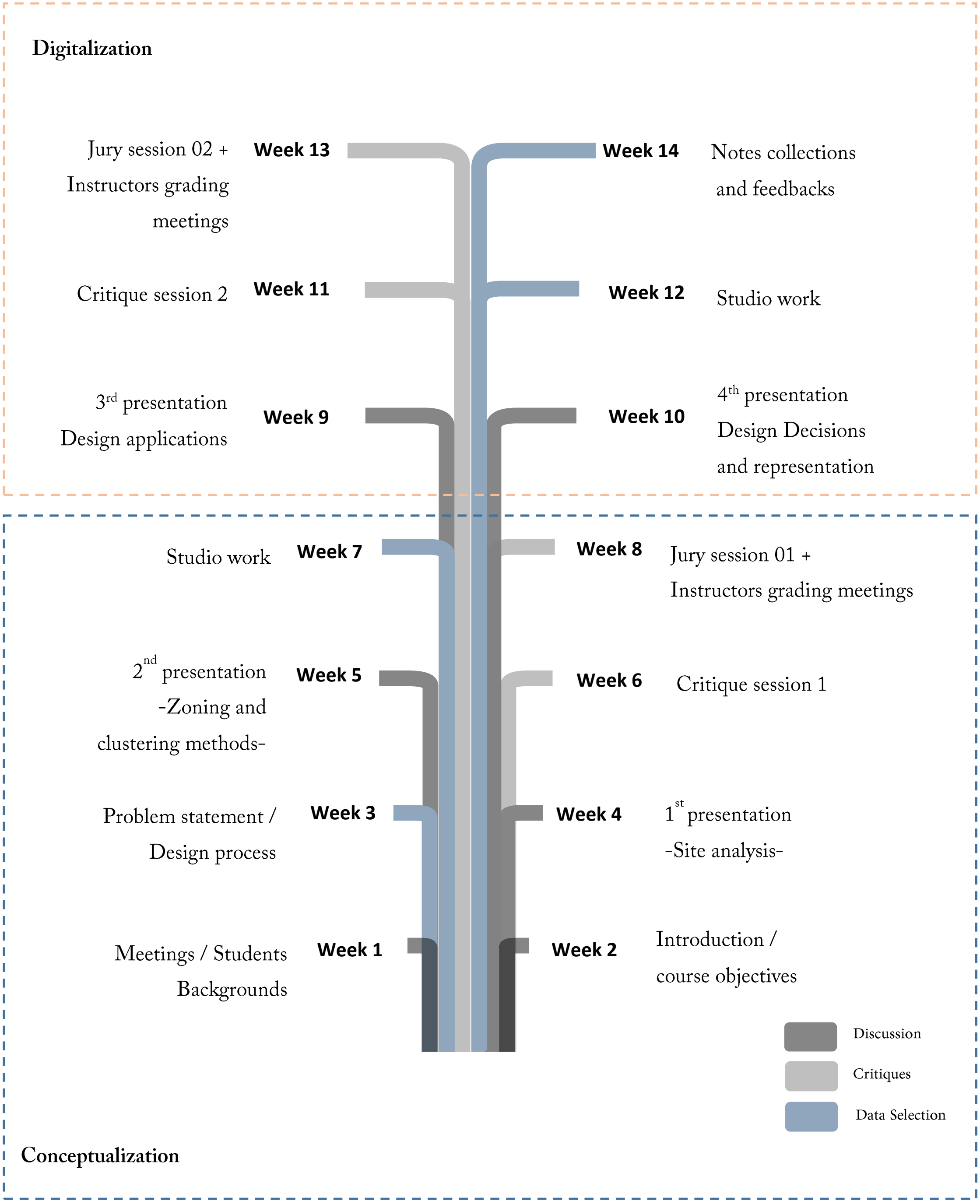


Figure 4.6. *The arrangement of theoretical design courses presented by instructors. (Source: by the author).*

1- Individual critiques: four weeks of face-to-face discussions and semi-structured interviews with students ended with notes taking.
2- Jury session: two weeks of jury session, midterm and final jury session.
3- Instructors grading meetings: two weeks of discussion meetings about students' works and grading agreement.
4- Notes validation: one week (notes collections and students' feedbacks).

The research methodology integrates three important design procedures. The first one is the key processes in which architectural design concept is explained during the design studio course. The second one is based on various critiques, jury sessions and instructor grading meetings during the whole semester. And finally, the interpretation of the outcomes was collected with a rigor and validation step to specify the appropriate spatial limitations and design challenges. This methodology could be summarized with the following schema:

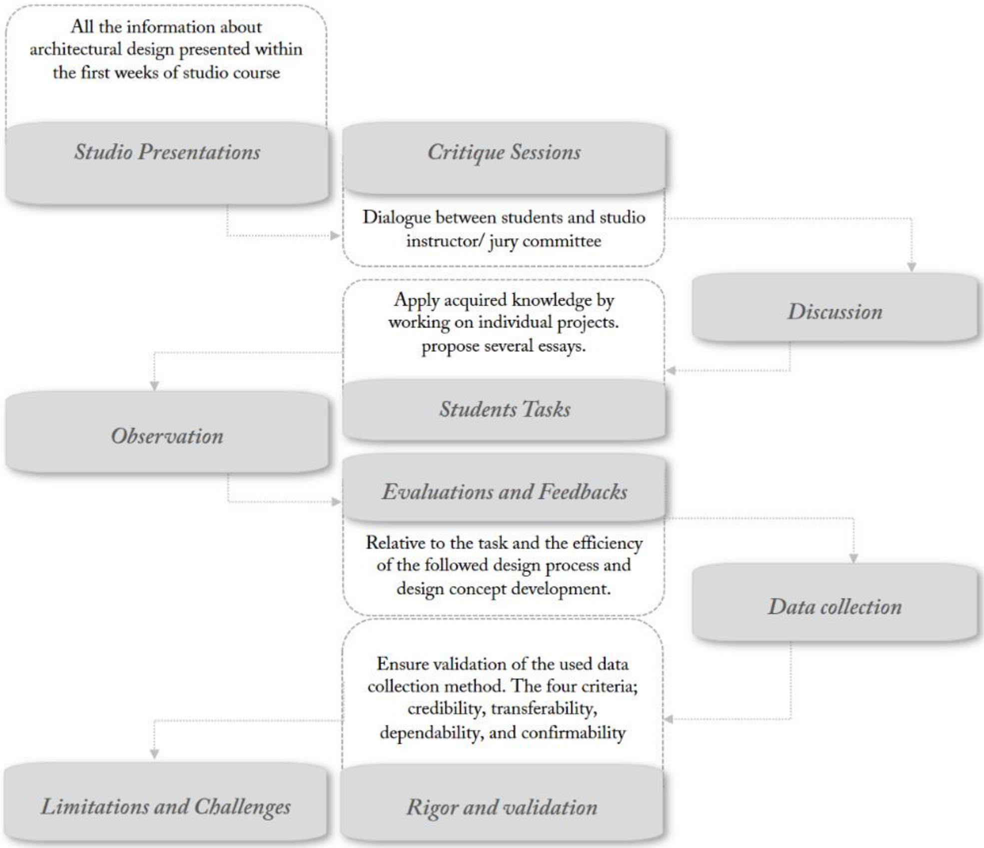


Figure 4.7. *Data Collection and methodology steps during Design-Studio Based Experiment. (Source: by the author).*

4.1.2.1. Participants and Research Environment

This study was carried out with the voluntary participation of students from the course “Architecture 4th Year Studio - MIM 435”. The course is compulsory for seventh-semester students at Eskisehir Technical University. Mason (2010) demonstrated that 15 to 50 group members are the typical sample size in qualitative research, 20 being the average for grounded theory studies. However, a large number of studies suggest guidance and consider 5 to 50 participants as sufficient depending on the reliability of data, the scope of the study, the significance of the subject and the level of useful data collected from each participant along with the qualitative method and study design used (Morse, 2000).

In the case of this research, a total of 45 students took part in the experiment (besides 23 other students who participated in the pilot study). 09 Students were female and 13 students were male. 12 students have applied their project within the case study area ESTU according to the task associated. They were identified and selected to be a part of the research according to their design performance and digital tools mastering. Almost all students had the chance to develop their designs several times during the whole semester which makes the number of evaluated projects sufficient for propositions' examination. The period of the study was September 2019 to January 2020. The main design objective of the design studio course is basically to know and apply the architectural design process underlying different spatial requirements and site conditions. One of the main topics covered is “master plan design and spatial analysis” implementing a “qualitative value review approach”. Different techniques such as analysis, perception, and observation are covered to explore the challenges facing students during the architectural design process with a focus on practical challenges.

Wren (1999) believes that the main objective of this type of methodology is to acquire a profound insight into the data to define the underlying design challenges. The study explores this question through qualitative analysis methodology to examine the systematic steps of the design process and identify specific components which obstruct spatial generation. The analyzed projects are a particular part of the content defined by being with class students, such as weekly critics, discussions, jury sessions (Glaser & Strauss, 2009) aiming to define the critical design parameters for the generative design system.

The sustainable development conditions are discussed according to the eco-campus development plan provided by the University. Each student had to develop an individual project based on these architectural ideas (Appendix-5). Students were free to use any computational tool they master to generate their projects, avoid any design and modeling challenges and focus more on the design generation and analysis. Results from the pilot study experiment are also considered important data to be analyzed.

4.1.2.2. Pilot Study

During the experiment development to identify and classify design problems through design studio-based methodology, a pilot study was conducted and documented. 23 students of the 3rd year architecture department of Eskisehir technical university are interviewed using a semi-structured interview methodology. According to Paul Oliver (2010), the participants in this type of researches generally do not feel comfortable when recording the discussion or a semi-structured interview. This affects their answers and feedbacks which affect the accuracy of method outcomes. A semi-structured method of research was not efficient for this type of study, focusing more on the observation technique and engaging instructors in the assessment and classification process may set out better results. To avoid that, the researcher has chosen to directly write down the notes on assessment forms that were developed especially for this experiment (Appendix-4), and revise them later on with both students and teaching instructors participating in the course (February 2019 to July 2020). In addition to that, it was found that the number of projects to engage in the final study analysis should not accede 12 projects to deeply focus on the design improvements and effectively assess design problems and spatial challenges (30 min discussion * 10 students = 6 hours every week). This is what makes it impossible to manage all students' design outcomes. The number of participants was enough to reach the desired results respecting the scientific conditions (Morse, 2000; Mason, 2010). In addition to that, it was found very difficult to focus and solve all the project aspects, so focusing on just master plan characteristics is the most important challenge that faced students. Besides that, to reach the research objectives, the engagement of other instructions on the analysis process was beneficial as well. Finally, considering the insufficient background of 3rd year students, it was recommended to work with final-year students that have the potential to design a perform a complete architectural project.

4.1.2.3. Individual critique session (Desk Critique)

Schön (1987) characterized the design studio environment as a place in which thinking occurs through a dialectic conversation between the design instructor and the student, and through the medium of external representations such as sketches. Accordingly, an active thirty minutes of one on one conversation between students and studio instructors have been weekly performed to act as critical feedbacks and data collection on both the design process and the design problem. During the desk critique, the studio instructors evaluate the student's progress in solving the design problem by reviewing the student's preliminary sketches, two-dimensional and three-dimensional drawings, detail drawings, and physical models. Often these materials are required by the instructor. Generally, the choice of the appropriate representation tool of the proposed design solution is left for the student depending on their level of skills and knowledge.

4.1.2.4. Jury critique session (Decisive Critique)

Critique sessions where the grade is provided to the work. Many studies show that students frequently find these critiques frustrating because they are unable to act on any criticism offered to develop the design project (Utaberta et al., 2013). Tutors state that the critics are to teach students how to evaluate and reflect on their work and develop their critical judgment, not be told what is wrong or right and the purpose of the critique needs to be made clear to students (Crolla, 2019).

Accordingly, the first jury session is based on the specific architectural program, design concept and site analysis (environmental requirements, functions organization, project general arrangements … etc.). However, the final jury session is based on evaluating zoning, detailed plans, distribution of exterior functions, deficiencies in technical drawings and representation. On the other hand, the critiques sessions and discussion with students were generally directed on the projects' technical materials such as sketches at 1/500 and 1/200 scales. At the end of each jury session, students' works were evaluated by grading them with the participation of the course instructors. The students' feedbacks and notes are taken in each phase are done with the support of developed assessment forms which allow to save details both documentary and graphically (Appendix-4). All the information is revised by the instructors before grading which makes them valid to be a part of the generative design system data.

4.1.2.5. Task Processing and Evaluation

During the first three weeks of the experiment, students were given theoretical courses about steps of the architectural design process and master plan design. These courses were based on different topics such as site analysis, concept development, zoning and clustering methods, design process phases, and master plan design requirements and conditions. After this informative introduction, students started to apply the acquired knowledge by working on their projects. Each student had to propose several projects essays. Some of them were chosen to develop their projects within the new proposed expansion land of the Eco-Campus development plan provided by Eskisehir Technical University.

The student was expected to demonstrate a design analysis summary of the design phase and to display the perceptions of all the project proposals before the first jury session. Then they could design the proposal in more depth using various graphical materials (textures, components, functionality, visualization, land usage, and volumes extrusion ... etc) for the final jury. The proposed projects for the study should provide interconnection with the whole university campus. Once the students finished all the steps of the assessment, they were asked to write a report containing all their ideas and critics about the final projects and give their opinion about design challenges they faced during the whole process of the design generation.

After finishing the final jury, a round table was created to hear from students. Feedback was focused on three main issues: architectural design process, challenges and problems found when designing the project, and suggested future improvements. Besides that, they were asked to summarize the critics of the final jury concentrating on the master plan development.

The interactions between the instructors and the students during the whole semester offered a framework for interpreting the design process context as they were performed in the university semi-open space within a comfortable and interactive environment. Discussion and individual critics which replaced the role of semi-structured interviews performed in the pilot study were transcribed and subsequently discussed with students on the very same day. Following that, and after collecting to required feedback and validation of the students, the outcomes were listed and analyzed until data saturation was achieved. As long as students are in their last year of education, there was no problem concerning the interpretation of the design process. instructors focused just on the needs of the study and the intended design outcomes.

As long as this research focused on a specific area which is the university campus of Eskisehir technical university, the instructor studied and analyzed all the projects with a deep focus on students' projects which were generated within the case study area. The different selection criteria applied by the author to choose the significant projects were as follows:

-Using the same area of the case study: as long as the whole generative design system will focus on a specific area, analysis relevant project will be more beneficial for the study.

- Feasibility of the design: the students designed a master plan that could be an expansion of the university campus.

- Level of details: selecting students with better performance in using digital tools and those to propose specific solutions for the defined problems.

The selection criteria were not directly mentioned to the student at the beginning of the course, they were frequently informed about the aim of the project and design process requirements, to avoid any impressions or pressure that could affect the final results. Besides that, those criteria are usually used in any architectural design studio to evaluate final year students' projects. Selection took into account both the design process steps presented at the beginning of the semester (Representation of students in their concept sheet), and the final representation of the generated project (with the necessary details) (Appendix-5).

The evaluation and feedbacks step focused on the assessment of the students' works, weekly critiques, jury sessions, and instructors grading meetings. It was relative to the task and the efficiency of the followed design process and design concept development. Throughout the whole semester, individual critiques were performed with each of the students to improve their project concept. During those discussions and using the pre-designed assessment form, the author was working on taking notes and writing every information in relation to design challenges, spatial requirements and user experience problems facing students in every step of the design process.

4.1.2.6. Methodological Rigor and Validation

To affirm the methodological rigor and ensure validation of the applied methodology, the four criteria; credibility, transferability, dependability, and confirmability stated by Lincon and Guba (1985) for the trustworthiness of qualitative research were followed. The credibility of the collected data was checked and preserved through different steps. After the weekly critics with each student, the notes taken by the researcher were discussed with them frequently and revised to ensure the accuracy of the information as well as an efficient interpretation of the statements and perceptions while receiving students' feedback. Meanwhile, transferability was enhanced through different jury sessions held during the course period. Each student stands in front of his fellows and the jury committee to present their work and receive critiques about the design process lacks. Thereafter, other students were able to gain more indirect critiques and information to improve their works.

To ensure the dependability of the data collection sessions, the students selected to design their projects within the case study were informed that their works could enhance the future expansion of the university campus explained within the Eco-Campus development plan and that is what establishes the consensual adequacy. Besides that, while the course was containing 22 students doing different projects in other areas, the information was discussed and analyzed with all students aiming to test the data saturation. The outcomes approved the accuracy of those of the data saturation test because all students were facing the same design process challenges and data collection problems. In the end, confirmability was affirmed by saving different organized note copies of the different stages of the data collection (Appendix-4). They were derived mostly from students' expressions and suggestions, as well as their stated thoughts on the difficulties of the design process, particularly during and after the jury sessions. As Lincoln and Guba (1985) confirmed that, saving copy notes boost both dependability and confirmability by engaging more persons in the analysis accuracy control and that what happened after every jury session by gathering three teaching instructors with the main course instructor to evaluate and assess the student works and grade them. After that, the different discussions were held with the teaching instructors that were present during the architectural design studio time especially during grading meetings. This responds to the belief of (Elo et al., 2014) that mentioned that, regardless of how much competence a researcher receives over quantitative analysis, a variety of assistants should also be consulted to ensure the reliability of the findings of the methodology.

4.1.2.7. Results Discussion

This part of the research demonstrates a definition of the design studio parameters through a new Design studio-based methodology that can respond to users' experience, spatial requirements and design conditions seeking for better spatial expansion possibilities. The findings of the study showed that many significant components and elements are challenging each step of the design process during project design. They are classified according to students' feedbacks to facilitate the evaluation (Table 4.2.). Reflection on these challenges introduces many major problems within the architectural education process. Correspondingly, many design factors such as time /cost efficiency, quality achievement and performance development of the architectural product are not evaluated. Simply, it can be said that the study focused on focal points of the design generation and design challenges that come out in architectural project courses and were conducted within the scope of the research. These challenges could be summarized as Data collection and integration, Design pattern and context requirements, Main generation element.

- Data collection and integration: which presents different geometrical and numerical information needed for the generation like (environmental parameters, spatial density, ……...etc.)
- Design pattern and context requirements: balancing between a creative design concept and the design pattern of the existed case study (design pattern of the university campus)
- Main generation element: there are three main components students find difficulties to generate which are "Street networks, Parcels division, Building extrusion).

The results also showed that a certain degree of guidance is required in many designs process' steps which could be detected in some good designs created by some students (Appendix-5). However, time does not allow to generate a variance of design that could be analyzed and evaluated. In addition to that, while exploring different design process phases, students faced many spatial challenges, functional problems and limitations in the usage of the digital tools, which make them choose to develop their designs in a limited way without full freedom.

Table 4.2. *Matric presents design challenges and limitations significance during design studio-based experience (**A** > **20** student, **B** =**10-20** student, **C** < **10** student) (**CS** = Critique session, **JS** = Jury session). (Source: by the author).*

		Design challenges and limitations	*Significance*
Program, Site analysis	CS1	Define the right programmatic needs for the design project	A
		specify the main functions and decide surfaces values	B
		Set the right relationships between all the functions	B
		Decide which analysis component needed for the study	B
		Use suitable methods of spatial analysis	C
		Integration of requirements related to the whole program with particular shared functions	A
	JS1	Manage Data collection, Accessibility and connectivity	A
		How space layout could match the Program requirements	B
		Plan for an effective zoning with right relationships	C
		Balance between all the design intentions and spatial preferences	B
		Well managing the land use and spatial organization	A
	CS2	Relationship between people and buildings, and between buildings and their environment	C
		Give final decision about the facilities needed for the design.	B
		Choose the right orientations of the function according to the environmental and spatial conditions	C
		Present a functional relationship between the main project parts	B
	JS2	Define the design requirements , planning and the skills involved in the planning process	B
		Solve difficulties in projecting effective accessibility to the area.	C
		Combine between all the design stages	B
		illustrate spatial interaction and understand geometrical interdependencies	B

		Design challenges and limitations	*Significance*
Design application	CS1	Create architectural designs that satisfy both aesthetic and technical requirements	C
		Maintain design pattern and freedom of creativity relationship	C
		Plan for a dynamic public transportation network inside the area	B
		Generate active accessibility possibilities within the area	B
		Computing the relationship of the project parts according to the project attractiveness	A
		Shifting from macro to micro with design detailing.	B
	JS1	Make a decision about the main accesses that divide the area of generation	A
		Specify relative adjacencies and location preferences	A
		Generate the secondary roads that subdivide the parcels	B
		Propose different block typologies	A
		vary visualization software to represent the design outcomes	B
		Propose different alternatives to solve the same problem	C
	CS2	Design skills to build user' requirements within the proposed challenges	C
		Measure the distance between each function of the project.	B
		Engage site conditions within design process	B
		Interconnect 2D and 3D design levels	C
		provide alternatives for the different design limitations and challenges	C
		Conduct different evaluations about the design and seek for better results	B
	JS2	Decide the parcels limits within the new design area	A
		The level of each building within the project (floor numbers)	A
		Key locations to settle the main buildings	B
		to create architectural designs that satisfy both aesthetic and technical requirements	C
		Make scenarios for future expansion that could affect the design	B

		Design challenges and limitations	*Significance*
Zoning and Concept development	CS1	Preserve continuity with the project context	B
		Define the spatial constraints and the percentage of open space	A
		Considering the suitable built area ratio related to each function.	A
		Combine spatial factors such as density and land use	A
		Set the right problem definition taking in consideration all the variances	B
	JS1	Placement of the main entrance and entrances of each block	A
		Diversification of multiple functions and spaces	C
		identify the spatial density of each function	B
		Efficient combination of user experience requirement and computational manipulation.	C
		Visualize the project idea according the design area	B
	CS2	Set relations between new concept and project limitations	B
		Make decision about the built and non-built areas within the design.	A
		set the street networks between all the buildings	A
		Propose various spatial typologies that enrich the design.	B
		Sustain the same design pattern of the surrounding	A
		Connect all the project by providing well organized roads (pedestrians, bicycle and bus/cars)	A
	JS2	Decide the final design patterns that will be followed with the generation.	B
		Include users' experience preferences	C
		The main attractive point in the design (Reference point)	B
		Define and engage user experience feedbacks	B
		Explain the main mechanism of the design process	C

		Design challenges and limitations	*Significance*
Design decision and representation	CS1	Vary methods of outcomes representation	A
		Usage of different tools (graph, graphics, tables, sketches).	A
		Visualize zoning alternatives for each proposition	B
		Identify the efficiency of each alternative	C
		Usage of representative diagrams to represent	B
	JS1	Problems concerning mastering digital design tools	B
		Idea interpretations from hand drawing to computer programs	C
		Vary the propositions and provide many information and illustrations about the project	B
		Interpret the design concepts into illustrative drawings	C
		Simplify jury critiques	B
	CS2	Multiply the possibilities formerly presented	B
		Provide different simulations of the project outcomes	A
		Use the computer as a design tool not as a design critical decision maker	B
		Improve the previous illustration according the jury critiques	C
		Establish a responsive and inclusive design processes.	C
		Implement design development plan according to future expansion	C
	JS2	Balance between the digital tools and user perception of the final product	B
		Improve functional optimizations for final design problems	A
		Provide explicit illustrations for the important design parts	C

Regarding the results of this study, involving new computational design tools for spatial analysis will strengthen the comprehension of site analysis, and may provide more data that boost the possibilities of the generative design system application. The role of the designer should not be stopped with a time limitation, but be able to more control and manipulate different design decisions.

Within the limits of this phase, the justification for utilizing a qualitative research technique rather than a quantitative research method is that architecture students typically do not have the adequate technical knowledge to comprehend the process involved in various design optimization. As a consequence, it is considered in this study that a back-and-forth discussion between instructors and participants is required during the information gathering stage. Discussions are required to inform participants about architectural fundamental optimization such that their contributions are a combination of suitably learned information and their academic and design practice experiences.

4.1.3. Phase 02: Master Plan Expansion Analysis (2005/2020 Maps)

Throughout the architectural design, decision making on spatial performance parameters such as land use, density, and building typology, are frequently taken by examining a limited number of materials, optimized by repetitive experimentations, without carefully evaluating the complete range of potential designs and their efficiency outcomes (Mueller et al., 2017). The university campus master plan presents a leading outline of expected campus growth and defines a set of architectural guidelines that are meant to direct design decisions in a way that adapts to the university's changing needs. According to the previous phases of research, the major master plan characteristics are dependent on the layout and spatial arrangement, connectivity and accessibility, and built area and open space.

ESTU was originally a campus linked to Anadolu university, two years ago the university detached and this campus become the main area of Eskisehir Technical University. Recently, the university aims to increase the land's growth capacity and optimize the successful outcomes of space creation and also maintain the validity and availability of an appropriate density of open space and built area on campus.

This section of the research tends to examine the university campus master plan efficiency to meet the university's changing requirements and cooperate with design specifications to direct the development system decisions. It examines such a process by comparing multiple maps at different periods to evaluate the expansion of the campus master plan as a case study (2005/2020). Furthermore, the analysis aimed to gain a better understanding of how this university campus master plan could evolve and expand and what are the main spatial elements and environmental components that control its mechanisms. The analysis tends to answer these questions: What are the main campus master plan elements that have a key role in directing the generation? How does the area perform for spatial development?

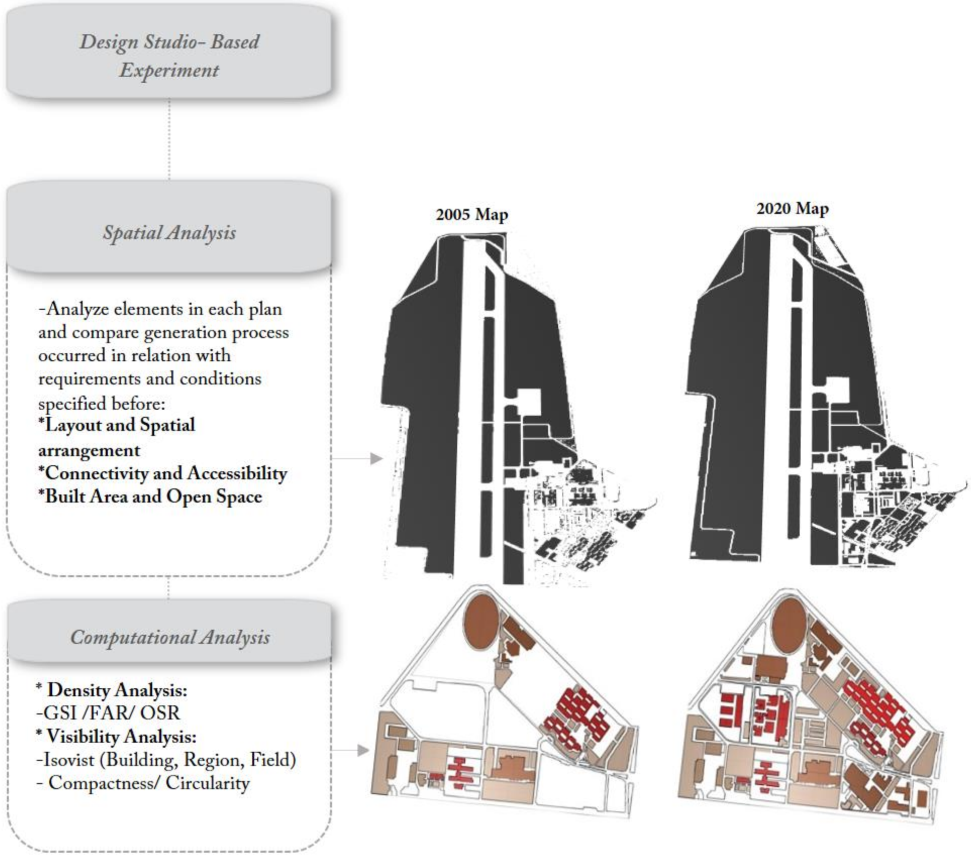


Figure 4.8. *Spatial analysis and computational analysis aspects for the data collection part (2005/2020 Maps). (Source: by the author).*

The analysis would not claim to give specific proposals to campus-decision makers or designers; instead, it helps to assess, classify and comprehend the existing data in reality as well as provide a conceptualization forward for research on the related subject. It employs the comparative research method (Voordt et al., 1997) to focus on architecture features and concerns responding to the improvement of campus infrastructures and mechanisms of integration. Special focus is given at particular points in time to the transformations of the master plans of the university, the map in 2005 compared to the map in 2020 (Figure 4.8.). The in-depth analysis of the campus master plan engages two different techniques, “Spatial Analysis” and “Computational Analysis”. It is through examining these master plans in an integrated and comparative way that we would be able to consider such discussions as the key that determines the main parameters required in future generations. The Spatial analysis is based on a qualitative assessment of the plans and observation-based interpretation of the needed data and information. Whereas, the computational analysis uses a quantitative assessment by engaging several parametric techniques to seek to explain various elements of the research subject.

4.1.3.1. Spatial Analysis

Studying the development of a master plan over time will allow exploring the various mechanisms that affect its formulation (Huang, 2007). For this aim, an in-depth qualitative analysis of the two different master plans was carried out enabling us to concentrate on the specifics and suggestive complexities of how the campus reacted to various circumstances and environmental limitations. The spatial analysis explores the connection between the different spatial elements through ESTU University's master plans. In doing so, it has sought to investigate how the plan has evolved in relationship to density, street networks and buildings patterns. The main intention is to clarify the university campus structure with the potential for sustained expansion, carrying the basic framework for the campus favorable development.

Hajrasouliha (2017) believes that the campus should be diverse, compact, strongly integrated, well-structured, sustainable and urbanized. The 2005 map demonstrates a significantly decreased degree of compactness compared to the subsequent map, significant areas are still being preserved given the major development of the campus, which has undergone a noticeable reconstruction in recent years. While on the 2020 plan, a compromise between conception and realization is becoming considerably more influential, and campus improvement and expansion are at the center stage. It was a challenge to maintain layout characteristics of the previous maps, while simultaneously developing new approaches to connect with multiple growing conditions throughout the university campus. To underline the aspects for evaluating the composition of the campus in this qualitative research, the results show that the main problems identified for university campuses are; layout and spatial arrangement, connectivity and accessibility, built area and open space.

Layout and Spatial Arrangement

The main campus layout is developed spontaneously as long as there was no clear development plan for its expansion. Its spatial arrangement is defined by a range of repetitive structures. The campus master plan is strongly representing the existing circumstances of the area. It is essential to explain, identify and encourage campus identity to build a clear sense of location (Li et al., 2018). Establishing a relevant layout for the campus area as well as the environment surrounding is a task that should be effectively accomplished.

ESTU campus master plan is created with regions geographically restricted or self-identified with the same initial progress and expansion. It is not impressive that the 2020 plan layout does not differ extensively from the 2005 plan, except that a few more buildings have been constructed inside the boundaries of the empty predefined regions (Figure 4.9.). In the north, the plan expanded in the same formularization with slight changes in buildings patterns. The layout allows for alignment along the main axis, starting from the lower region of "Muttalip Bulvarı" to the northern area where there are a variety of important university functions (basically social functions).

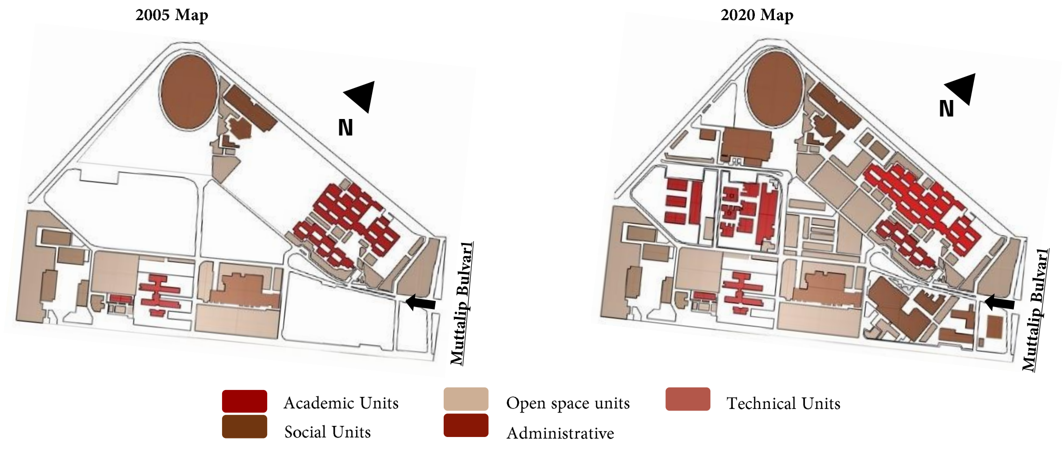


Figure 4.9. *Layout and spatial arrangement of the university campus master plan (2005/2020 Maps). (Source: by the author).*

The pattern of expansion is maintaining the initial pattern that creates a focal point and a central dense environment with an appropriate distribution. Buildings placed in the north and northeast areas show the same patterns and look similar in several characteristics, thus highlighting an ideal continuity and a simplified identity of the master plan. Placing the main entrances of each building in all the regions away from the main street was also an investigation. This has created a boundary between the inside and exterior of separated regions with interconnection and thereby enables the campus inward centralization. The spatial arrangement of the campus master plan does not anticipate sustainable growth guidance proposing for future spatial expansion and generation.

Connectivity and Accessibility

The campus master plan is segmented with intersections between a series of the main axis and sub axis which permit street networks to be one of the essential elements of spatial connectivity. The main street as a core of the plan is dividing the area into two main parts north/south. It remains the same in both maps while other street networks disappeared and some others emerged. The main street has major importance and centrality which could be seen from its connectivity with other street networks and that make it a geometrical force to areas division. The creation of a significant linear sub axis connecting the main street and the north part along with its boundary features progressively declining lines to the South allow the master plan to be more accessible. Also, every part of the plan is properly identified by the circulation of streets and bypasses that describe the connection between the buildings and their surroundings in two different patterns (Figure 4.10.).

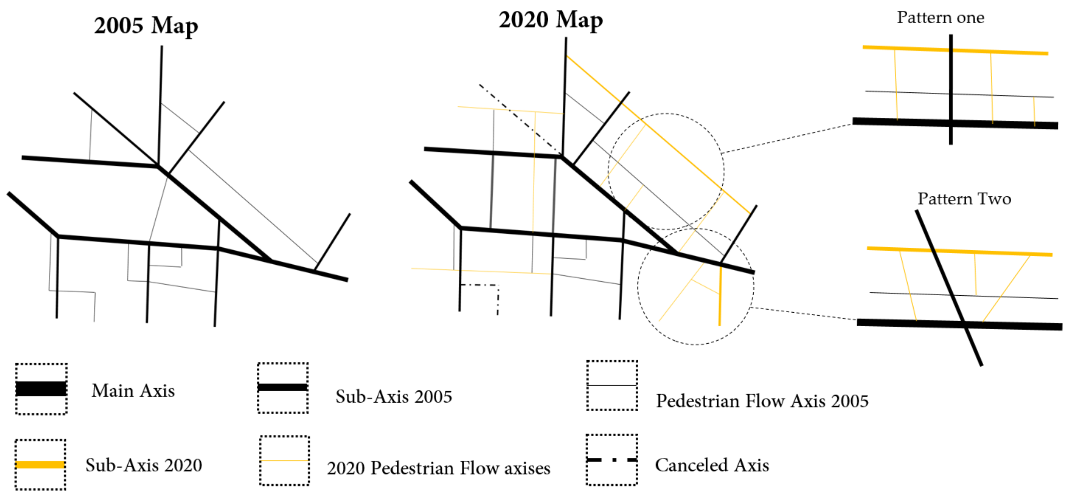


Figure 4.10. *Connectivity and accessibility of the university campus master plan (2005/2020 Maps). (Source: by the author).*

The plan establishes vertically high division paths leaning significantly to the right. They allow for external circulation of the area while setting the key buildings inside the circulation zone in a symmetrical plan and generate spatially different street network patterns. The street on the west-east side of the university serves as a basis for the campus, with small service streets connected to it. The most significant pedestrian spine existing at the campus is that of the northeast. In addition, the external pedestrian street specifically marks the boundary between the inside and outside of each section of the plan. The comprehensive public transport network covers also easy transport and bus lines within the same main street direction. Some parts adjacent to the main street were kept unplanned, visibly emphasizing different paths that entered the main street. Pedestrians and vehicles move in parallel in the same direction. This is what makes the quality of pedestrian routes across the campus don't respond to the general accessibility. Although the main entrance orients the street network and the distribution of the parcels and functions within the master plan, the accessibility is not effectively integrated as a key element in the expansion of the university campus master plan. Furthermore, the relationships between various parcels and functions are neither geometrically represented nor integrated to maintain campus continuity.

Built Area and Open Space

The university campus master plan was not fully built but somehow defined as an expression toward randomization, which can be demonstrated by the grid system arranging in different locations without any expressive logic. The open space implementation and character are significantly presented as identification of the campus layout. The spatial arrangement was not a challenge towards uniformity but on the contrary in the creation of proportional distribution that connects the campus.

The university master plan includes many open spaces, primarily in the campus core. It is providing a strong distinction between the north and the south, which highlights the central region. This refers to the spatial alignment of buildings around the main street, the layout of the plan in the north and the development of the eastern area where the main entrance is situated (Figure 4.11.).

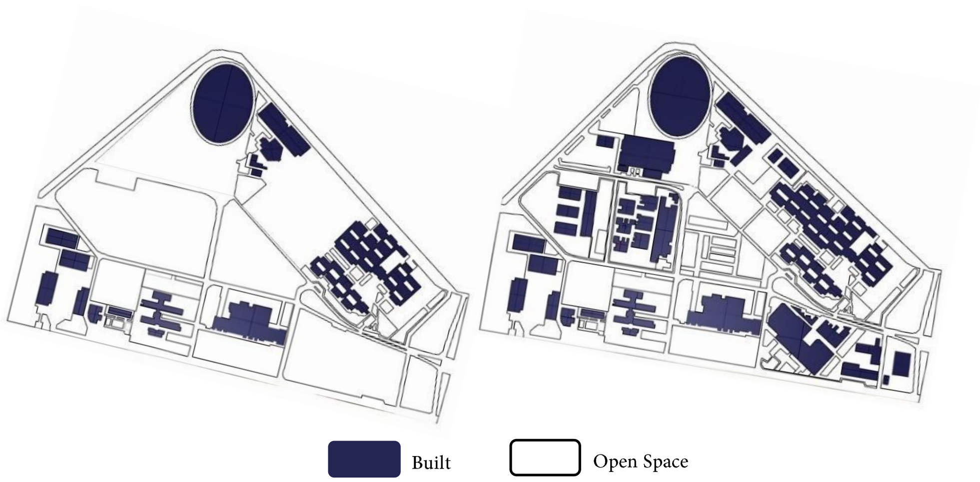


Figure 4.11. *Built and Open Space of the University Campus Master Plan (2005/2020 Maps). (Source: by the author).*

The relationship between buildings, parcels and the street networks was a result of unplanned generation which called for a focus on the spatial typology. A significant built and open space proportion is presented in each of the northern and south-western regions of the campus. This combination reflects simultaneous campus components, interaction centers and a prosperous university campus social environment. The master plan for the campus though proposes increasing growth rates to generate open space. This approach is retaining the same design pattern in almost all parts of the master plan. The buildings' designs are based on four main different patterns (Figure 4.12.).

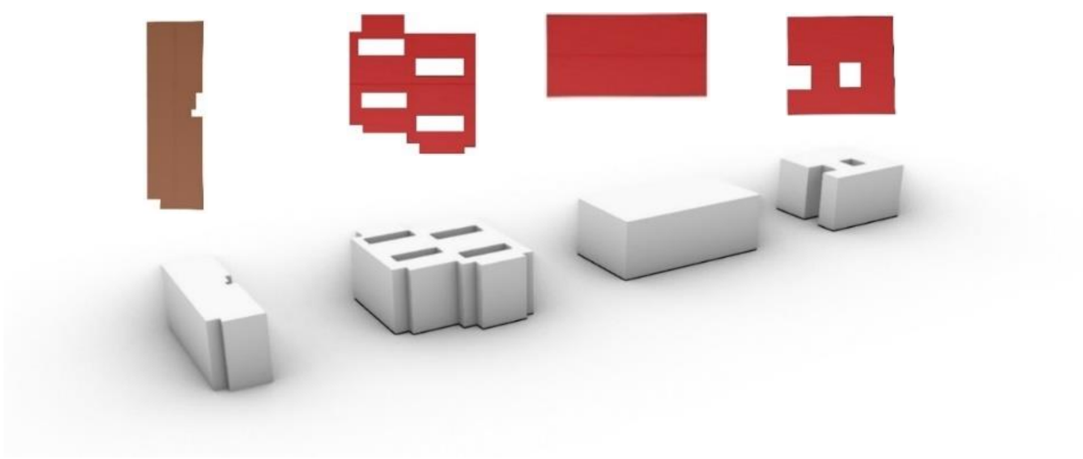


Figure 4.12. *Buildings Design Patterns at the University Campus Master Plan (2005/2020 Maps). (Source: by the author).*

One thing worth mentioning is that in the far northeast there are a collection of horizontal long buildings which mark a visual difference from the rest. This integrates a conceptual sense of variety in campus design. Each building in the far north is unusually huge and therefore not exclusively in relation to the surrounding environment. Therefore, such an individualistic design provides signs of the lack of knowledge regarding the environmental conditions and context requirements (Table 4.3.).

The use of different design patterns without clear respect to the proportion of open space in a combination of built and non-built areas in the university campus highlighted difficulties in analyzing the environment by observation and visual analysis. As a result, utilizing computational techniques to evaluate the same master plan maps might be more effective.

Table 4.3. *Numerical data of the university campus master plan from spatial analysis (2005/2020 Maps)*

	OLD MAP 2005 (m²) / (R%)	EXISTING MAP 2020 (m²) / (R%)	EXPANSION 2035 (m²) / (R%)
Eskişehir inhabitants Number	546,304	957,879	Ratio 0.94%
ESTU Students number	7000-9000	12500	Ratio 1.38%
Campus Total Area	11403447 m2	11403447 m2	11857447 m2
campus expansion area	/	/	= 454 000m2
Administrative Units	0.91%	≈ 2.1%	+ 10.000 m2
Social Units + Outdoor	80.32%	≈ 62%	+71.837 m2
Technical Units	0.87%	≈ 1.9%	+10.000 m2
Academic Units	17.9%	≈ 34%	+170.000 m2
Total distance/circumference	/	9.46 km = 9.460 m	/
Total parking area	/	49,044.00 m2	Ratio: 0.0113

4.1.3.2. Computational Analysis

Within this section of the research, an analysis of the two university campus 2005/2020 plans relied on computational techniques by measuring different features such as density, visibility compactness and circularity. It tries to explore the potential of the computational analysis methods to understand the university campus master plan development mechanisms and approaches. The computational analysis method is used effectively on the master plan scale to test various designs and their performance, but many challenges are presented while applying it on the real scale due to data calculation and parameters manipulation (Koenig, 2015). Several difficulties in limiting inputs and more important specifying the time involved in the process.

The computational analysis demands qualified practical designers to determine success purposes based on the understanding available at each phase of the creation of a master plan and interpreting the implications of the land use, density and design choices on those aims into numerical and geometrical data. For this experiment two different techniques of analysis have been performed, density analysis and visibility analysis.

Density Analysis

Density as discussed previously plays a crucial role in the formation of university master plan development phenomena. The relationship between the built environment and open space is very important to understand the growth behavior and predict future alternatives for space generation. This analysis is based on considering those two spatial elements with each ones' characteristics. The set of indicators is modeled considering the morphological properties of the elements. Stahle (2008) believes that density analysis is one of the most used techniques to recognize spatial development. It allows measuring different indicators considering open space partition and building volume. This technique engages different parts of the urban fabric such as parcels, footprints, blocks and streets to measure density in a specific area. For that reason, many other analytical applications could be anticipated in further advanced measures. Frequently a ratio between different techniques can be also engaged to comprehend relatively the performance between different elements. Berghauser and Haupt (2007), examined how each street is connected to the network in terms of integration and direction variance. While Pont and Haupt (2010) proposed another approach to analyses density by using different variables such as GSI, FAR, OSR.

The Ground Space Index (GSI), measures buildings footprints in a specific area by dividing the total built footprint area by the base land area. The outcomes are usually visualized through ground-based drawings. The Floor Area Ratio (FAR), essentially focuses on calculating the built area density in combination with the building's floor area existing in the same environment divided by the general base land area. It is known also as the indicator of land-use intensity that aims to understand the effect of volume features on a specific site. The higher level of ratio signifies a high number of floors per area. The Open Space Ration (OSR) is focused on measuring the existed open space through a specific area. The ratio of open space is calculated by dividing the non-built area by the floor area. It is also engaged in measuring the indicator of an area's spaciousness, daylight measurements and ground levels (Figure 4.13.).

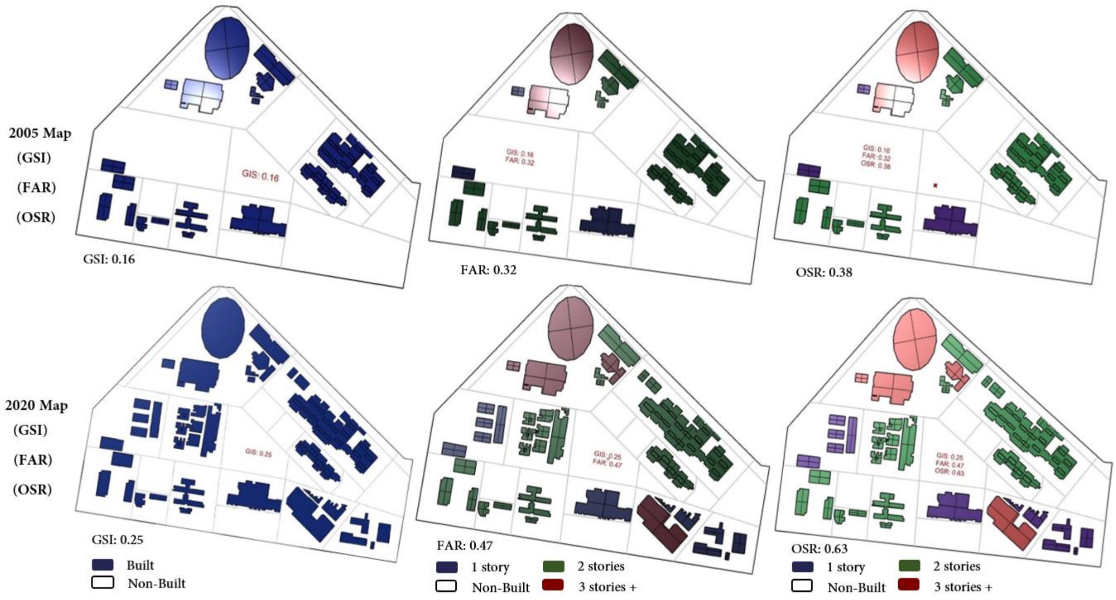


Figure 4.13. *Indicators of the morphological properties at the campus master plan (2005/2020 maps). (Source: by the author).*

The main indicators measured with this computational analysis showed a significant level of effectiveness in spatial analysis and simulation requiring just buildings' footprint as input data. It is a visual examination of the space density based on the buildings' footprint data applied with parametric design tools (GH codes). Engage both open space and building blocks, as well as computational techniques, to decode the university campus master plan's characteristics into indicators. First by formulating a computational data set for each building plan footprint recognizing both the volume and the environment open space. It is also shown that the density analysis gives accurate outcomes than the spatial analysis methods concerning open space proportion and spatial layout structure classifications.

Henriques et al., (2009) stated that attractiveness could be discovered in different forms such as closeness, relationship, usage, and importance according to the design aim. The design method in this study only focused on the interaction between open space and built areas. Many other social and cultural aspects are not involved in the research because they depend on the users' personal feelings and desires that do not enhance the objectivity of the generation parameters. The attractiveness potential for ESTU campus is calculated to embrace the street networking, open space, build environment, and the buildings' interconnections. The calculation considered the distance between the various campus facilities, the distance to the main entrance, and the user experiences resultant attractiveness of a grid point.

University campus buildings with their simple design pattern are distinguished from early buildings' characteristics. Also, it can be noticed that some of the buildings that were designed later have different architecture. The outcomes from this analysis highlight the development behavior of the university campus master plan give much more about the urban fabric morphology. This allows seeing that spatial development is differing from structured axial morphologies of the street network to a non-structured street network where the buildings and blocks are not regularly located alongside parcels division. The decision of the most attractive point for the design system differs from an area to another and it is linked to the user experience. In this study, the weight adjustment was permitted to be modified based on the unique requirements and characteristics. A more accurate analysis could be done to specify the exact attractive locations of each user of the university campus. Many other attributes such as social and cultural characteristics may be involved in future researches.

Visibility Analysis

Visibility analysis requires a careful calculation of different parameters such as compactness and circularity (Benedikt and Mcelhinney, 2019). The complex relationship of the built area and open space in the campus master plan are reflected by this analysis. To have desirable results a large amount of computing time should have been carried out in both formulation and application of the parametric model. The visualization of spatial visibility is performed by colors referring to different results (Figure 4.14.). The results are showing several possibilities from different locations according to the specified design pattern and spatial features. The evaluation experience is applied by several parametric Grasshopper analysis components (GH code).

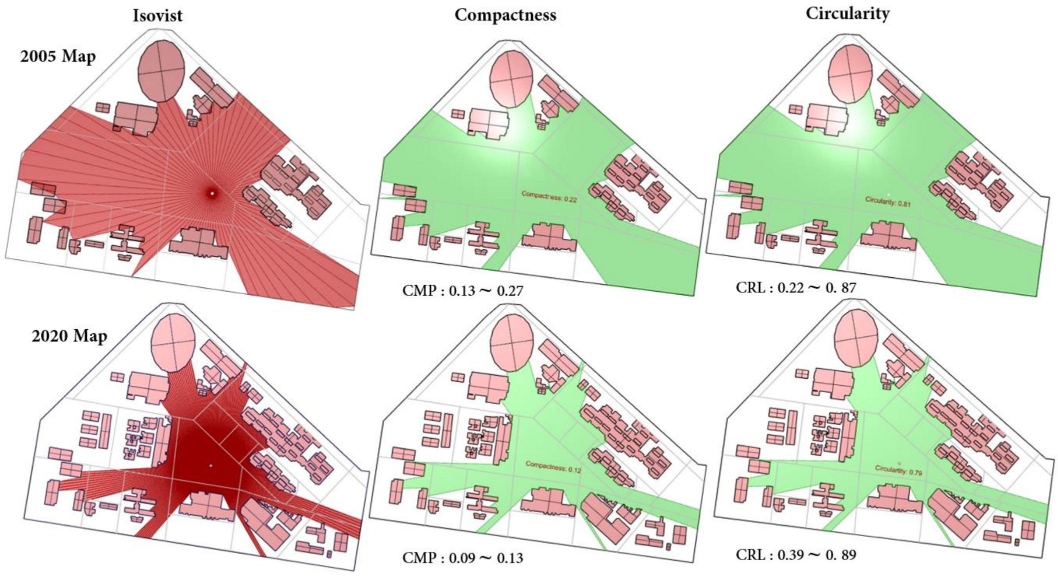


Figure 4.14. *Visibility analysis results - CMP/CRL (2005/2020 Maps). (Source: by the author).*

The visibility analysis focused as well on different Isovist applications, it was instructive to see the closeness of the plans as well as the openness of the areas and how they behaved. These applications are mainly used to calculate the visibility of the buildings and their relations with the open spaces (Xiang et al., 2021). Isovist describes the part of space that can be seen from a certain viewpoint and calculates the visibility of objects. The properties of Isovist are the correlation with subjective spatial experience. The Isovist region works with mapping the changes of visual properties along a specific path where the Isovist field is mapping properties on a scalar field. By displaying the number of arrays in contact with each face of the extruded volume, it is also conceivable to compute the building visibility and gather numerical data (Table 4.4.).

According to the Isovist analysis, the high visibility is shown more at the intersection of the streets which could be taken as a context requirement for generative design system application. There are also significant trends of open space existence from the southwest to the northeast, which are illustrated in orange and blue colors. The coherence presented in the distribution of volumes within the area, some of them are better integrated and have high visual representation values, other ones show the opposite features. Both plans analysis results lead to an assumption that integration and openness central environment of open spaces are unclear concerning design.

Some areas in the university campus give the chance to visually connect all the parts of the plan while moving through the center. The main street in the center of the campus coming from the northeast main entrance is more dynamic than the others, and this provides both diagonal and horizontal connections between all the regions inside the campus. The open space between buildings is much visibly presented in the design of most buildings. The Isovist shows that these types of design patterns are strongly clear enclosed. Also in terms of measure, the buildings with interior open space present a contrasting character to the rest of the environment (Figure 4.15.).

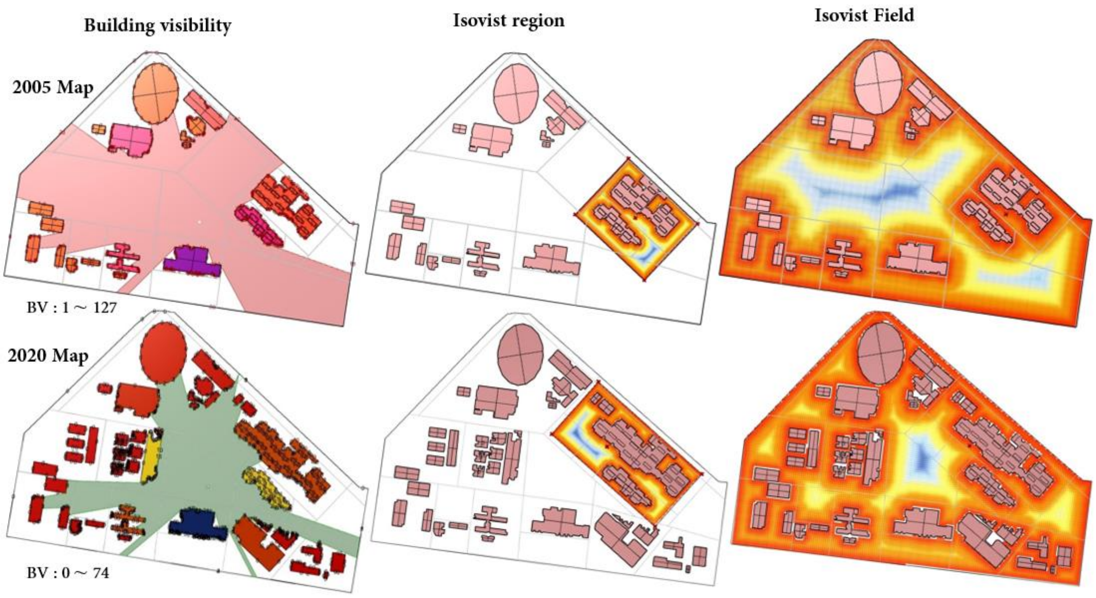


Figure 4.15. *Visibility Analysis Results Isovist (2005/2020 Maps). (Source: by the author).*

The colored space in between the buildings represents a relatively compactness and circularity even if the results of the Isovist area seem to be nominal. This is the case in different open spaces which connect the area and play the role of central environment. The blue color symbolizes exceptionally high space openness as seen from a given location, whereas the orange color represents relatively low space openness as experienced from a specific point. The point of reference is chosen to be on the center of the maps where all street networks intersect. The visibility analysis shows the value of centrality within a specific area. Some point of the environment has a small Isovist area but has relatively a high visual integration value because of density variance. These types of spaces are more considerable when it comes to inside integration, however, they feel very disconnected from the whole environment. Some other parts remain discrete to be detected by the analysis tool.

The analysis values show that the proportion of open space within the environment is decisive to highlight integration and openness of the space. The main benefit of this computational analysis is to facilitate the interpretation of the design environments where the marginal visibility is colored with orange and central visibility in red. The following table summarizes the features and related indicator values of the investigated university campus master plan, such as GSI, FAR, and OSR, among others, that are required for the development of a generative design system:

Table 4.4. *Computational design analysis outcomes (Numerical Data) (2005/2020 Maps). (Source: by the author).*

	OLD MAP 2005 (m^2) / (R%)	EXISTING MAP 2020 (m^2) / (R%)	EXPANSION 2035 (m^2) / (R%)
Campus Built Area	≈ 67230 m2	454034 m2	79.10 % (R 6.76 %)
Campus Un-built area	≈ 52736 m2	119966 m2	20.90 %
Active campus area	≈ 187196 m2	574000 m2	761196 m2
General open space	≈ 67%	20.90 %	< 20.90 %
Open space per parcel	40.30%	20.90 %	20.90 % – 40.30%
Open space per building	17% - 20%	17% - 40%	17% - 40%
GSI	0.16	0.25	0.25 <GSI
FAR	0.32	0.47	0.47 <FAR
OSR	0.38	0.63	0.63 <OSR
Building Visibility	1~127	0~74	74 >VB
Compactness	0.13~0.24	0.09~0.13	0.24<CMP
Circularity	0.22~0.87	0.39~0.89	0.89<CRL

This section of the research shows that density and visibility analysis leads to predicting open space proposals for future design processes. A better analysis still can be engaged by many other computational tools among several practices. However, for this study scope, the visibility and density analysis can allow a generative design system to engage the collected data in the generation process. Besides, the university campus plan that was analyzed is mainly focused on features such as open space, street networks and buildings blocks interconnection. It also provides a comprehensive visual representation of the results that could be improved and clarified. It was interesting to comprehend how the space function and either how should future growth behave. The visual analysis methods could be used as well to evaluate different other studies and assess the strengths and weaknesses of many design proposals to reach some effective design decisions.

The adoption of this assessment technique is quite efficient in analyzing user experience, which was highlighted during phases one and two of the site study. Outcomes from both students' works and instructors' observations asserted the importance of attaining user feelings within a generative design system. There is a relation between the visual perception of users and the spatial characteristics while navigating any space. Thus, ensuring well integration of those parameters will make the design reach the early defined objectives.

4.1.4. Data Collection and Analysis Outcomes

The data collection and analysis developed in this work are based on two main experiments. The first one is the design studio-based experiment that aimed to limit the design problems and seek systematic classification of the context requirements. Responsive street networks generation, parcels division and building extrusion are the most important challenges facing the students. It is important to consider these findings when implementing the new generative design process and choosing the digital tools for its conceptual design. Students seemed to be open to more freedom concerning the design process, so the proposed generative design system should allow for that; however, it permitted also to control and set the spatial requirements and design conditions of the chosen case study. Engaging new computational methods within the design process can provide support for some of its steps, by generating several possibilities that search beyond predetermined design concepts or by changing some phases in unpredicted procedures. It seems that computationally generated design possibilities will be further responding to the user needs and integrated by the designer into a coherent whole under relation software-designer. The students' final designs fulfill a certain set of ideas and challenges.

The second experiment is based on spatial and computational analysis of the university campus master plan in two different periods. On one hand, spatial analysis enabled one to pay attention to the specifics and suggestive complexities of how the campus reacted to various circumstances and environmental limitations. On the other hand, visibility and density characteristics of a university campus master plan development showed that these analytical techniques are very responsive to the design limitation and context requirements. Some spatial characteristics are formulated and converted into indicators so may be computed using Grasshopper as a computational tool. This initiates a particularly appropriate data collection for both campus buildings and open space. Perhaps in a more complex spatial fabric environment, these techniques have to be improved to process a huge number of numerical data and spatial structures. The analysis techniques used in this section of the research can be enriched and introducing some other data processing methods and morphological assessment approaches that consider open space and built area characteristics.

The Analysis of different university campus master plans that was conducted along with results from the design studio-based experiment clarifies the different elements that may control spatial development and provide the study with the effective data values that are needed to integrate into generative design systems such as density, connectivity and design pattern alternatives. To sustainably design or generate an expansion of any university campus master plan, there would be a complete understanding of the development mechanisms and the interconnection logic of its spatial elements. For a public space and as a part of the urban tissue of the university campus, functional connectivity, responsive density and design pattern are the major elements that influence the generation process of the master plan. Consequently, to simplify the outcomes and make them more valid for the implementation in the generative design system, they were summarized as the following:

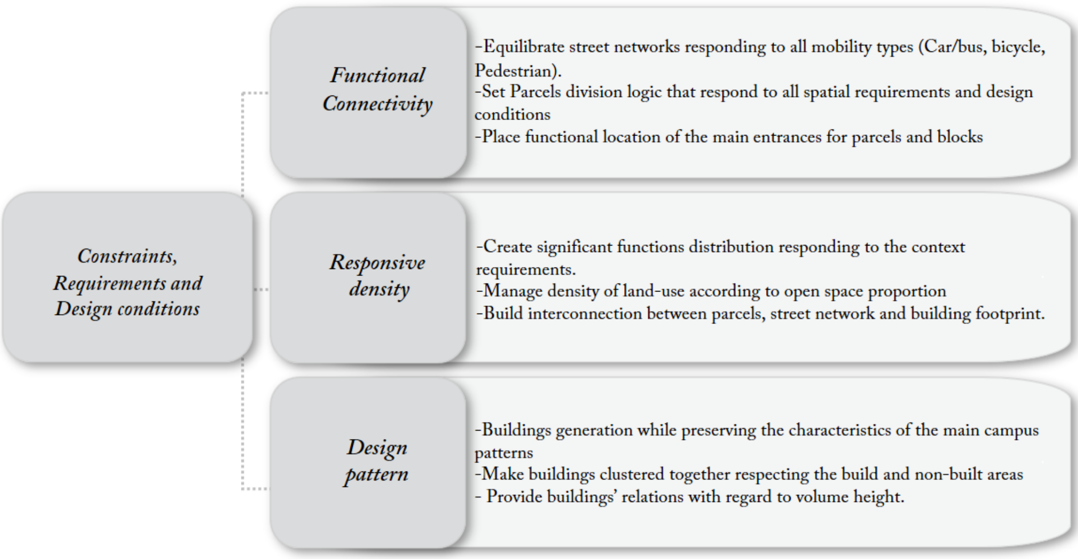


Figure 4.16. *Design problems and spatial requirements intended for the generative design system. (Source: by the author).*

4.2. Generative Design Process

In an era of technology and digitalization where a large amount of data is spread in several forms, an architectural project is not generated by just geometrical elements but requires several design details and further specifications. The generative design process gives the chance to generate many possibilities engaging these data for the aim of developing an efficient design framework. It permits to improve varied ideas without wasting time on just one of them.

This section of the research introduces the formulation and application of a generative design system as a response to the specified design problems, design requirements and limitations. It explores a flexible, adaptable system using the 3D modeling software Rhinoceros along with the parametric plug-in Grasshopper and different other Plugins. Therefore, the main objective of this application is not based on the generation and analysis of specific design characteristics, however the formulation of a generative system that could be used in future relevant works. The development of the process is based on the outcomes of the data collection analysis phases.

The selection of effective computational tools and their application is explained in detail within the following pages (see page 163). Several visual scripts are created in combination with software libraries. Thus, existing plugins and components are used within the design process to generate a fast and efficient application framework, once the design idea has been interpreted into geometrical data and computationally evaluated.

To be studied, every design pattern needs different parameters adjustment by the designer, to seek different results with the needed context requirements and spatial qualities. After collecting all the data and making the technical drawings ready for manipulation, the following important step is the work on Rhino and Grasshopper. Inside Grasshopper the use of several advanced components with their libraries takes the crucial part of the system. After that, the outcomes of the generation could be engaged in design development, analysis and evaluation. The synchronization between both design environments Grasshopper and Rhino allows us to maintain all design information and make them able to be imported with all their attributes. This section is structured under three phases: 1) Generation scope and limitation,2) Algorithmic Model Representation, 3) Optimization of the Generative System application.

4.2.1. Generation Scope and Limitation

The main concept developed within this generative design system is based on the combination of three stages "Functional connectivity, Responsive density, Design pattern" and engaging them into a system that provides multiple solutions possibilities responding to the design conditions and limitations. Each stage focused on specific problems without giving any particular importance to one of them. The major concern was determining how to create a responsive system capable of producing different outcomes. After defining the generative design concept, the application process is set up with different parameters which are defined in advance and tested in different variants and possibilities to prove the performance of the concept. All outcomes from master plan analysis, design-studio-based experiment, limitations of the sustainable eco-campus development plan are taken into consideration.

As long as this experiment focused on the university campus master plan as a case study, the design process covers many spatial elements such as street networks arrangement, parcels division and building extrusion. The area that is chosen for generation is currently empty and planned for future university campus extension which allows for non-directed applications. There is no exact intention that the final designs will respond exactly to all conditions, but multiple possibilities are presented for decision chances. While the experiment seems to be simple, several complexities of the system were experienced. As multiple experiments and applications were performed engaging an algorithmic system, subtraction approach, parametric approach and many more. The base geometry has been chosen to be simple with an aim of searching for multiple design possibilities.

Rather than involving the complex advanced systems of biology and nature, many researchers in the domain of design chose to study their components by isolating them from the general phenomena to gain insights into their specific problems (Frang and Casadeval, 2011). However, it is very difficult to understand either the complex dynamics of the systems or the failures happening during any design application. In addition to that many interactions and development influences of the parameters are still not technically explained. The evolutionary generation systems are not exclusive to specific fields studies; they can be used for different problem-solving in various design experiments. University campuses as complex organisms with several systems that develop and evolve show similar features in both interactions and expansion (expansion through new generation area or interaction between the old and new design). The design researches thus far have focused on separate steps of university campus design generation, however, a holistic generative design system with crossover interactions and association should be the central development and evolution concern of the design process.

The challenges are both posed on the interconnection of the system itself, which means the dynamics of the process which connect different components with different characteristics and different data lists. Besides that, the system has to represent the spatial requirements and design conditions digitally while trying to generate outputs in a wider range of alternatives and an unknown amount of time. In any university campus master plan design, the complexity of the process is treated as one block entity with very limited inputs and outputs to arrange all steps of generation and analysis. However, the generative design system focused more on the development of connectivity between the study context and computation tools by varying the number of data collection and analysis along with providing better outputs possibilities.

Grasshopper as several computational software in the design field is one of the parametric modeling tools that represent large functions into distinct components and establish relationships between them employing different geometry as a generation origin. What this research tries to clarify, is how to implement this tool in the university campus master plan design and generation. After data collection from different resources, an interpretation of the needed ones is executed in the appropriate projection as a first step of the process. Different files format and extensions are used according to the software requirements. Besides that, many other libraries and plugins are experienced to facilitate the transaction of data information to geometry which is generally integrated within Grasshopper software. For sure the use of only visual scripting in Grasshopper is not enough to solve all the mentioned problems, hence scripting using the C# component is involved to wider the generation possibilities (not included in the system explanation).

In the case of the university campus master plan generation, the involved input parameters are just a part of many other configurations that could be integrated. Several aspects which need intervention could bring challenges for designers during computational setup. Visual programming environments such as Grasshopper are a step by step components combinations that require a strong interconnection between all the parts to create particular forms and shapes. Using the same generative system proposed within this research to respond to different design problems will pose many challenges as it imposes interpretation of multiple related data and accurately integrates them as input parameters.

Some many systems and approaches could be involved in the formulation of this generative system. The exact methods and approaches of this system were turned in conjunction with previous university campus master plan growth characteristics using algorithmic system, evolutionary system and parametric approach to identify the irrelevant input parameters in terms of density, volume height and distribution. Additional techniques and tooling were engaged to improve and ensure the interconnection of the computational components.

Importantly the algorithmic system which is discussed in the previous chapters reflects better on space planning for how to interconnect the functional connectivity and responsive density of the master plan design and generation. It reduces the number of components needed for iteration and allows for better interaction of the design model on all parts of the design process. Besides that, it represents a higher degree of flexibility and processing and leads to the rapid integration of models. The system itself comprised a number of applications and assumptions that define the process, and that is what makes the specification of design problems and space requirements control the dependency of the generative design system. The designer might use an explicit computational description that stores the indices and values of the input parameters as well as provides appropriate data for the subsequent component to define the practices of the system. The different mechanisms of the system should be effectively combined and data needed for generation should be as little as possible.

4.2.1.1.Functional Connectivity

This stage of the generative design system's formulation aims to set a functional connectivity application as a part of the generation process by engaging a computational parametric approach and subdivision system principles. It tends to equilibrate street networks responding to all mobility types (Car/bus, bicycle, Pedestrian), determine a parcels division logic that responds to all spatial requirements and design conditions and then place the functional location of the main entrances for main parcels as well as buildings blocks. It is important to mention that the functional connectivity part is not studied in isolation with the other parts, however, the whole system is working as a block while generating design possibilities. Otherwise, many other factors could be involved in the study which are out of this research scope such as walkability, traffic studies and many more. The same system is applied engaging three different initial-grid patterns (Figure 4.17.).

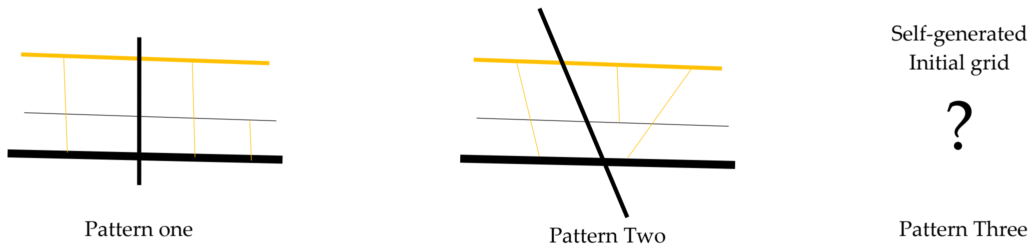


Figure 4.17. *Different Initial grid patterns for generation process. (Source: by the author).*

The street networks generation is occurred by engaging all the results gotten from the data collection phases. After defining the general boundary of the new extension (454 000 m2) aimed to be generated and the initial grid pattern, line segments intersections are computed by involving various parameters and manipulated starting from the general outline. They are computed according to the ratio between segment length and the generation area. Geometrically it is the total length of the networks relating to the area where networks are responding to the different movement types (e.g. vehicular, pedestrian). The analysis of the shortest paths to the points of interest within the closer area shows the variance of design proposals. Some other measurements are related to polylines calculation and the design objective (Min/max Length of the initial street). The bus/cars street networks result from the offline of main axes decomposition (blue dashed line), the bicycle streets are represented by the boundaries of the general block (orange continues line) where the pedestrian streets are formulated when parcels division is arranged (yellow hidden line) (Figure 4.18.). The manipulation of the parametric approach which is based on different parameters was beneficial in designing a structure for networks capable of generating a variety of functional connections for our generative system. Street network generation allowed to arrange the base of parcels divisions.

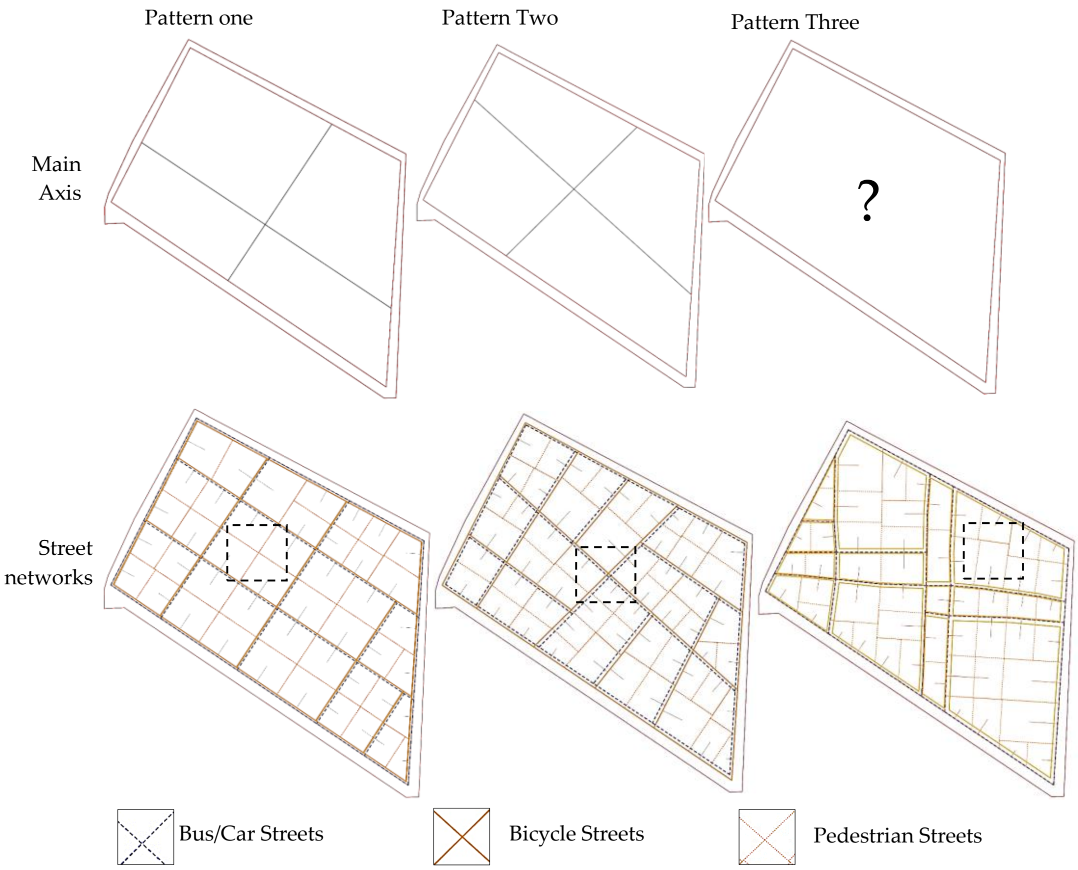


Figure 4.18. *Street network generation according to the initial grids. (Source: by the author).*

After generating the street network, the second step is to create the parcels division inside the networks. The size of each parcel depends on the input parameters and the origin pattern chosen for the computation (manipulation according to initial grid pattern). The design process allows for several divisions arrangements possibilities by using different parameters such as parcels area range, minimum parcel size and distance between two vertices. The location of each parcel on the generation area is structured in terms of its dimension and center point. Any segment belonging to a parcel will have a value indicating the intersection where the parcel itself will be represented with another value (in Grasshopper generally is set between 0 and 1). The parcels division logic is following the same main axis of the initial grid pattern in each application. In pattern one the division is linear following the same characteristics of the sustainable eco-campus development plan. In pattern two, more fitness is observed concerning sub-axis division which showed some different orientation results. However, pattern three does not engage any initial grid but is left to the decoding space plugin to generate a non-linear axis and sub axis, and this is what could be seen in the variety of final results. The application is respecting many geometrical properties of street networks such as length, segments and range of angels. This gave significant control throughout the process while generating street networks that respond to all types of movement employing subdivision system principles (Figure 4.19.).

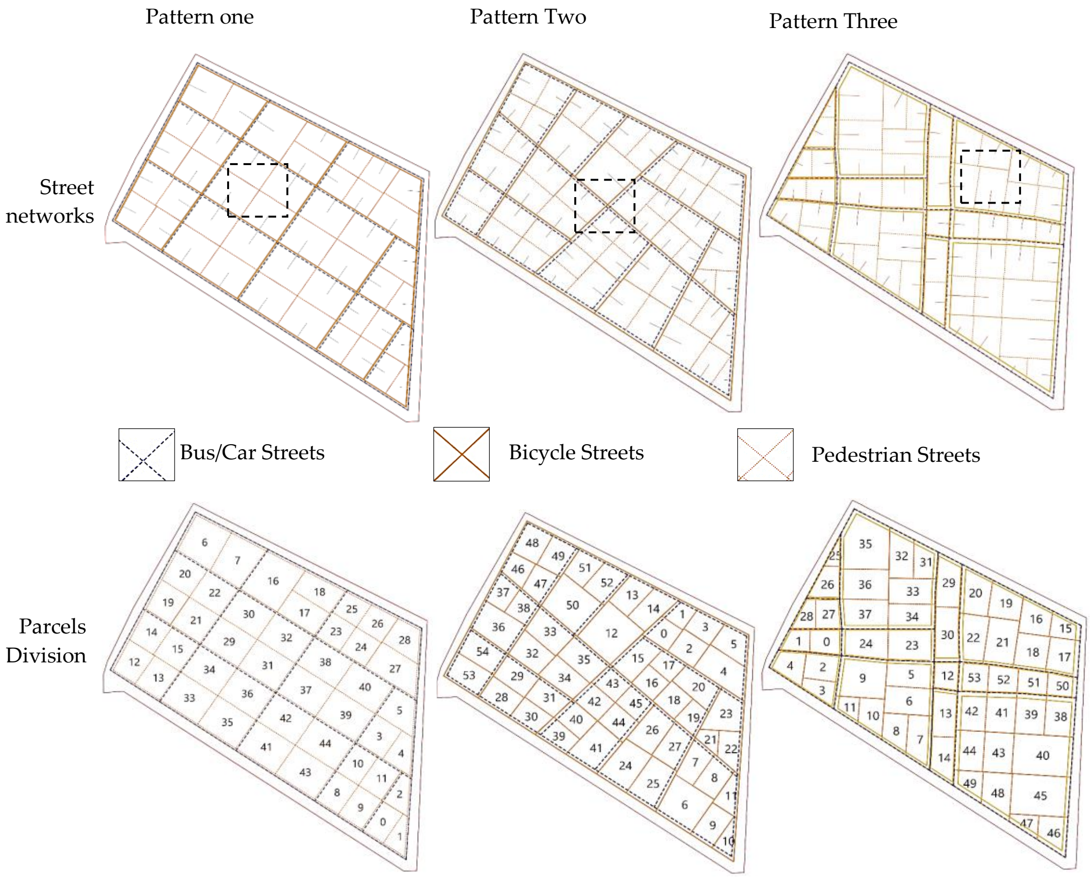


Figure 4.19. *Parcels division logic with colors differentiation. (Source: by the author).*

According to the data collection phase, one of the main design elements for sustainability is the functional link between campus buildings. Each building's main entrance is set to be linked to the nearby street network as well as other buildings on campus. Accordingly, the main entrances' functional locations are placed by calculating different distance values collected with data resulting from street networks and parcels division applications which represent the shortest distance between all segments in the street network (polyline deconstruction/ boundary). The application has been adjusted by calculating the distance between each of the parcel's center (PC) with all the other parcels centers. Besides that, the distance between the center for each parcel and the nearest pedestrian street network (NS) is calculated taking into consideration the main access of the university campus master plan and the generation area's characteristics. The data structure from the calculation allowed us to find the shortest path which is shown later by a polyline (Figure 4.20.). The most important input parameters in this calculation are the shortlist of street length and structured data of parcels width where they were pre-processed and prepared to be fed to other computation (see page 167).

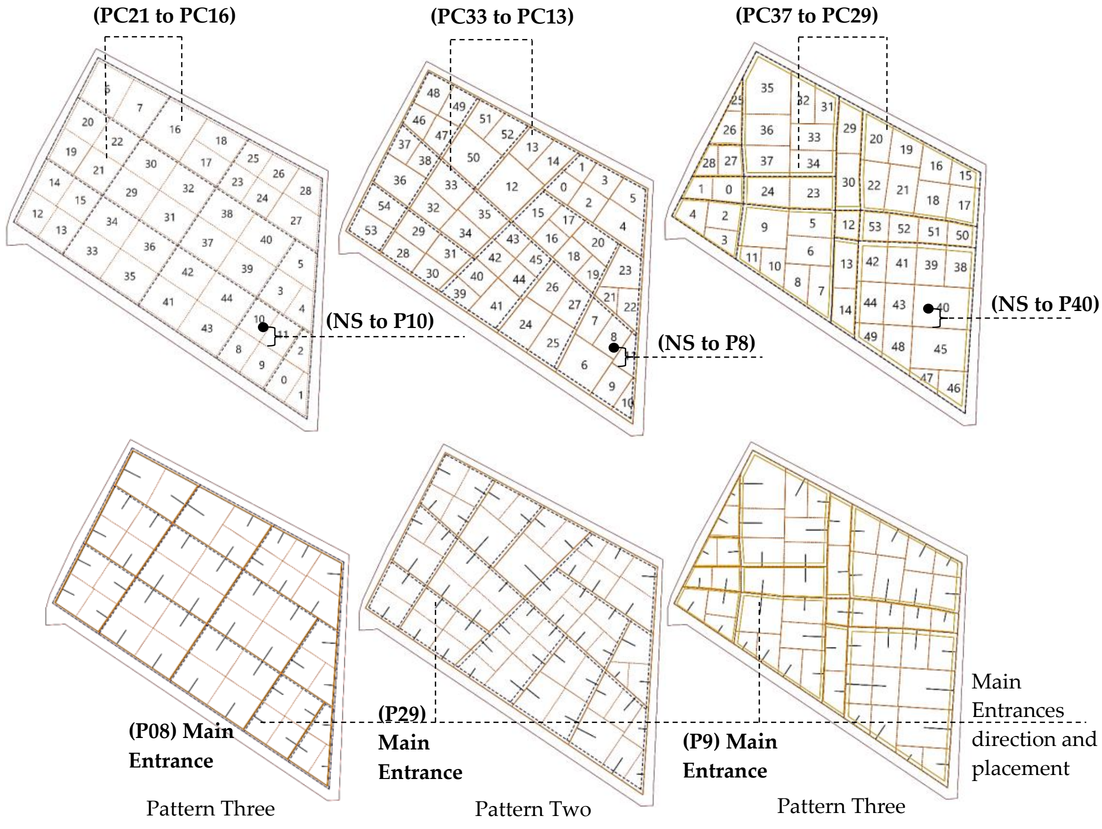


Figure 4.20. *Main entrance calculation and manipulation. (Source: by the author).*

The functional connectivity experiment has been tested for the two different street network patterns that use the initial grid as a reference, with another test which gives the chance to the system to predict a self-generated grid opened for many propositions but also resulted in challenges of design decision. The challenges are basically on the control generation behavior which requires a strong background in both mathematics and understanding of computation and one of the programming languages which is C# in our case (details about this application are out of the research scope and objectives). Other challenges are generally concerning the number of iteration (Decomposition repetition) required and the amount of computation time to reach the needed outcomes. However, once this parameter is implemented the system becomes faster and contributed to the whole process as it is presented within the next section of the research.

4.2.1.2.Responsive Density

In this section of the experiment responsive density is the main focus of the generative design system. This part allows for many elements such as density of land use, parcels division and university campus functions distribution to be implemented as input parameters to drive the process towards a variety of generation alternatives (Graphically presented in the subsequent sections). By employing data collected from the previous section, the Anemone plugin as a computational tool is used to respond to multiple design problems such as creating significant functions distribution responding to the context requirements, managing density of land-use according to open space proportion and building interconnection between parcels, street network and building footprint. The Anemone plugin is doing the same work as "for-loop" in real programming and gives the chance to perform several iterations according to multiple input parameters. Many applications such as recursive behavior, rectangles' subdivision and segments of the initial polygon are exerted by controlling the loops count during iterations (1 to 30). The analysis of different area distribution focused on the existing facilities and functions of the university campus. The functions vary between academic units, social units (+ open space), administrative units and technical units presented in different colors (Figure 4.21.). The relationship between the build and non-build is also taken into consideration as the main generation parameter. The support work performance of the application, focused mainly on built space and open space proportions, more sophisticated component is integrated to set the reference point of our generation and to decide how individual areas are developed through time (number of iterations/ loop). Many Statistics of the iteration and loop application such as values of built spaces (max 79.10 % / R 6.76 %) and values of open space (min 20.90 %) along with street network distance are provided as outcomes of the application.

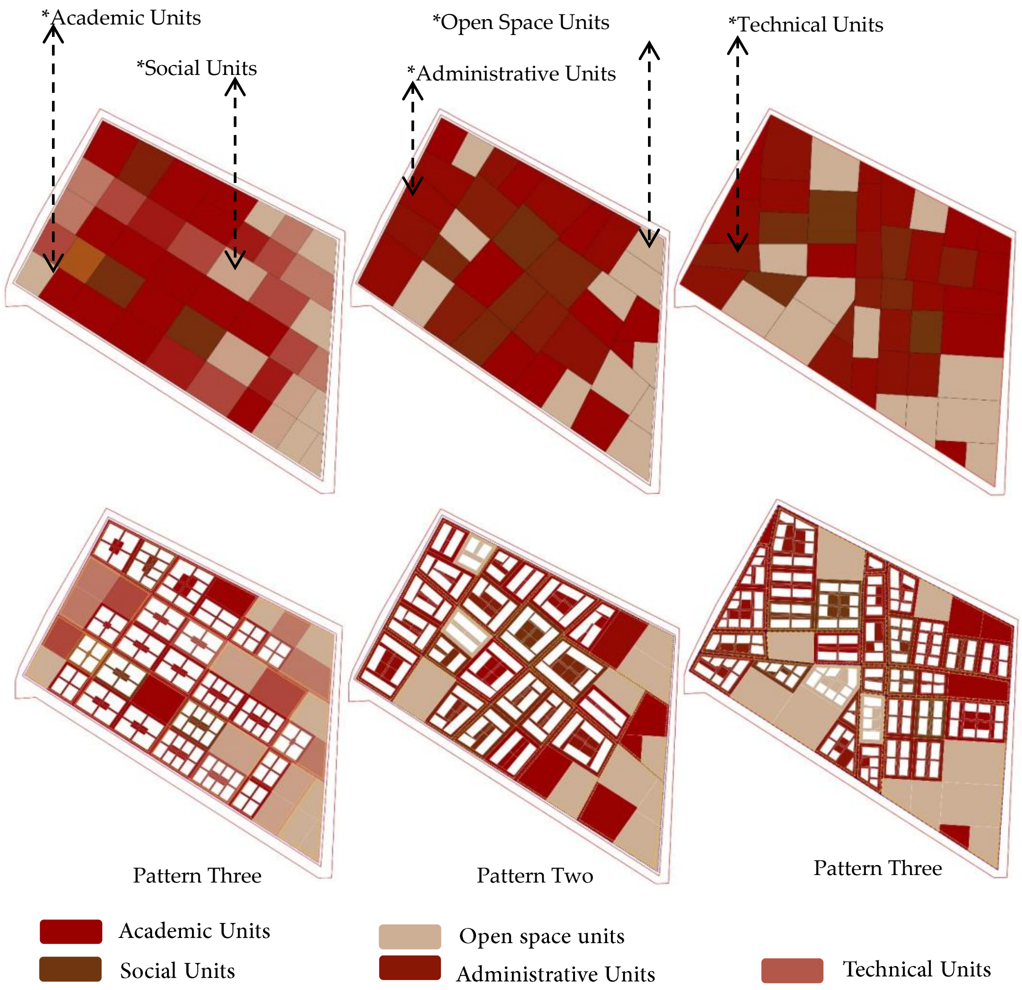


Figure 4.21. *Calculation of academic, social units, open space units, technical units, administrative units' ratio. (Source: by the author).*

Despite the parameters numbers and the genesis of the generation, the system is still using randomization to provide multiple design alternatives. The design strategy is to generate many propositions during fifteen different iterations which could be changed according to any other study objectives. Besides that, the value of maximum spatial density has been set relatively between 80% and 90% to represent the university campus master plan characteristics and to ensure the continuity of the same design pattern (future extension).

The next step is related to how parcels are distributed across generation areas. The process uses some different data given in previous parts of the research that respond to the design problems and context requirements. The distribution follows the genesis grid developed in Rhino and internalized in Grasshopper, where the main axis and sub-axis from a primitive pattern of generation, as well as other parcels division depend directly on the resulting geometries. So, the automation of the system is related to the inputted data. Each division is created by repeating the same pattern through calculation percentage of density which is varied from 20% to 25% as it results from the data collection section. When the parcel reaches the proportion a parametric division is performed creating a new search for parcels creation within the same design pattern. This is accomplished by repeating and randomizing the list of data where all generational options are evaluated and decided. The fitness function that defines the best solution is embedded within the generative system through the C# component (Appendix-6).

Changes in spatial density will have an impact on parcel division and street networks, as well as the building scale and shape of the final design pattern. The denser the area, the more street networks are connected, and the number of parcels increases. The more parcels there are, the more the building's features, such as the number of stories, footprint, and open space, will be influenced. After that, the generation area is fragmented into colored parcels following both patterns resulting from the data collection phases. More than that, the resulted parcels divisions are used to be the base of the building extrusion alternatives. Everything is linked to each other according to the requirements specified. Each one on the generation stage could be done alone or with connection to the other generations parts.

The geometry in the design process is often represented in arranging colored polygons, differing from smaller to larger. The intersection between these polygons form zones that represent parcels and buildings footprints. The lines lie alongside the parcels division are forming the street networks. The responsive density and functional connectivity are 2D generated patterns, characteristics such as ground space index, floor area ratio and open space ratio are taken in the designs' generation. The two first generative design system parts, responsive density and functional connectivity determine the parcels division and buildings footprints (Figure 4.22.), only the variation of block distributions and buildings height are provided within the last system part. The input parameters were chosen according to the analysis outcomes. During responsive density application, interconnection of network segments needs to be considered to reach better results and allow to control block sizes later on which focus on covering as much as possible the area provided for generation and building an interconnection between parcels, street networks and building mass.

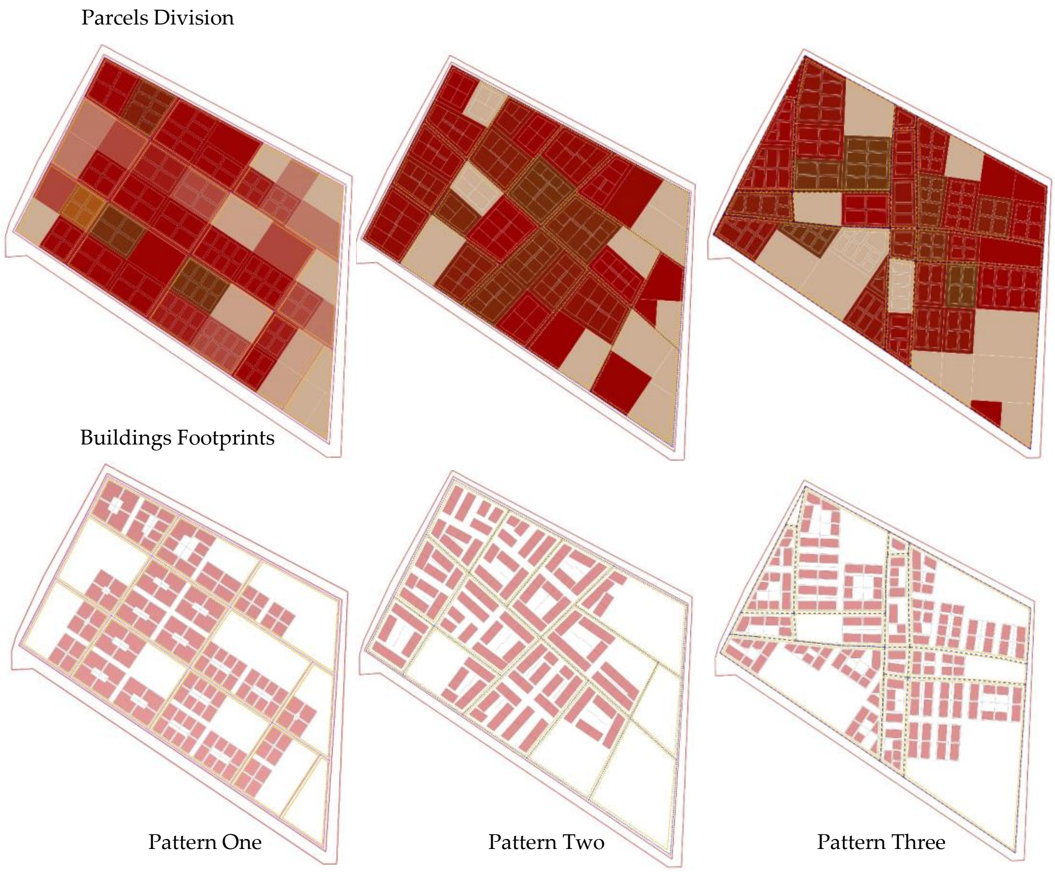


Figure 4.22. *2D generated patterns, characteristics such as ground space index, floor area ratio and open space ration. (Source: by the author).*

4.2.1.3.Design Pattern

In this section of the research, the generative design system tends to engage different buildings typologies to generate blocks based on data structure and results from previous phases. The step after parcels division and function distribution is the generation of building footprints which will be the base of the volume extrusion (simplified forms). The dimensions of each building block and its relation with the general parcel are calculated and defined inside a geometry cluster that contains a collection of functions in Grasshopper components. The main difference occurs in blocks height and design patterns characteristics such as built- non-built and open space proportion. These parameters play a key role in the decision of block genesis. The application focused more on buildings generation while preserving the characteristics of the main campus patterns and making buildings clustered together respecting the build and open space areas. Besides that, providing buildings' relations concerning volume height is taken into account. The resulting design patterns' simplification of the university campus buildings is chosen to be the main input parameter of the generation (Figure 4.23.).

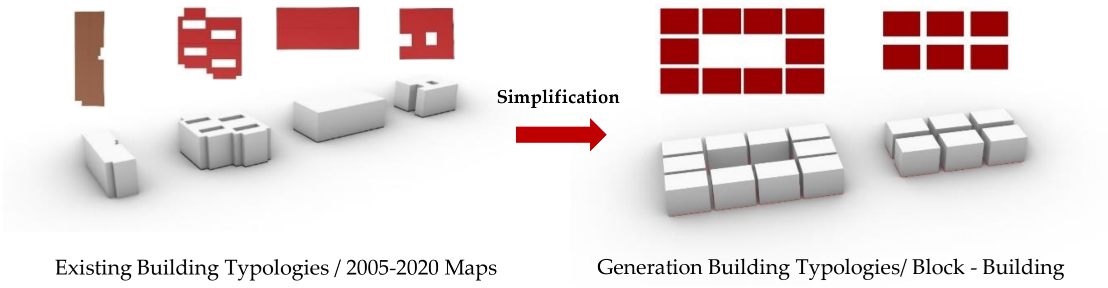


Figure 4.23. *Simplification of the main campus patterns characteristics. (Source: by the author).*

Using the Decoding space plugin as a key component allowed us to control the general characteristics of each block such as deciding the footprint size, volume height (0.47 <FAR), buildable area and built/ non-built proportion. As long as the functional connectivity is performed based on a parametric approach, each building has its height which determines the general block height when all the buildings' heights are summed up. During each iteration, the design results change. Many illustrations of the generative design process are provided according to some specific criteria. The first step is to collect data from previous steps of the generation system. The second step is to generate an initial population which will later be evolved and varied responding to the input parameters provided by the author. The process is repeated till the needed results are reached and design problems are responded to. The number of parameters involved within the definitions in Grasshopper is representing the extent, center of each parcel alternatives. All of the used components have a direct impact on the final outcome of the building volume and location.

More often, the resulting blocks are arranged based on the proposed responsive density and plan grids. The spacing between buildings and blocks represents the street networks' properties such as length and width. All these parameters can be changed and manipulated according to the desired characteristics of the design (building typology, built/open space, density and space index) (Figure 4.24.).

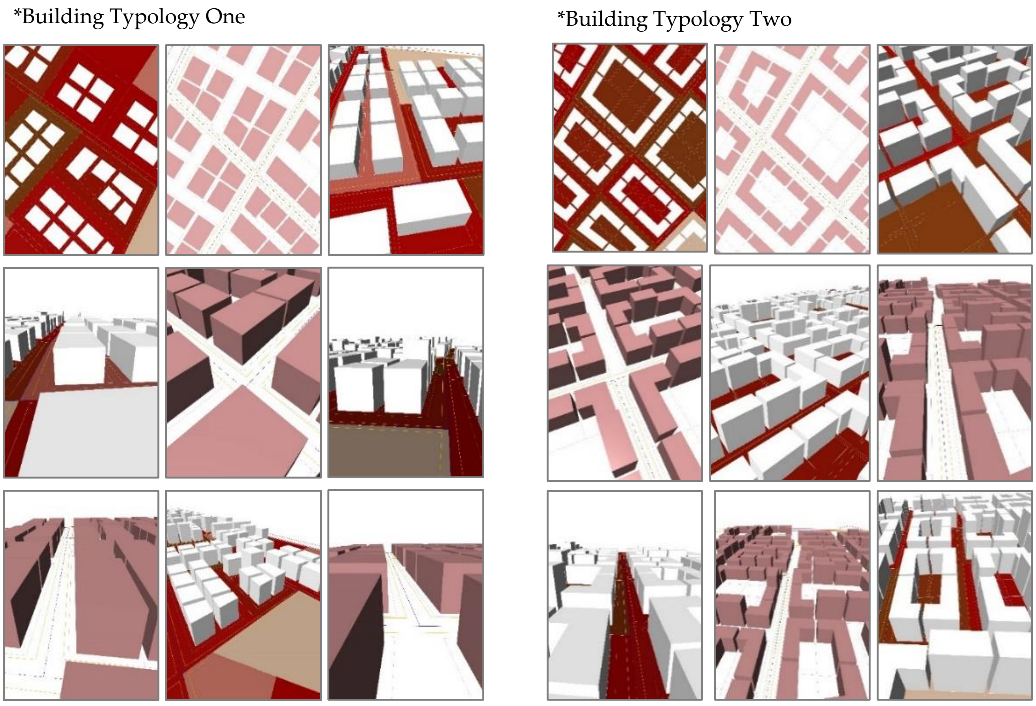


Figure 4.24. *Representation of the building typology, built/open space, density and space index. (Source: by the author).*

The main parameters used to control the calculation are the spatial density and open space proportion which is valued between 20% and 25 % and visualized at the end of generation by different colors to distinguish between functions. The campus itself contains too many open spaces in-between buildings which affect the perception of a general scale. The master plan with the blocks patterns and central courtyard gives spatial design characteristics that will be interesting for generation and analysis. It can get more attractive for future expansion if different possibilities are performed taking into consideration all the requirements and conditions specified within the early design beginning.

The generative model is very efficient in varying the generation of the buildings extrusion from just previous parts resulting in data. It is computationally processing the requirements using different visual representations. within this part of the system is the height range which uses responsive density parcels division as a building footprint. One of the advantages of the system was the applicability of the process in generating various design possibilities of the buildings' height respecting the university campus design pattern. The system required a collection of data and decision-making for each parameter intending to reach an appropriate result within less computation time. The main challenge is the data structure and the decision of values during parameters input. Hence, this is what restricts the flexibility of design outcomes. As long as the value is changed from the optimal one the relation between buildings height and the generated parcels start to be uncontrolled. The system would require more intervention of the designer by setting multiple programming components such as C# or Python to make the generation more homogenous and all the relations between the system parts coherent and integrated. The next chapter will give more details about the application and optimization of the results according to the design patterns resulting from previous phases of data collection.

4.2.2. Algorithmic Model Representation (Rhino/GH)

The following part of the research describes the step-by-step process followed to perform a generative design system within the platform Grasshopper inside Rhino software. The design entails a generative system for ESTU university campus master plan in Eskisehir intending to optimize the design pattern possibilities for new area expansion and design pattern generation.

The logic of many platforms such as Rhino or Revit -which have specific task limitations is based on scripting practice that gives the ability for designers to create and redefine tools and components for particular applications and allow interconnection with solution-based plugins to solve problems and overcome constraints presented in every studied design context.

After defining the scope and limitation of the research, an algorithmic model was prepared to simulate all the parts of the generative design system. The model is based on visual scripting that may be represented in long definitions and several components. This made the manipulation and control of all the processes difficult and time-consuming. Therefore, many of those components are grouped under clusters with names to facilitate intervention (size, heights and depth). The modeling process depended on several steps. First, a digital file of the generation area and different design pattern maps was designed from scratch and imported to Grasshopper using the geometry component. With the help of many other components, the needed data could be extracted very easily. After that; functional connectivity, responsive density, and design pattern application were performed with the help of other sophisticated plugins. As all the data required were available from previous parts of the research, they were inputted based on the extracted data by the three experiment trials (Three patterns). Although the system will not lead to a complete and perfect design process, the results showed interesting mechanisms and patterns that could be improved in future studies.

The algorithmic model is a significant structure that went through many iterations to define the interconnection between the three system parts (functional connectivity, responsive density, and design pattern) by engaging several components and combining transmission between them. A large number of input parameters have to be redefined and engaged within the process to conduct more flexible actions. This makes the definition of the system inside Grasshopper canvas more complex and lets the designer intuitively face difficulties in managing components interaction.

The generative design system takes the design characteristics of the university campus master plan as input parameters during the three experiments trials. The input parameters can be inserted based on different design problems and spatial requirements such as length of the street network, number of parcels and buildings height. The interconnection of all generation steps in the Grasshopper model allows to perform generic applications and apply the same system on different patterns which respond to the research objectives (Figure 4.26.). The combined generative design system in Grasshopper definition consists of three main Parts:

a) Definition for functional connectivity to equilibrate street networks responding to all mobility types (Car/bus, bicycle, Pedestrian), determine a parcels division logic that responds to all spatial requirements and design conditions and then place the functional location of the main entrances for main parcels as well as buildings blocks.
b) Definition for responsive density with input parameters to create significant functions distribution responding to the context requirements, manage the density of land-use according to open space proportion and build an interconnection between parcels, street network and buildings footprint.
c) Definition for design pattern focused more on buildings generation while preserving the characteristics of the main campus patterns and making buildings clustered together respecting the build and non-built areas. Besides that, providing buildings' relations concerning volume height is taken into account.

The main objective is to design a system that could combine the parts and engage computational capacities to seek better possibilities and alternatives. The generative design system setup consists of many steps which are mainly summarized as the following:

Step 1: Divide the generation area by main axes and sub-axes (Two first patterns)

Step 2: Generate parcels according to the division logic (calculation of street networks)

Step 5: Calculate main entrances locations and distances (For main blocks)

Step 6: Interconnect parcels with street networks arrangement (2D data of the system)

Step 3: Divide parcels into buildings footprints according to open space proportion

Step 4: Loop feedback for function density inside parcels (Colors and placement)

Step 7: Integrate design pattern into building generation (Building typologies)

Step 8: Generate building heights according to input parameters (FAR and OSR)

Step 9: Provide each part of the generation with the needed visualization (graphs and diagrams)

Step10: Save needed results and collect data for evaluation and final decision (30 generations).

Many designers see Grasshopper as user-friendly due to its geometric visual programming capabilities for applying parametric modeling. For generative design modeling, the available components employ a programming language. It does not have visual capabilities, but it allows for functional modification through the use of scripts. Rhino/Grasshopper is a great tool for design exploration throughout the diagrammatical design phase due to its refined area interpretation and dimensional visual programming capability (Figure 4.25.).

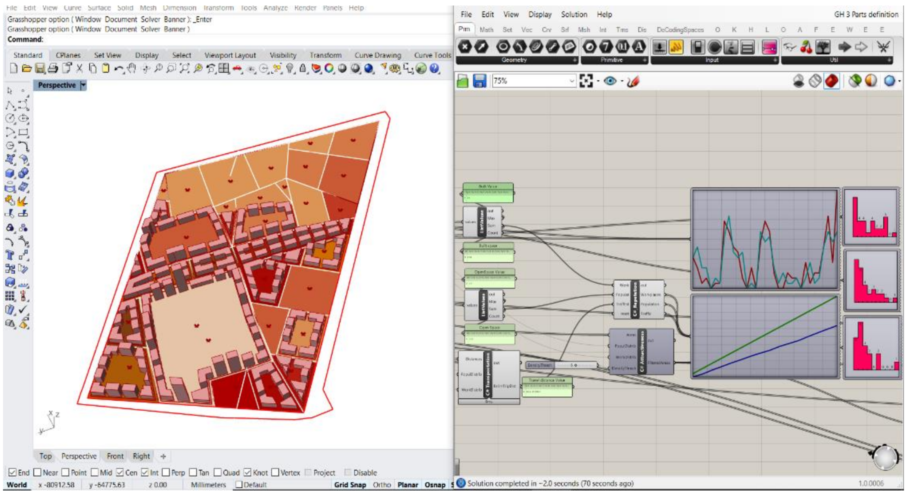
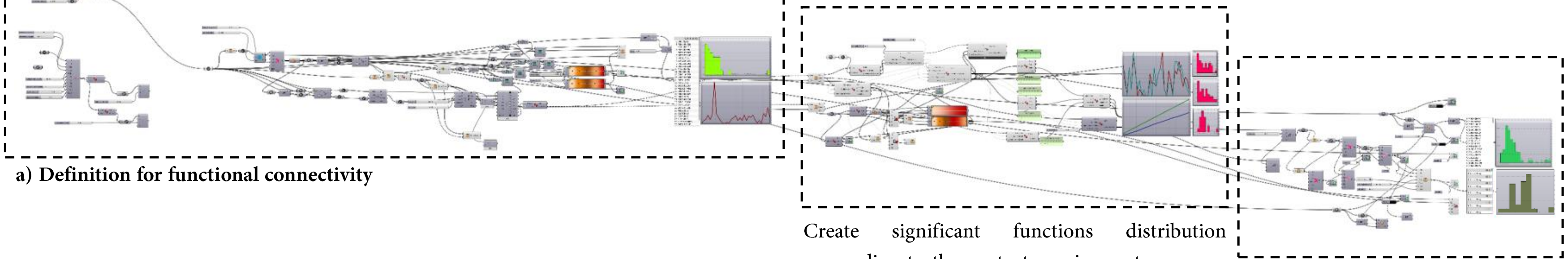


Figure 4.25. *The canvas of GH inside rhino. (Source: by the author).*

Equilibrate street networks responding to all mobility types (Car/bus, bicycle, Pedestrian), determine a parcels division logic that responds to all spatial requirements and design conditions and then place the functional location of the main entrances for main parcels as well as buildings blocks.

Buildings generation while preserving the characteristics of the main campus patterns and making buildings clustered together respecting the build and non-built areas. Besides that, providing buildings' relations concerning volume height is taken into account.

b) Definition for responsive density



a) Definition for functional connectivity

Create significant functions distribution responding to the context requirements, manage the density of land-use according to open space proportion and build an interconnection between parcels, street network and building footprint.

c) Definition for design pattern

Figure 4.26. *The interconnection of the three definition developed for the generative design system. (Source: by the author).*

To simplify the combined generative design system, the algorithmic model was created with three parts; the first part represents functional connectivity by computing the location of main entrances, parcels division logic and their relations with street networks, the second part focused on the responsive density and functions distribution within generation area, and the third part generated different design patterns of the buildings and their clusters according to the previous parts in which each part could be modified responding to the experiment trails. An efficient interconnection of the algorithmic model enabled for fast generation and instant results interpretation in any stage of the generation so that the impact of each specific data input could be tested and compared for both 2D (responsive density, functional connectivity) and 3D (design pattern) scale.

The visual programming definition contains input geometry which is based on different generative systems and approaches (explained in the previous chapters, see page 57). The generation is done according to all recommendations and requirements gotten from experiments explained in phases one and two of the site analysis (see page 148). To carry out the investigation, the researcher employed the Decoding Spaces, Anemone plugins in Grasshopper as a computational tool. And numerous scripts were used within complex components to explore new possibilities.

4.2.2.1. Computational Definition for Functional Connectivity

Based on the three design patterns, functional connectivity tends to provide an associated parcels division and blocks footprints in with the buildings' characteristics. Where the design pattern has aimed to involve the different characteristics of the university campus buildings in the generation process while seeking various results propositions. All the parts are interconnected so that any manipulation in one of them will be reflected on the other (Figure 4.27.). The functional connectivity input parameters setup consists of many steps which are mainly summarized as the following:

A. Set the general borders and genesis grid that specify the main axis and sub-axis of the generation area. This does not limit the system to search for as many as alternatives possible.
B. Process street network by exploding curve into smaller segments and dividing multiple curves at their intersections. The generation is happened from the outer boundaries to the inner grid axes and is redefined for each design pattern.

Create a set and series of numbers to measure the length of the main street networks. This helps the process to optimize the generation of possibilities responding to the input parameters in each process stage.

C. Create parcels division and blocks to set the shortest path calculation by solving a network of lines and merging nearby vertices. Split curves at their intersection and convert them into segments to use them as input and generate parcels inside street blocks (Decoding Space Components).
D. Transfer curve to line, sort parcel to the closest street segment and find the nearest point on the curve. Compute curve with the closest point and sort all resulted in data as a list. Create a line between two points to formulate a new branch with the specified path and then add a specific value to a specific path in the data tree.
E. Use a data list from components and collect shattered curves to set the main entrance of each building in the area. Set size of parcels and number of divisions (x*y), Offset a curve with a specific distance and compute the distance between all the points and iterate through the path (List N).
F. Final data visualization and representation using different graphs and diagrams to facilitate evaluation and final decision such as parcels size values (min/max), Density values (built and open space), built area values and gross floor area.
G. Mange input parameters: Street Length (min/max), Distance to next street, Division orientation, Street depth, Seed number for calculation, Distance between vertices, Parcels width (min), Block size (Min)

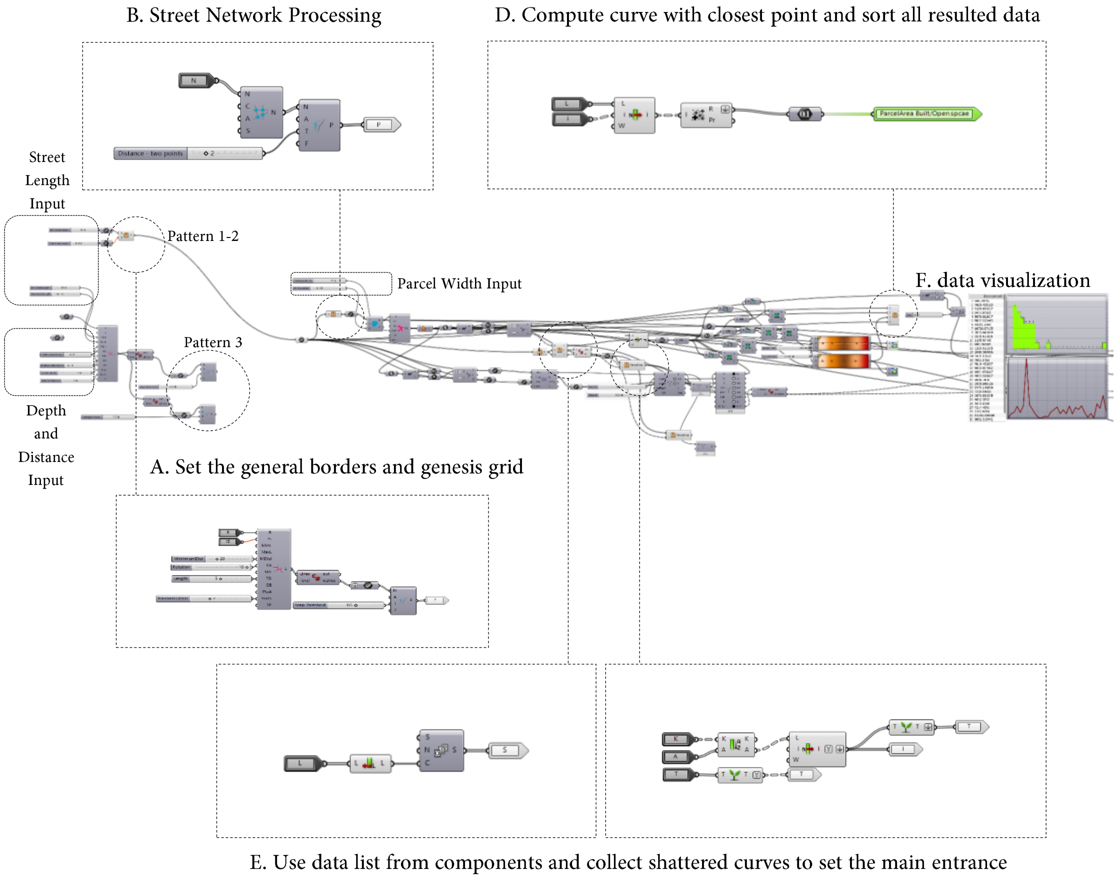


Figure 4.27. *Computational definition for functional connectivity. (Source: by the author).*

4.2.2.2. Computational Definition for Responsive Density

Responsive density is in control of the distribution of different functions according to the provided values and requirements from the data collection phases. The generative definition performed for this part of the study is based on different computational tools provided by Grasshopper but mainly the Anemone plugin with all its components. However, it is not enough to reach different possibilities just by using those components, because those different scripts are used within C# components (Figure 4.28.).

Some components are managed under cluster to avoid any distraction during parameters manipulation. The most important component and elements for responsive density in Grasshopper definition and script are shown as the following:

H. Extract and compute data from (C) and (D) and then iterate them by Anemone plugin with all its components: fast loop start /end, loop start/end. The specification of the initial point as a reference for generation is crucial for the function distribution. The proportion of built space and open space is set with several input parameters.
I. Calculate several statistics based on the outcomes from the iteration and loop application such as built and open space values, transport distance computation.
J. Visualize different functions distribution by collecting data from Anemone plugin outputs to number components. specify max and min value and create planar surfaces from the collection of boundaries edge curves using boundary surface components. Custom preview materials and Gradient are used for representation.
K. Calculate spatial density to be able to systematically search among all the generation area zones to test if the surface could support any more spatial division or function arrangement (C#).
L. Visualize final outputs using the same color gradient that represent the function distribution of the university campus master plan (Academic units, Social units, Open space units, Administrative units, Technical units). Representation using different graphs and diagrams to facilitate evaluation and final decision.
M. Manage input parameters: Shortest path collection, Growth time (number of iteration), Density value (Location variance), Distance of data tree values, Reference point location (PN attractiveness).

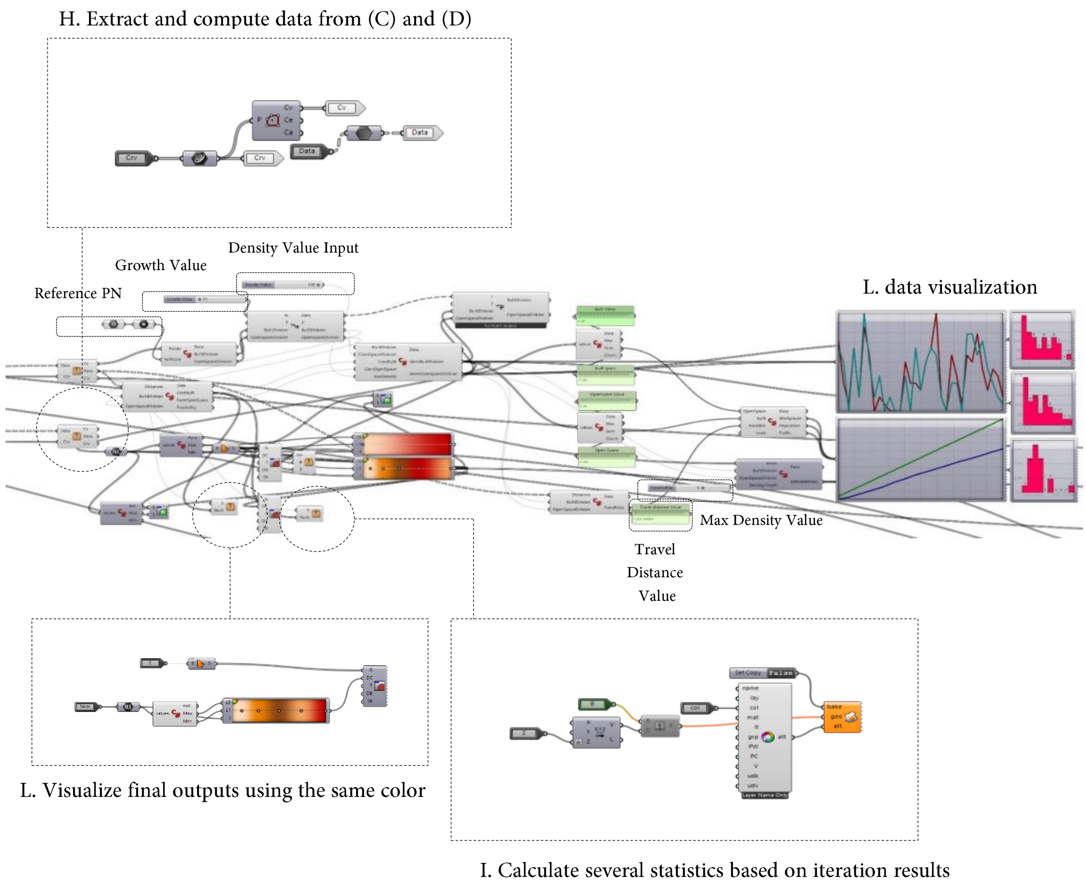


Figure 4.28. *Computational Definition for Responsive Density. (Source: by the author).*

4.2.2.3. Computational Definition for Design Pattern

The two first design pattern experiments are not deterministic in their generation process; a predefined genesis grid is provided to allow the system to seek multiple outcomes. The outcomes seem to be simple, however, several lists of data are arranged and matched by Grasshopper components to allow for intermediary applications to be processed during growth simulation. This serves the interconnection of the generative design system parts and the interpretation of data into geometrical forms, along with testing the capacity of the computational process characteristics at a specific period.

The design pattern part of the generative design system has several opportunities to visualize data output by extruding the resulted footprints according to the buildings' heights for each design pattern. Many existing Grasshopper components are engaged to specify the volume characteristics and display them in different forms:

N. Set building footprint value according to the spatial density (min/max) and data collected from both parts one and two which contains a collection of generic values (C) and (G) (C#).
O. Generate parcels division with a specified parcel density and convert the collection of generic values into geometry than to polyline to ease manipulation.
P. Explode curve to small segments and smooth network of lines by merging near vertices. Split curves at their intersection and convert them to line segments and take line segments as inputs and identify closed polygons to form the footprint boundaries.
Q. Collect all generics to generate parcels inside street blocks. Convert resulted data to curve to be able to process them to generate buildable areas on a parcel (Decoding space plugin)
R. After Collecting buildings' footprints and setting them in a boundary component, extrude the building within a predefined buildable by assigning building depth (parcels density) building typology (Buildings typology = 1/2/3 value list) and FAR values (heights). Buildings height set by collecting data into unit Z component.
S. Visualize outcomes by connecting (Q to R) inside an extruded curve or surfaces along a vector and previewing them (visualization) with the use of swatch and preview components.
T. Manage input parameters: Density threshold, Footprint values, Distance from the street, Buildable area value (in parcel), Buildings footprints values, Design pattern type.

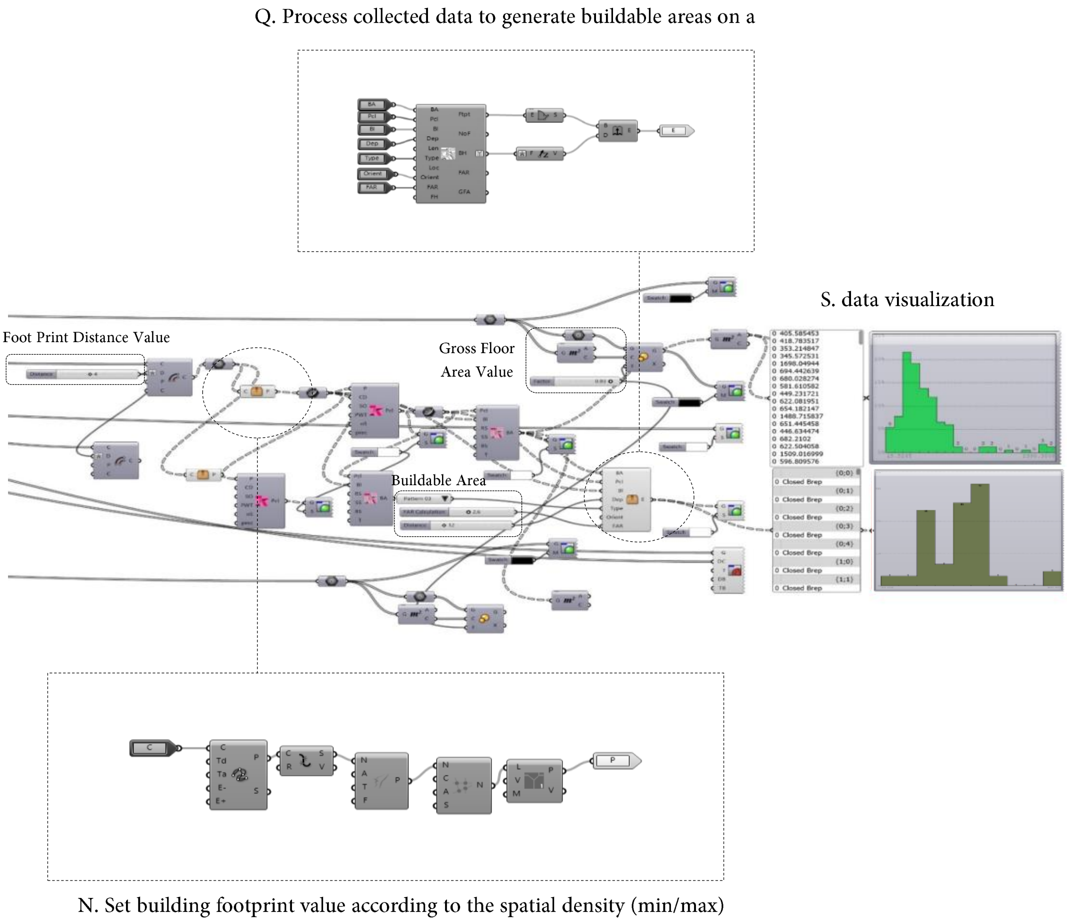


Figure 4.29. *Computational definition for design pattern. (Source: by the author).*

Many libraries inside Grasshopper are used to efficiently control the generative system. For the scope of this research, many display graphs and diagrams have been formed to instantly show the details of the generated results on the working screen. While using Rhino/Grasshopper many procedures are requiring scripts to be conducted through components to avoid recursion and repetition of the process. To maintain more flexibility and automation during the design generation many components with their complex logic helps to accommodate a fast calculation and make crucial decisions to reach a variety of outputs and interoperate between different types of data such as geometrical and mathematical ones (Appendix-6).

The addressed components involved in the system are not the only way of representing the generation process stages of the algorithmic model representation, just one of many methods that could make the system applicable and affordable for architects and designers to reach outcomes to a specific extent. The anemone plugin with all its components provides a means of algorithmic system application explicitly. Similarly, the decoding space component provides a means of the evolutionary design system and parametric approach more simply and practically. All of these components are interconnected with fundamental other components in Grasshopper canvas to create an abbreviation of numerical data that reflects the main design problems and context requirements with different generative approaches and techniques.

The generative design system refers to the combined applications between the different steps of the process through the loops feedbacks during every evolved iteration. In addition to that each step's results are interconnected with the others steps to form a responsive final design proposition. For sure each part of the system makes decisions based on the provided input parameters, however, outcomes are controlled with the overall process and the interaction types.

The Grasshopper script is applicable for all experiment trials that have different patterns according to their input parameters and data manipulation. The variances from simple parcels division logic to an evolutionary generation of the street network, and from basic buildings footprints to irregular blocks cluster are related separately to the modification of the design pattern in the early initial-grid selection. More complex and revolutionary propositions could be reached if the generative design system is supported by several scripting applications. For an architect to deeply understand these approaches and integrate them freely within the computational process, a strong background in both mathematics and programming languages will be needed. As far as this experiment tends to combine different variations to test the system, still many other explorations could be mathematically abstracted to simplify the interconnection between all the parts of the system.

As with many generative design systems and approaches discussed in the previous chapters, the main concern here is not found in just a particular component or its application, but rather in the formulation of a computational interconnection between various components so that they are adaptable and flexible to a specific case study. Many other sets of approaches and techniques could be applicable to represent and develop the entire generative system to integrate a comprehensive algorithmic model of a university campus master plan generation that solves the specified problems.

4.2.3 Optimization of the Generative System Application

During the early stage of the generative design system formulation, several generations are examined focusing on their efficiency and performance responding to different requirements and conditions of the defined concept (studio-based experiment, master plan expansion analysis, spatial requirements and computational limitations). Clustering data into different files formats is only the beginning of the process. After that, more challenging steps are lied on the re-arrangement of these data into a combined process that responds to the design problems. Moreover, different representations of the results are performed within tables and graphics for comparison and evaluation.

The design of the university campus master plan involves different design patterns and seeking a new composition that responds to the general research problems. This could be done by integrating the data collection results through the generative system and engaging multiple applications such as recursive and iteration forming a collective campus tissue. Through this experiment, the focus was on testing the algorithmic process for a more flexible and non-refined system of a generation that could assist with the challenges faced in applying the methods and approaches. The algorithmic model is initially developed by extracting data from the main gird-based division and involving them in the subsequent components such as lines and polygons that represent street networks and parcels division. The lines are then divided again according to the density input parameters defined to represent the new distribution of the area.

The main focus was established on the interconnection of the three university campus master plan elements in generating design possibilities. The context is defined within a particular generation area that relates to the outcomes of the data collection phases one functional connectivity, responsive density, and design pattern. The experiment focuses on three grid-based trails; the first is the generation process based on the ‘Pattern One’ that represents the linear grid of the area, main division axes and subdivision access that are resulted from the 2005 and 2020 university maps’ analysis. The second scenario focuses on ‘Pattern Two’ that is based on a non-linear generation area-grid with both main and sub axes. The third scenario “Pattern Three” is an evolutionary process without any grid genesis specified concerning the generation area. It has given the autonomy to generate any type of grid according to the computational capacities provided by the Decoding space plugin. It has varied responsive density calculations, including the parcels divisions and the footprints of the buildings blocks. The focus is also to manage the process through feedbacks loops while performing the development of the system. The resulted buildings' morphologies are not restricted to a particular pattern or spatial density type.

For each design pattern 10 generations were performed (A total of 30 generations) with manipulation of different input parameters such as parcels area range, density ratio, open space ratio, built area ratio and many more. In each generation, the generative design system likely could not be controlled without a key data redefinition that would drive the system toward an interpretation which makes the intervention of the designer crucial in almost every step of the application. The presented design variation becomes more valuable when it is generated by maintaining the interconnection of the system parts with a negotiation between design problems and context requirements for each particular design pattern.

4.2.3.1. Pattern One Generation

The first experiment trail using pattern one is a simple generation with a parcel size between min 483.52 and max 2984.32 m2 and a maximum building height of 17 m and travel distance of max 63.37 m. Some other details of the input parameters are provided as presented in Table (4.5.). This part of the experiment aimed to seek design possibilities of the university campus expansion through generation and evolution according to the planning grid resulting from data collection part "Pattern One". The main goal of engaging a simple genesis grid as a first model variant is to investigate the whole system. After that, the observed effects and issues could be reinstated to be engaged in more complex generation grid patterns.

Both elements are the main inputs of the responsive density that describe how the parcels were divided and how the whole system reacted based on street networks and building interconnection.

Table 4.5. *Input data for generative system pattern one. (Source: by the author).*

Data Input	Input value	Max value (ESTU)
Parcels area range	50	100 GH
Density Ratio	4	< 6.76 %
Open Space ratio	30	>20.90 %
Built area ratio	70	79.10 %
Distance between two vertices	0.9	0.9
Minimum parcel size	400 GH	<
Footprint Distance	10 GH	<
Building footprints factor	12 GH	<
Building length	50 GH	<
FAR	0.87	(0.8)
OSR	>	(0.36)
GSI	>	(0.25)

The final generation results vary with a major difference in each process iteration. The generation of the buildings also responds to the interconnection of all the system parts such as spatial density, parcel divisions and patterns of the initial grid (Figure 4.30.). The alterations come through their computational evolution and calculation. In most cases, there are restrictions with the input parameters that could be changed and manipulated according to the research problem that is intended to be solved.

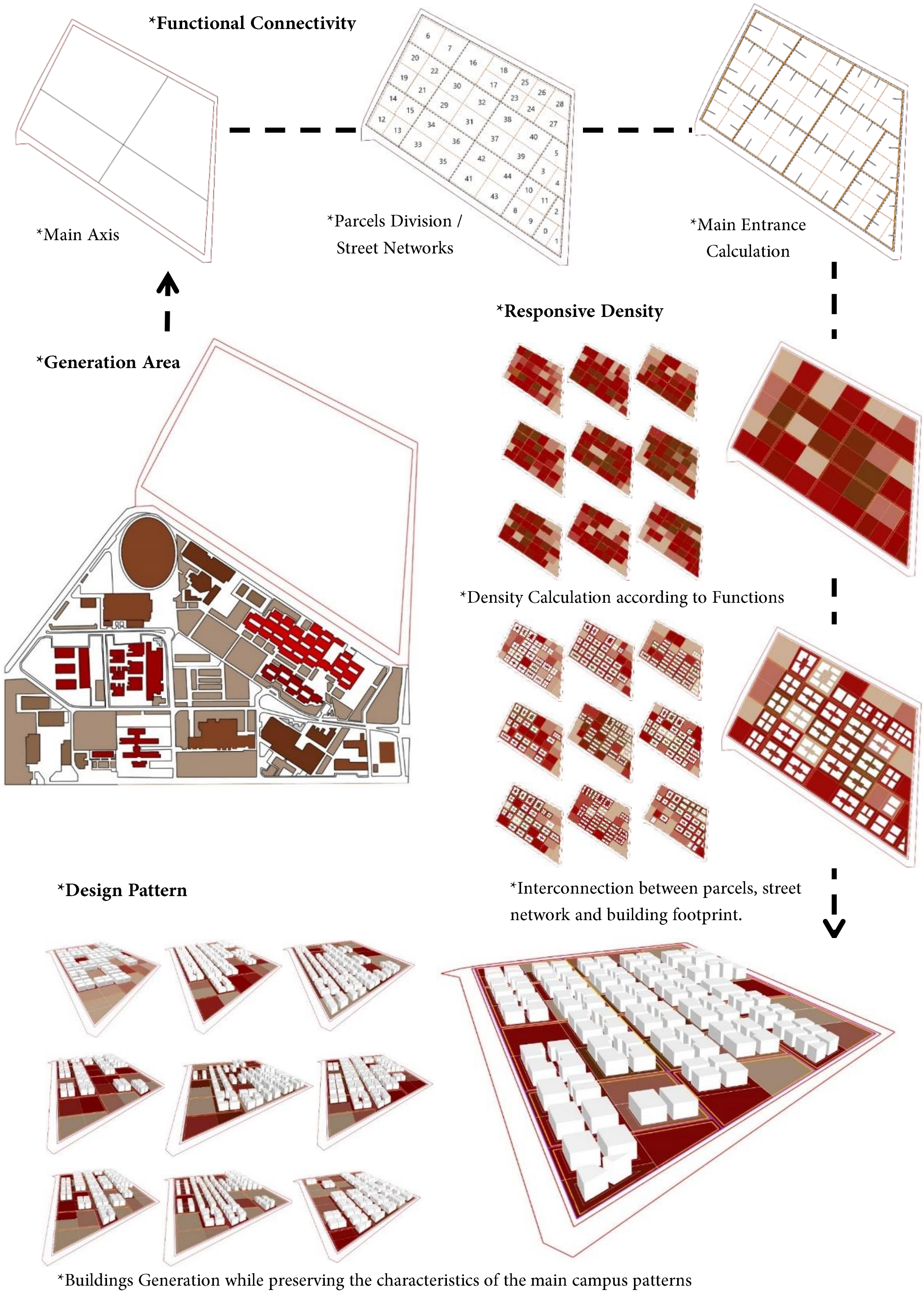


Figure 4.30. *Generative system pattern one optimization results. (Source: by the author).*

4.2.3.2. Pattern Two Generation

To seek different university campus master plan design possibilities referring to the planning grid resulting from data collection part "Pattern Two", the second pattern application resulted in different parcels sizes ranging from min 362.17 to max 2435.54 m2 with a building height of 24 m and travel distance of max 58.67 m. It should be mentioned that the number of total generations as long as input parameters showing the number of iteration needed for the study have to be appropriately decided and entered while setting the system towards research objectives (10 generations for this study) (Figure 4.31.).

The main role of genesis geometry is to behave as a basic input parameter more than a key element of generative process application. This is to confirm that, it depends on the provided interconnection between all the system parts to respond to the design intent and multiple details of the university campus master plan. These interconnections between the different components are illustrated across the algorithmic model engaged for this research. The exact details of the input parameters engaged in this generation are presented in Table (4.6.).

Table 4.6. *Input data for generative system pattern two. (Source: by the author).*

Data Input	Input value	Max value (ESTU)
Parcels area range	60	120 GH
Density Ratio	5	< 6.76 %
Open Space ratio	28 %	> 20.90 %
Built area ratio	72%	79.10 %
Distance between two vertices	0.8	0.9
Minimum parcel size	200 GH	<
Footprint Distance	8 GH	<
Building footprints factor	16 GH	<
Building length	55 GH	<
FAR	0.85	(0.8)
OSR	>	(0.36)
GSI	>	(0.25)

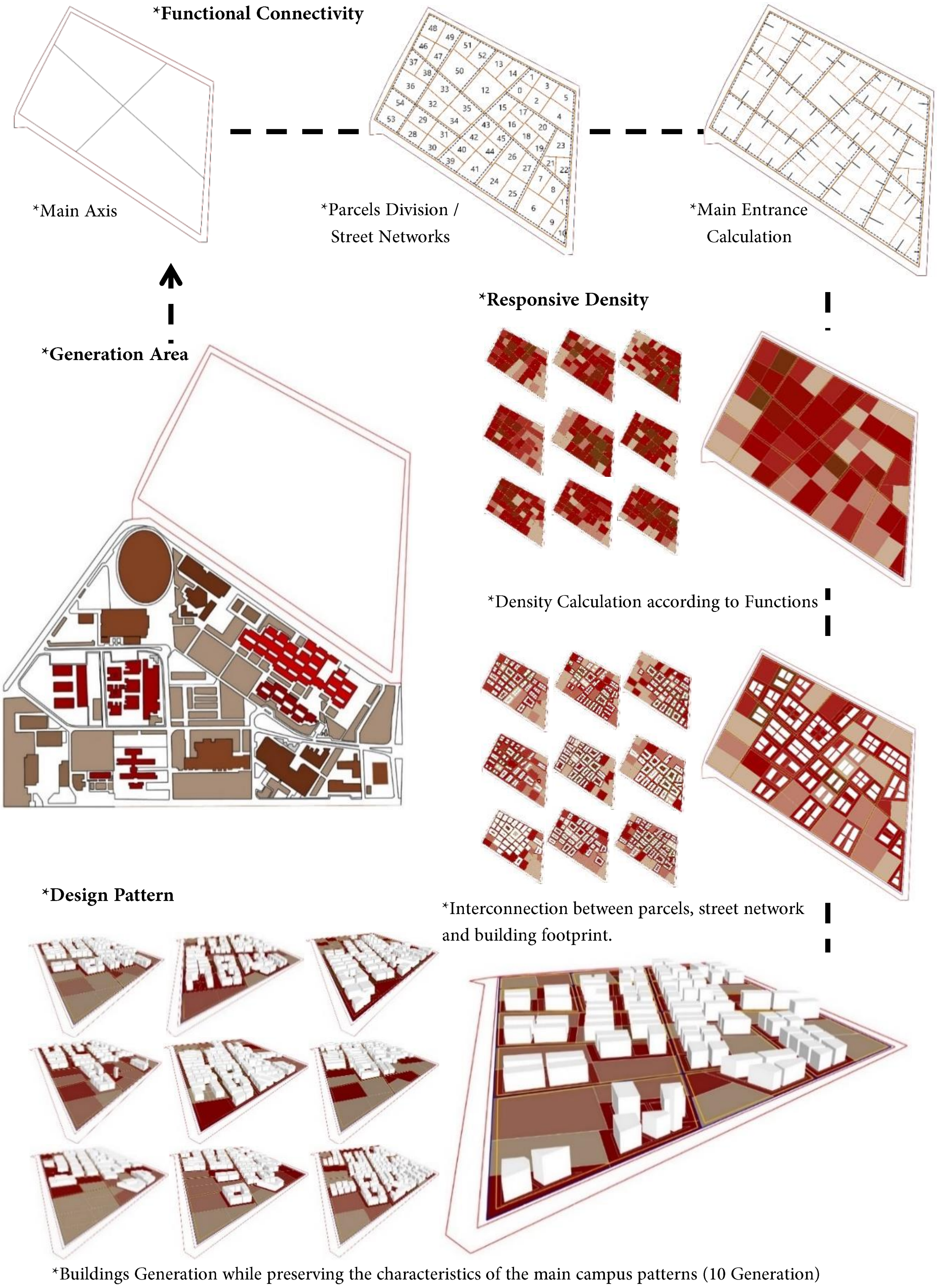


Figure 4.31. *Generative system pattern two optimization results. (Source: by the author).*

4.2.3.3. Pattern Three Generation

This part of the experiment aimed to seek self-generated design possibilities of the university campus master plan expansion without referring to any grid-genesis. This gives more freeness to the system to predict different scenarios and morphologies that arise through the connection of the three design characteristics; functional connectivity, responsive density, and design pattern of the system. The evolution properties are found in the generative capacities of systems directed to look for emerging alternatives in design development (Figure 4.32.).

The evolutionary generation gave variance in both parcels size (min 212.51 / max 2500.07), buildings height (18-29) and travel distance (max 165.35 m). To explore how these forms of evolutionary generation can work first is by testing the same system used in the previous two design pattern experiments. The second is engaging different systems and approaches as a design solver for the university campus master plan. To do so, tendency and feedbacks from previous generations are taken into account by assessing how this generation might be performed.

The system used the same computational components and parameters prepared for both pattern one and pattern two (Table 4.7.). They are all interconnected to compute and interact under one single design process allowing them to be as one single system which makes the interaction easier. Both context requirements and design limitations are parametrically represented to formulate the buildings' generative process.

Table 4.7. *Input data for generative system pattern three. (Source: by the author).*

Data Input	Input value	Max value (ESTU)
Parcels area range	55 -120 (GH unite)	120 GH
Density Ratio	6	< 6.76 %
Open Space ratio	29	> 20.90 %
Built area ratio	71	79.10 %
Distance between two vertices	0.7	0.9
Minimum parcel size	200 GH	<
Footprint Distance	8	<
Building footprints factor	16	<
Building length	55	<
FAR	0.89	> (0.80)
OSR	>	(0.36)
GSI	>	(0.25)

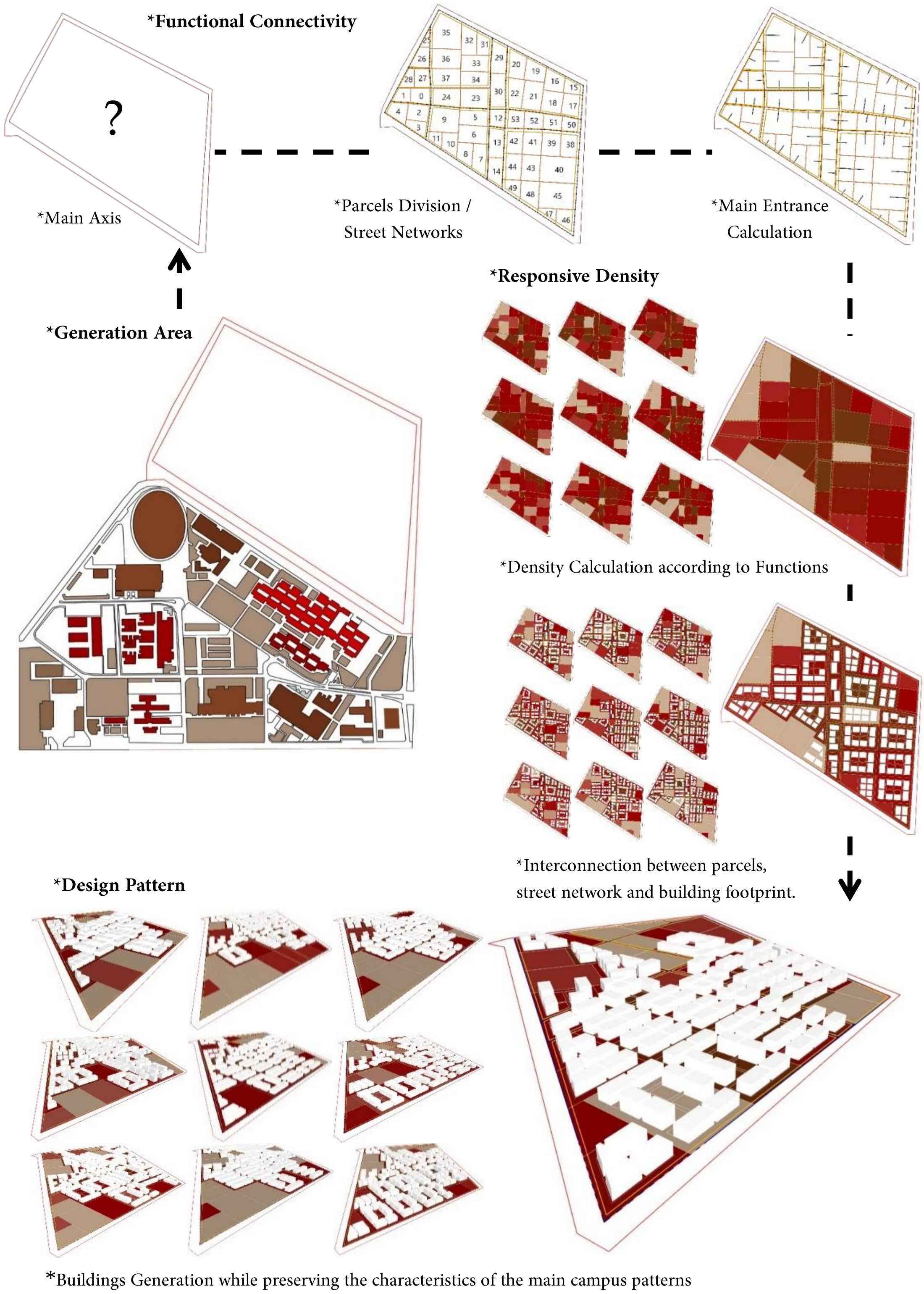


Figure 4.32. *Generative system pattern three optimization results. (Source: by the author).*

As long as all the three parts of the system are embedded together, the behavior of the final designs is based on the interactions between them. Each part of the system has several components and functions that control how a process interacts with another one. As an example, responsive density has to interact with functional connectivity's outputs and this determines the design scenarios of the buildings' design pattern and volume extrusions (Figure 4.32.).

The prior design objectives of this system lay on the generation evolution that maintains the coherence while seeking a non-controlled process. This is what was presented by the absence of any grid-plan as a seed of the generation. Another objective was the exploration of several morphologies while ensuring the same interconnection between the parts of the generative system. However, as it is posed in the other generations, this one also has its challenges and limitations such as controlling the pattern of design pattern and number of street networks according to specified spatial density as well as time required for generation. Every single trial took a significant amount of time while other trials took anywhere less than others (trials with pattern three self-generation). To evolve the iteration of each of 10 generations it would take up to 5-9 hours of testing for each pattern when all the components and parameters are well arranged. It should be mentioned that the results of generation have a partial relationship with the plan analysis provided within the data collection section as the input parameters are simply based on such randomization to optimize. Therefore, the focus is on generating different design patterns without relying on any grid genesis. In addition to that, a sustainable eco-campus development plan has also not been taken into account even though some of the basic data have been engaged as input parameters. This could be considered as a limitation of the generative design system which is discussed later on.

The Functional connectivity often integrates the two patterns presented in the previous research section as the connective network of the generation area which discretizes the parcels' boundaries. The subdivision of the resulting basic geometrical forms further generates the buildings' footprints that will be extruded later according to the computational calculation of the process. Due to the interconnection of the whole system, there will be a relation between both street networks and the generation of parcels and buildings.

The responsive density is stemmed from those proposed within phase one of the data collection section with a freeness to search for better propositions that matched the design goals. Characteristics such as open space built and non-built and many other factors influence the final morphology of the generation and the arrangement of the final parcels division.

The design pattern of the buildings and blocks are included together with the whole mechanism that forms at the end of the university campus master plan. In this type of generation, it is hard to predict exactly the particular pattern type and the generation hierarchy, as the evolution of the plan is based on algorithmic applications decided by the plugin such as Decoding space and Anemone. Many other factors and characteristics are a part of the design possibilities identification.

The final university campus master plan morphology can be optimized in future researches by the integration of other implications and factors such as energy use, climate region and society features. The generative design system could be developed on a large time scale, by engaging many other factors such as walkability, movement of pedestrians and vehicles and through other socio-cultural, political and economic conditions. This application has shown that the performance of a generative design system required an understanding of the computational interactions between the different parts of the process such as functional connectivity, responsive density, and the final design pattern of the university campus morphology. Thus, it can be understood that the effective generation is not based on just the performance and capabilities of the used digital tools, but many other factors and input parameters play almost the same important role to respond to the research problems.

4.3.Evaluation and Decision Making

The main objective of the generative system is to build a process that allows to adaptively control the modification, simulation of the whole design evolution by changing specific parameters seeking performance possibilities and alternatives. A total of 30 generations has been performed in this case study, 10 generations for each pattern (unlimited generation applications could be performed). Within all the possibilities chosen to be studied the same requirement is specified to support a validated comparison and allow for optimized geometry decision making. For sure, it is nearly impossible to test all the potential possibilities and conditions because of the time and computing performance limitations, but a general understanding of the process opens doors for future applications to seek better outcomes.

Several parcels sizes and building extrusion heights are compared with different street networks lengths ensuring the same requirements and analysis conditions. The evaluation of different possibilities which will be discussed in the following parts is also important to make a decision on which design outcome is efficient according to the data visualization diagrams and graphs involved in the generation process.

Working on a generative system of an existed spatial area creates different restrictions because of the limitation and considerations that should be taken into consideration during all the early stages such as street networking division orientation, the design pattern of the studied buildings, and arrangement of the parcels. Hence, choosing the dynamic tools according to different aspects of the university campus is necessary to come out with efficient possibilities results.

Within this research scope, the evaluation step is less influential than the previous ones, however, some interesting results emerged where the role of the designer is to select and decide the final one according to the main research objectives. As it is explained in the different phases of the data collection part of the research, the generation area is analyzed to understand the main physical characteristics and spatial features such as street networks patterns, design evolution and land use density which are used as main elements of evaluation. The characteristics are specified and integrated into the design process as values to drive the system to reproduce evolving networks with different parameters (see page 148).

4.3.1. Results Discussion

The generative design system is not itself novel, but the formulation of the computational design process provided through this research and the interconnection between different system parts in conjunction with design problems and context requirements is making the research original. However, the highly practical parametric tooling and the availability of data to choose key design features, have allowed for better alternatives and possibilities to solve the predefined problems and challenges. While each used method and technique is relatively limited, the level to which they are involved in combination shows how computational techniques can be developed in a way that ameliorates the context adaptability.

Since the university campus master plan has a significant open space existence presenting the empty parcels and a design pattern that is based on built/open space proportion in each parcel and building, the input parameters of spatial density arrange the same proportion during generation. The value of the ground space index (GSI) in the existing map (2020) is 0.25 <GSI which accounted for all parcels division. The floor area ratio (FAR) on the other hand, was set to 0.47 <FAR which accounted for different buildings stores variations and street network relations. The open space ratio (OSR) is specified with 0.63 <OSR value taking into consideration both types of parcels or in-between buildings as observed in some design patterns of the university campus buildings patterns.

The level of consistency between the system parts is related to the design problems that tend to be solved within the experiment. In this case study, the interconnection between all the parts are forming the final generated possibilities. According to the first system application by engaging pattern one, the street networks are evolved with linear growth and usually stop generation when intersecting another network. Some of the resulting designs looked uncreative due to the simple parcels division and buildings clustering alternatives. This is not seen on the second system application where many different propositions are allowed with every iteration which ends showing a much sophisticated design pattern in both functional connectivity and design pattern of the blocks and buildings. In the evolutionary application, the system was processed to give better designs possibilities due to the relations between buildings extrusion and parcels division logic which was randomly varied. The final design of the three system application varied with each step of the generation; responsive density, functional connectivity and design pattern. The evaluation and decision section enabled a comparison between 30 possibilities provided by the generative design system within three different patterns. The decision making concerning the best design is done according to several characteristics. The best street network connections for all users (pedestrian, cars/buses, bicycle), performance parcels division respecting the design pattern and giving different possibilities for open space and build/non-build spatial structures, and the building extrusion’s distribution density through general boundaries

(FAR and GSI). As long as the generations are based on many requirements and conditions, it is not simple to reach one optimal solution. Many solutions possibilities will be evaluated and the decision making will be done responding to the research objectives (Figure 4.33.). The data outcomes used for analyses are presented in a form of graphics (Appendix-8). The numerical data both involved and resulting from generation application are provided in (Table 4.8.).

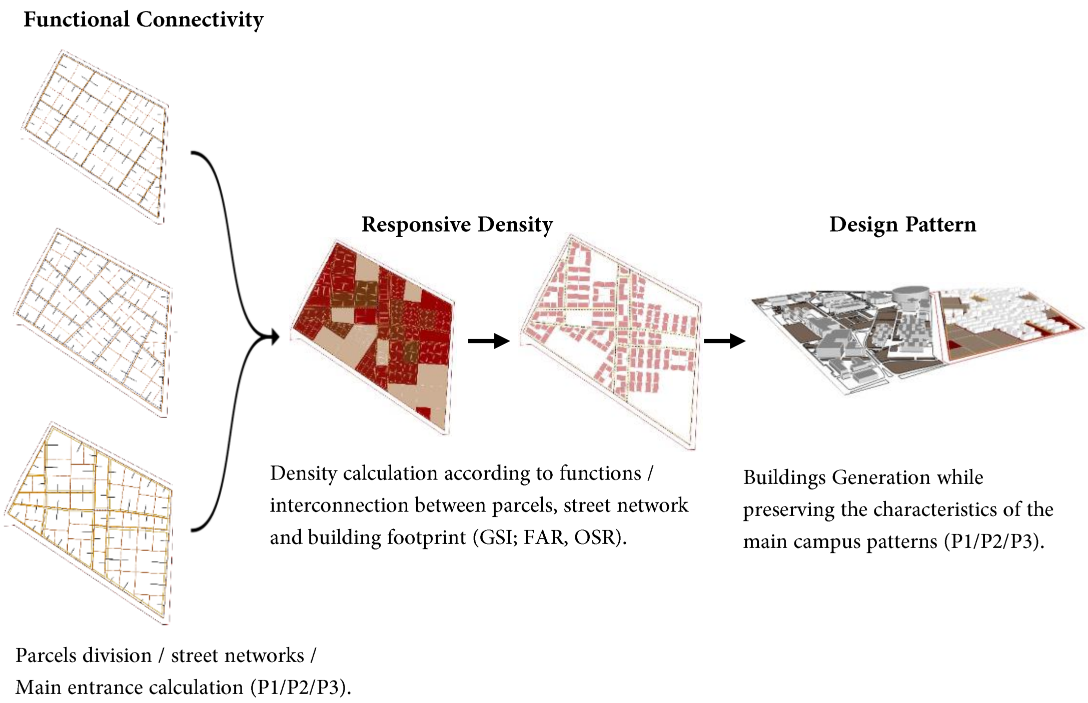


Figure 4.33. *Step by step process application of the generative design system (30 generations, 10 for each pattern). (Source: by the author).*

Figure 4.34. *The outcomes of generative design system/ Functions Distributions (30 generations, 10 for each pattern). (Source: by the author).*

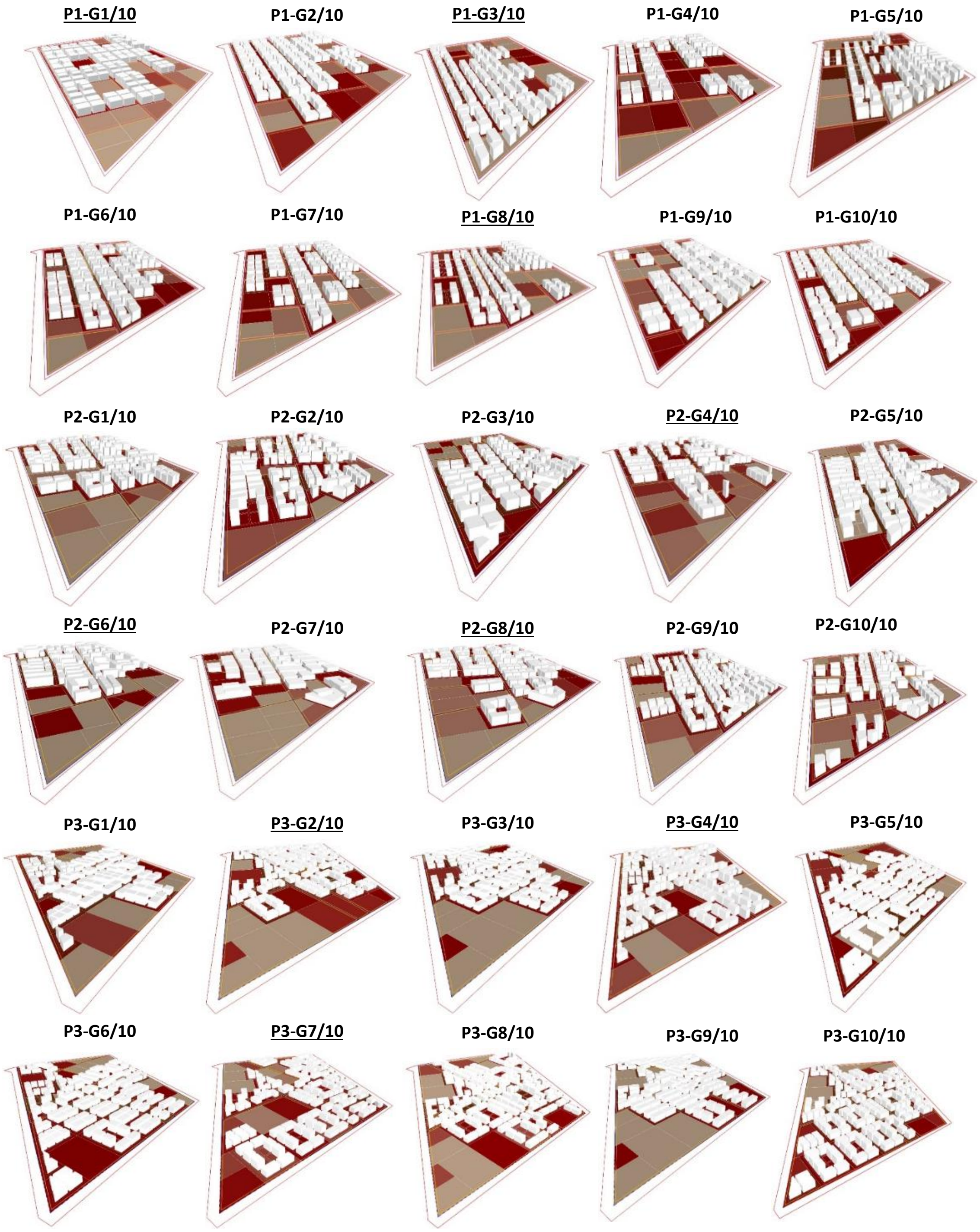


Figure 4.35. *The outcomes of generative design system / 3D perspectives (30 generations, 10 for each pattern). (Source: by the author).*

Table 4.8. *Numerical data both involved and resulted from generation application (10 G*3 P).(Source: by the author).*

	Possibilities	Generation	Iteration (loop)	Reference (Parcel Number)	General Density	Street length	Parcels width (Max)	Parcels Size (Min/ Max)	Dense Area (Min/ Max)	Buildable area (Min/ Max)	Gross Floor Area GFA (Min/ Max)	Min Footprint size (GH)	Open space Value (GH)	Built Values	Travel Distance
Pattern 01	P 1	P1-G1/10	3	PN 26	100	60-150	50	2175.80/ 8582.32	236.80/ 371.49	419.31/ 1331.56	1257.91/ 3322.87	100	12	161	242.39
	P 2	P1-G2/10	5	PN14	60	45-110	55	2883.03/ 9294.36	236.80/ 387.45	344.38/ 1281.09	883.31/ 2870.98	50	12	161	261.383
	P 3	P1-G3/10	7	PN36	60	55-125	60	2883.03/ 13429.41	238.19/ 369.05	164.68/ 905.28	494.05/ 1967.63	110	12	161	256.34
	P 4	P1-G4/10	9	PN35	70	60-200	60	2883.03/ 13429.41	258.87/ 371.49	249.26/ 1005.97	747.76/ 2422.46	250	11	161	285.14
	P 5	P1-G5/10	12	PN46	70	45-110	56	2883.01/ 9294.36	221.76/ 387.45	160.46/ 1281.09	481.38/ 2412.16	75	10	161	260.29
	P 6	P1-G6/10	1	PN16	80	40-110	55	2883.01/ 9294.36	237.21/ 387.45	347.73/ 1281.09	776.22/ 2870.98	50	9	161	260.49
	P 7	P1-G7/10	4	PN06	60	45-110	55	2883.01/ 9294.36	236.78/ 387.45	274.27/ 1144.01	822.80/ 2663.42	50	11	160	259.28
	P 8	P1-G8/10	3	PN01	69	55-110	60	2883.03/ 13429.41	267.30/ 387.45	331.58/ 1061.31	902.53/ 2640.02	100	12	161	255.81
	P 9	P1-G9/10	15	PN44	60	45-110	48	2157.80/ 8582.32	221.64/ 371.49	143.67/ 1069.05	431.01/ 2911.23	200	15	161	272.71
	P 10	P1-G10/10	10	PN28	68	45-110	49	2157.80/ 8582.32	215.03/ 371.45	96.44/ 1074.55	385.76/ 2457.56	140	10	161	263.67
Pattern 02	P1	P2-G1/10	4	PN42	60	45-110	55	1632.37/ 9966.42	219.14/ 405.32	168.87/ 1067.91	675.46/ 3260.84	200	10	161	229.30
	P 2	P2-G2/10	7	PN29	70	45-110	55	1632.38/ 9966.42	173.05/ 405.32	168.87/ 1022.19	506.60/ 2516.74	50	15	161	231.75
	P 3	P2-G3/10	11	PN35	60	40-120	52	1632.38/ 9133.67	173.05/ 382.62	86.16/ 1127.67	430.77/ 3111.63	200	09	161	241.35
	P 4	P2-G4/10	14	PN12	65	45-110	54	1632.38/ 9966.42	173.05/ 405.32	29.79/ 1112.49	208.50/ 2579.07	150	13	161	245.65
	P 5	P2-G5/10	3	PN08	60	45-110	60	2799.74/ 10959.92	241.33/ 422.48	148.84/12 47.40	446.50/ 2479.28	210	13	161	229.39
	P 6	P2-G6/10	12	PN01	70	45-110	58	1632.38/ 10823.57	242.44/ 418.89	325.71/ 1287.91	648.65/ 2041.27	222	12	161	245.24
	P 7	P2-G7/10	5	PN27	65	75-210	51	1632.38/ 9933.70	198.56/ 382.62	323.57/ 1423.47	647.13/ 3346.24	200	12	161	245.24
	P 8	P2-G8/10	13	PN32	60	45-110	53	1632.38/ 9133.70	216.38/ 382.62	170.56/ 1274.40	552.03/ 3080.72	202	13	161	252.36
	P 9	P2-G9/10	2	PN20	70	45-110	55	1632.38/ 9966.42	173.05/ 405.31	138.74/ 1205.23	416.22/ 2596.60	50	10	161	246.08
	P10	P2-G10/10	8	PN49	75	45-110	51	1632.38/ 9933.70	198.56/ 382.62	22.29/ 1228.36	156.01/ 5452.12	220	12	161	246.31
Pattern 03	P 1	P3-G1/10	6	PN12	78	50-150	60	956.31/ 11250.29	192.09/ 426.76	39.17/ 1331.21	156.66/ 1752.51	210	12	161	165.35
	P 2	P3-G2/10	13	PN26	79	50-150	60	956.31/ 11250.29	156.40/ 426.76	39.17/ 1331.21	149.37/ 1752.51	210	10	161	153.58
	P 3	P3-G3/10	9	PN04	77	55-160	65	956.31/ 11250.29	156.40/ 426.76	22.58/ 1258.39	153.67/ 2013.48	215	11	161	153.74
	P 4	P3-G4/10	12	PN08	75	50-150	67	956.31/ 12327.84	192.9/ 574.50	40.98/ 1331.21	149.37/ 1948.02	215	14	161	135.20
	P 5	P3-G5/10	11	PN46	75	50-150	55	956.31/ 9955.75	208.22/ 404.56	94.34/ 1092.02	188.67/ 1649.99	235	11	161	174.33
	P 6	P3-G6/10	4	PN38	78	60-155	75	956.31/ 9955.75	156.40/ 404.56	39.17/ 1331.21	156.66/ 1656.20	205	09	161	166.33
	P 7	P3-G7/10	14	PN15	90	50-150	60	956.31/ 11250.29	156.40/ 426.76	39.17/ 1331.21	149.37/ 1656.20	209	12	161	135.33
	P 8	P3-G8/10	9	PN32	80	70-180	61	956.31/ 1125029	156.40/ 426.76	21.37/ 1233.49	85.47/ 1703.07	211	13	161	164.99
	P 9	P3-G9/10	2	PN24	80	50-150	57	956.31/ 9955.75	156.40/ 401.73	72.64/ 1128.73	202.77/ 1741.75	210	10	161	176.50
	P10	P3-G10/10	9	PN52	80	60-190	60	956.31/ 11250.29	156.40/ 426.75	39.17/ 1331.21	156.66/ 1752.51	210	10	161	164.71

Since the process output of the generative design system provides a significant range of differentiated possibilities; evaluation, optimization, and decision making are practically essential. Its only by employing evaluation and optimization in a certain direction based on the generation results the extent of alternatives can be improved. It is necessary to vary parameters to seek alternatives that would not be considered appropriate but maybe the greatest performing solutions. If the provided possibilities have more sophisticated criteria, using specific evaluation and optimization tools may be more practical.

4.3.2. Evaluation and Optimization

Evaluation of street network, parcels division and building extrusion has been done respecting the design requirements and spatial conditions of the studied area. The generations are performed in a scaled size (x/÷ 5) due to the large amount of data processed during the street network division, densities distribution and buildings volume extrusion (for real dimensions see Appendix-7). It is seen that the generations presented in pattern one are mostly providing simple and linear results with buildings heights between 2 and 3 stores responding to the spatial density specified in the early stage of the system. Whereas the pattern two generations are giving different results with high density plans and irregular buildings footprints in different stores heights and variant parcels sizes (362.76/2435.45 m2). This is also linked to the initial grid pattern and street networks generation that influences the behavior and patterns of the final buildings' possibilities. The design results presented on pattern three demonstrate efficient outcomes which respond to the main objectives of the research. Even if the formulation of the generative design system is more important than the final decision, 3 possibilities from each pattern (total of 9 generations) are chosen according to the specified evaluation characteristics and optimization parameters (Figure 4.36.). The comparison of different design possibilities shows the results of street network division, parcels arrangement, volume extrusion and interconnection between spatial elements on a normalized scale. Pattern three that was chosen for the self-generation initial grid shows different performance and is characterized by a varied building extrusion and includes several typologies of the final campus master plan. That could be seen clearly in (P3-G2/10), (P3-G4/10), (P3-G7/10) generations. Pattern two also showed some interesting generations such as (P2-G4/10), (P2-G6/10), (P2-G8/10). These designs partially respond to the spatial parameters results from data collection analysis phases and are presented in the previous Table (4.48.). Even the initial grid generation engaged in the generative design process of pattern one has restricted the performance and flexibility of final possibilities, however (P1-G1/10), (P1-G3/10), (P1-G8/10) expressed a significant relationship between the desired characteristics of the final design.

The generative design system with its different parts' applications showed that design pattern with volume extrusion takes a long time to run. The Grasshopper plug-ins 'Decoding Space' and 'Anemone' and the C# Component incorporated were tested on the usability and performance. Computational analysis performed in the previous sections of the research assisted the system to specify values of visibility and accessibility as long as the implementation of street networks is an important part of the concept. For the optimization part of the experiment "Street Length", "Footprint Size", "Travel Distance", "Gross Floor Area", "Parcels Size, "Reference Point", "Buildable Area", "Parcels Width" are taken as the main parameters (Figure 4.37.).

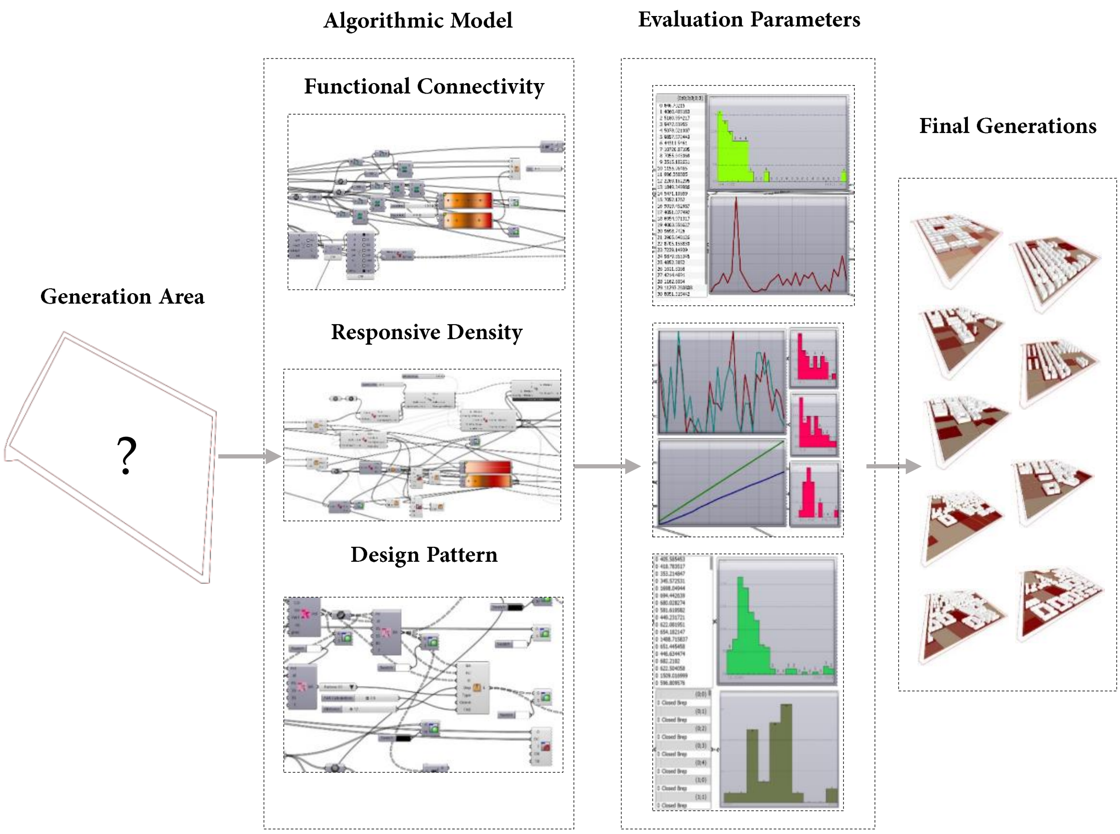
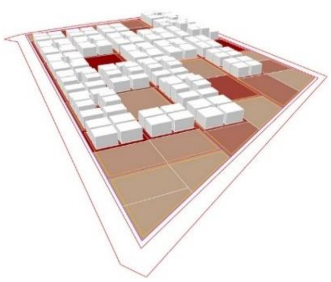


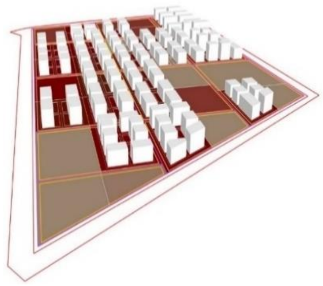
Figure 4.36. *Visualization of the generative design system for architecture "university campus master plan as a case study". (Source: by the author).*

P1-G1/10
Reference (Parcel Number): PN 26
Street Length: 60-150
Parcels width (Max): 50
Parcels Size (Min/ Max): 2175.80/ 8582.32
Buildable Area (Min/Max): 419.31/ 1331.56
Gross Floor Area (GFA): 1257.91/ 3322.87
Min Footprint size (GH): 100
Travel Distance: 242.39

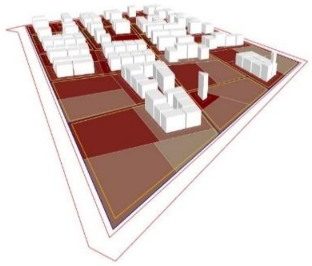


P1-G3/10
Reference (Parcel Number): PN36
Street Length: 55-125
Parcels width (Max): 60
Parcels Size (Min/ Max): 2883.03/ 13429.41
Buildable Area (Min/Max): 164.68/ 905.28
Gross Floor Area (GFA): 494.05/ 1967.63
Min Footprint size (GH): 110
Travel Distance: 256.34

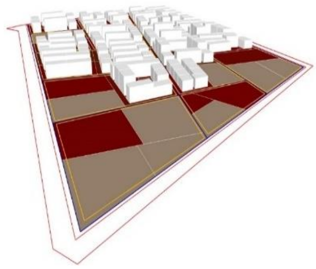
P1-G8/10
Reference (Parcel Number): PN01
Street Length: 55-110
Parcels width (Max): 60
Parcels Size (Min/ Max): 2883.03/ 13429.41
Buildable Area (Min/Max): 331.58/ 1061.31
Gross Floor Area (GFA): 902.53/ 2640.02
Min Footprint size (GH): 100
Travel Distance: 255.81



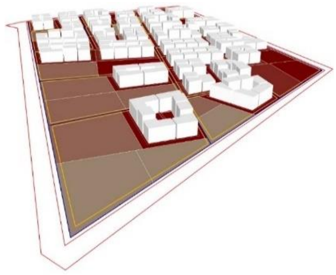
P2-G4/10
Reference (Parcel Number): PN02
Street Length: 45-110
Parcels width (Max): 54
Parcels Size (Min/ Max): 1632.38/ 9966.42
Buildable Area (Min/Max): 29.79/ 1112.49
Gross Floor Area (GFA): 208.50/ 2579.07
Min Footprint size (GH): 150
Travel Distance: 245.65



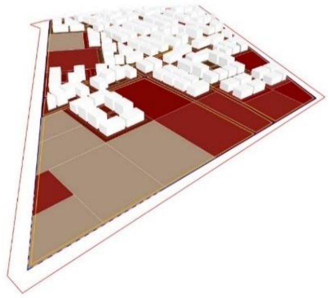
P2-G6/10
Reference (Parcel Number): PN01
Street Length: 45-110
Parcels width (Max): 58
Parcels Size (Min/ Max): 1632.38/ 10823.57
Buildable Area (Min/Max): 325.71/ 1287.91
Gross Floor Area (GFA): 648.65/ 2041.27
Min Footprint size (GH): 222
Travel Distance: 245.24



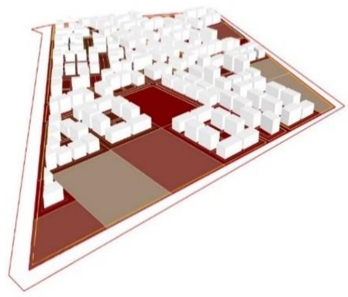
P2-G8/10
Reference (Parcel Number): PN32
Street Length: 45-110
Parcels width (Max): 53
Parcels Size (Min/ Max): 1632.38/ 9133.70
Buildable Area (Min/Max): 170.56/ 1274.40
Gross Floor Area (GFA): 552.03/ 3080.72
Min Footprint size (GH): 202
Travel Distance: 252.36



P3-G2/10
Reference (Parcel Number): PN26
Street Length: 50-150
Parcels width (Max): 60
Parcels Size (Min/ Max): 956.31/ 11250.29
Buildable Area (Min/Max): 39.17/ 1331.21
Gross Floor Area (GFA): 149.37/ 1752.51
Min Footprint size (GH): 210
Travel Distance: 153.58



P3-G4/10
Reference (Parcel Number): PN08
Street Length: 50-150
Parcels width (Max): 67
Parcels Size (Min/ Max): 956.31/ 12327.84
Buildable Area (Min/Max): 40.98/ 1331.21
Gross Floor Area (GFA): 149.37/ 1948.02
Min Footprint size (GH): 215
Travel Distance: 135.20



P3-G7/10
Reference (Parcel Number): PN15
Street Length: 50-150
Parcels width (Max): 60
Parcels Size (Min/ Max): 956.31/ 11250.29
Buildable Area (Min/Max): 39.17/ 1331.21
Gross Floor Area (GFA): 149.37/ 1656.20
Min Footprint size (GH): 209
Travel Distance: 135.33

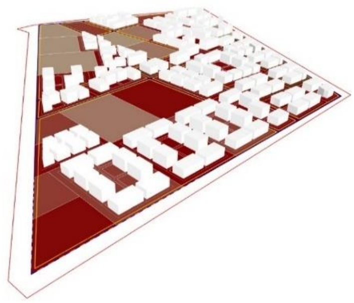


Figure 4.37. *The 9 possibilities selection after evaluation and optimization. (Source: by the author).*

Table 4.9. *Real Numerical data resulted from the generative design system (9 Generations). (See Appendix-7 for all results).*

	Possibilities	Generation	Iteration (loop)	Reference (Parcel Number)	Parcels width (Max) GH	Parcels Size (Min/ Max) m2	Dense Area (Min/ Max) %	Buildable area (Min/ Max) %	Gross Floor Area GFA (Min/ Max)m2	Travel Distance (Min)m
Patterns	P 1	P1-G1/10	3	PN 26	50	483.52/ 1907.19	53.07/ 82.55	93.18/ 295.91	279.57/ 738.42	53.87
	P 3	P1-G3/10	7	PN36	60	640.68/ 2984.32	52.93/ 82.01	36.59/ 201.17	109.79/ 437.26	56.97
	P 8	P1-G8/10	3	PN01	60	640.68/ 2984.32	59.40/ 86.01	73.69/ 235.84	200.57/ 586.68	56.84
	P 4	P2-G4/10	14	PN12	54	362.76/ 2214.76	38.46/ 90.07	6.26/ 247.22	46.34/ 573.13	54.59
	P 6	P2-G6/10	12	PN01	58	362.76/ 2405.24	53.88/ 93.09	72.38/ 286.21	144.15/ 453.62	54.50
	P 8	P2-G8/10	13	PN32	53	362.76/ 2207.49	48.08/ 85.03	37.90/ 283.2	122.68/ 684.61	56.08
	P 2	P3-G2/10	13	PN26	60	212.51/ 2500.07	34.76/ 49.83	8.71/ 295.83	33.20/ 389.45	36.75
	P 4	P3-G4/10	12	PN08	67	212.51/ 2212.39	42.69/ 127.66	9.11/ 295.83	33.20/ 423.89	30.05
	P 7	P3-G7/10	14	PN15	60	212.51/ 2500.07	34.76/ 94.83	8.70/ 295.83	33.20/ 368.05	30.07

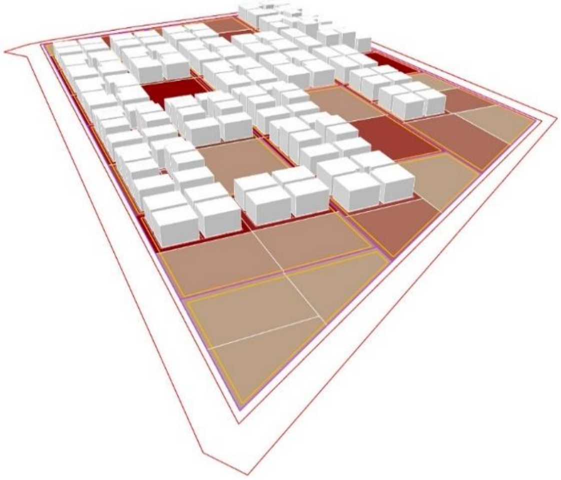
Table 4.10. *Results of the functions distributions after generation (GDS).(9 Generations). (See Appendix-7 for all results).*

	Possibilities	Generation	Academic Units	Social Units	Administrative units	Technical Units	OSR	GSI	FAR
Patterns	P 1	P1-G1/10	≤	≤	≈ 2.6%	≈ 2.2%	12	≤	0.48
	P 3	P1-G3/10	≤	≈ 64%	≤	≈ 2%	12	0.30	≤
	P 8	P1-G8/10	≤	≈ 63%	≤	≈ 2.1%	12	0.28	≤
	P 4	P2-G4/10	≈ 37%	≤	≈ 2.6%	≤	13	≤	0.49
	P 6	P2-G6/10	≤	≤	≈ 2.7%	≤	12	≤	0.47
	P 8	P2-G8/10	≤	≤	≈ 2.6%	≈ 2.2%	13	0.28	≤
	P 2	P3-G2/10	≈ 37%	≈ 64%	≤	≤	10	≤	0.47
	P 4	P3-G4/10	≈ 38%	≈ 66%	≤	≤	14	0.30	≤
	P 7	P3-G7/10	≈ 36%	≈ 63%	≤	≤	12	0.29	≤

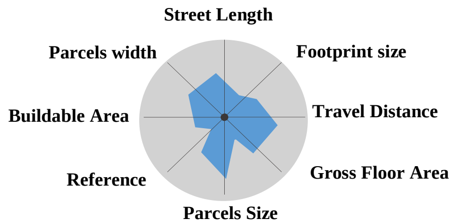
4.3.3. Final Decision

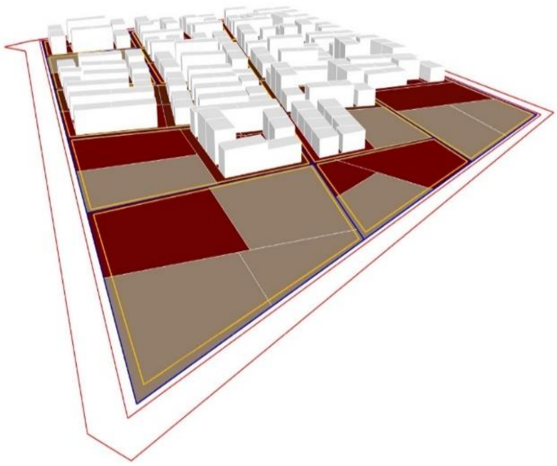
There is no perfect method to reach the optimal solution of problems, however, each problem required a specific application to be performed to pertain all the design limitations. In addition to that, the density value is one of the important factors that control the number of possibilities being generated. From all the resulting alternatives three of them are chosen taking into consideration the shortlisted parameter and requirements of the initial design model. The comparison of the alternatives the outcomes of 2005/2020 university campus plans analysis and students' designed projects which are presented in phases one and two are taken into consideration. The final representation is provided in form of schemas, diagrams and technical drawings following the traditional design process. The advantages and disadvantages of different analysis tools, urban structures and typologies are worked out. Based on this differentiation, one generation from each design pattern is selected and presented in more detail (Figures 4.38.-4.44.). From the resulted possibilities the important process starts by focusing on the proposals responding to the main problems and considering the spatial requirements and conditions. The advantage of the used platform for generation is that the researcher could use a different process to define the workflow of the application (segmentation, density, structure, blocks) which does not matter which characteristics the project holds.

The non-generated parcels are those that the system perceived as open space or non-built area (future expansion) according to the ratio of spatial density defined through the input parameters. At the same time, the proportion between the general area size is compared by the data such as GSI, FAR, OSR, and the left non-built parcels are the areas excluded by the system to be non-generated. This application is mainly done within the "Responsive Density Part" of the generative system. The comparison between the possibilities gives many similar results concerning buildable area and buildings footprints, but the three chosen designs are more responsive to the major design objectives. They are the preferred solution for the system generation because they respond to the defined requirements and conditions resulting from both phases one and two, and spatial parameters specified with the strategic plan of the university campus. This is presented by the performed simulations, analysis and evaluations. As a result of the evaluation, it is clear that these designs are to some extent sustaining the same design pattern of most university buildings and give better results of the open space ratio and buildings extrusion (Figure 4.40. /4.42. /4.44.).

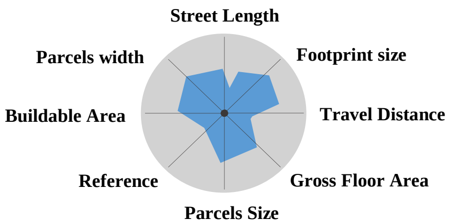


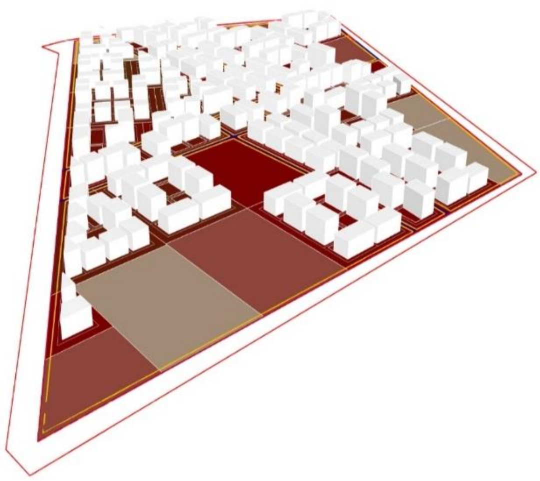
P1-G1/10
Reference (Parcel Number): PN 26
Street Length: 60-150
Parcels width (Max): 50
Parcels Size (Min/ Max): 2175.80/ 8582.32
Buildable Area (Min/Max): 419.31/ 1331.56
Gross Floor Area (GFA): 1257.91/ 3322.87
Min Footprint size (GH): 100
Travel Distance: 242.39





P2-G6/10
Reference (Parcel Number): PN01
Street Length: 45-110
Parcels width (Max): 58
Parcels Size (Min/ Max): 1632.38/ 10823.57
Buildable Area (Min/Max): 325.71/ 1287.91
Gross Floor Area (GFA): 648.65/ 2041.27
Min Footprint size (GH): 222
Travel Distance: 245.24





P3-G4/10
Reference (Parcel Number): PN08
Street Length: 50-150
Parcels width (Max): 67
Parcels Size (Min/ Max): 956.31/ 12327.84
Buildable Area (Min/Max): 40.98/ 1331.21
Gross Floor Area (GFA): 149.37/ 1948.02
Min Footprint size (GH): 215
Travel Distance: 135.20

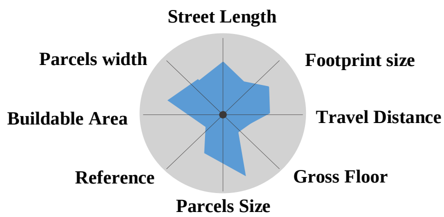


Figure 4.38. *The final outcomes of 3 generative design possibilities. (Source: by author).*

Generation P1-G1/10

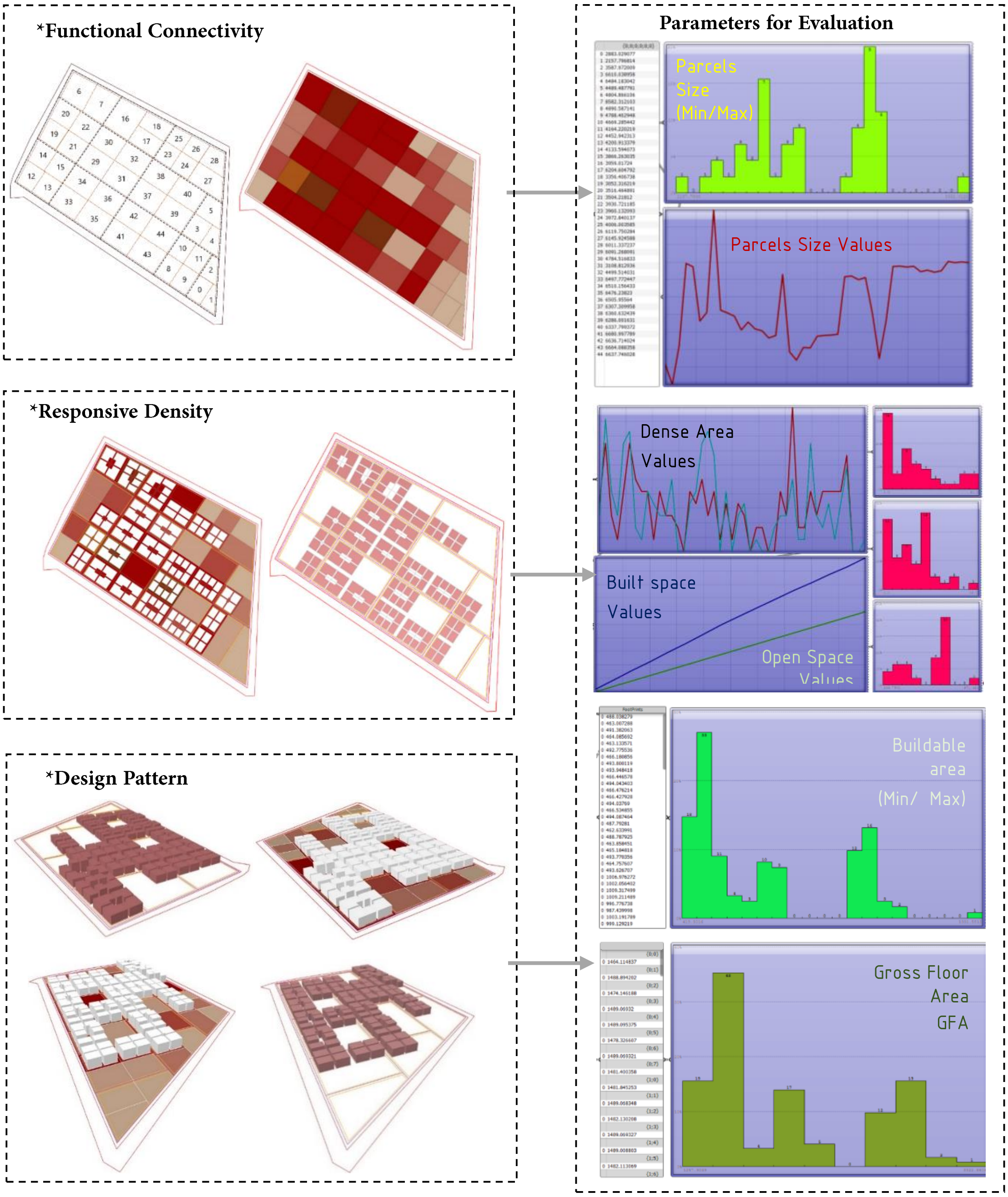


Figure 4.39. *Generation P1-G1/10 evaluation parameters for final decision. (Source: by the author).*

Figure 4.40. *Generation P1-G1/10 visualizations. (Source: by the author).*

Generation P2-G6/10

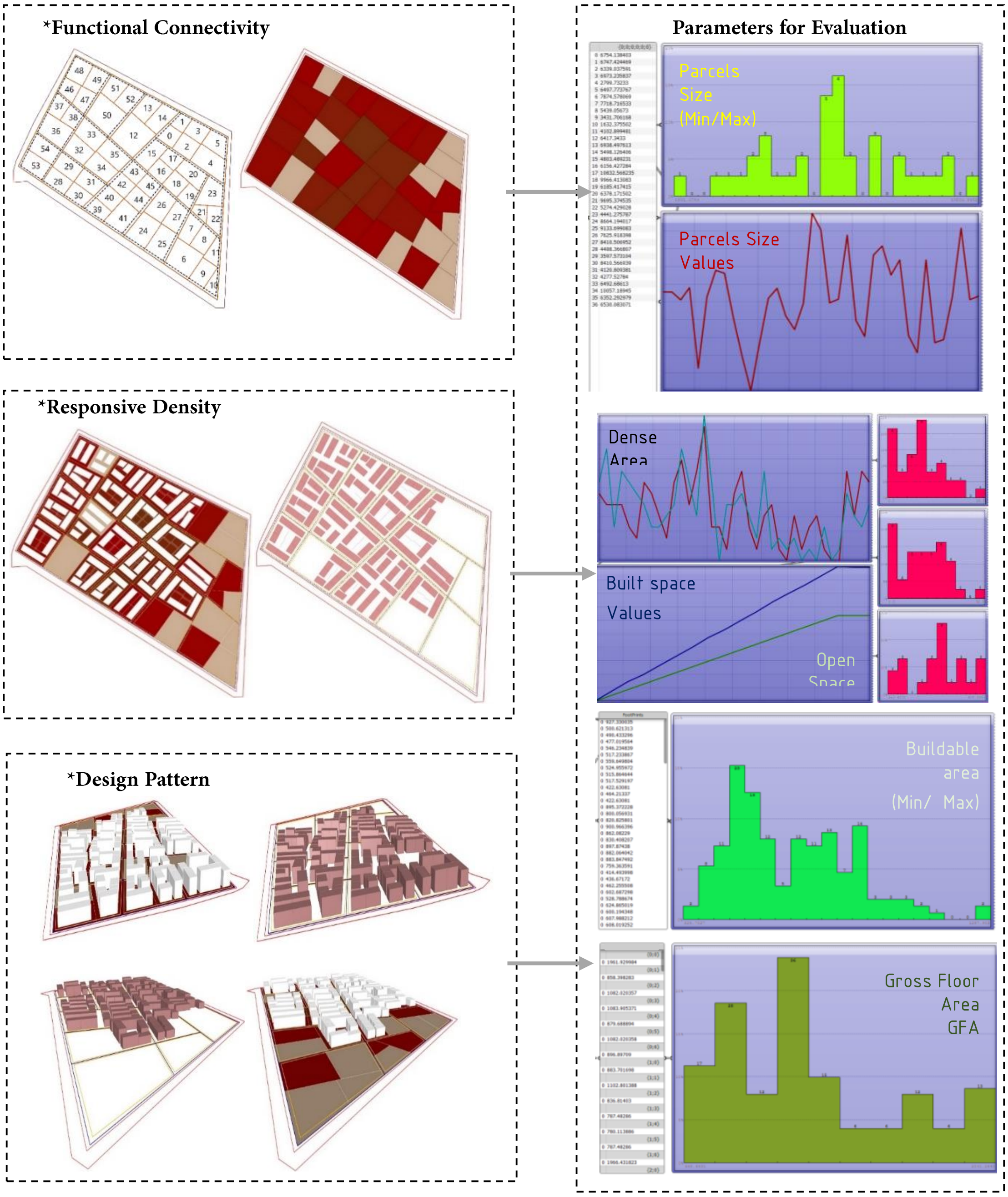


Figure 4.41. *Generation P2-G6/10 evaluation parameters for final decision. (Source: by the author).*

Figure 4.42. *Generation P2-G6/10visualizations. (Source: by the author).*

Generation P3-G4/10

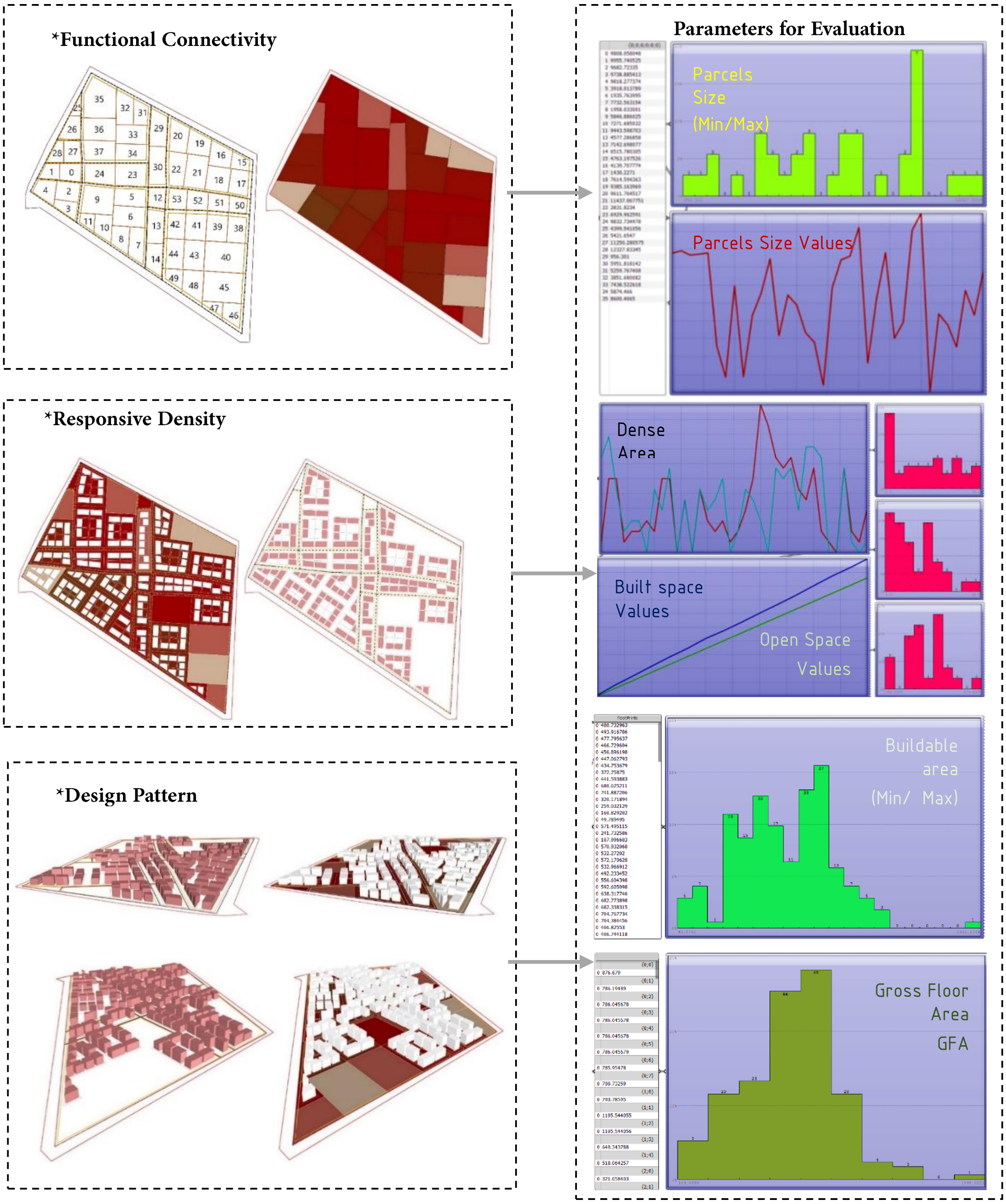


Figure 4.43. *Generation P3-G4/10 evaluation parameters for final decision. (Source: by the author).*

Figure 4.44. *Generation P3-G4/10 visualizations. (Source: by the author).*

This experiment looks at the possibilities for effective interconnection methods and approaches for developing a university campus master plan generative system. As it is previously mentioned, the main objective for this generative design system is to search for the best solutions among several possibilities that respect the design pattern of the chosen case study (Figure 4.45.). The importance of this research is that based on a real future need of the university campus planned under its sustainable design committee which will be applied as soon as possible.

The generative design system allows us to create a limitless number of possibilities by adding new parameters or by manipulating the existed ones in any stage of the design. During that, all the calculations and geometry relationships will be updated automatically. Throughout generations, some geometry changes could be done manually to support the whole process according to the results gotten from phases one and two of the analysis without any further applications. It is a combination of computation extension and human intention and intervention.

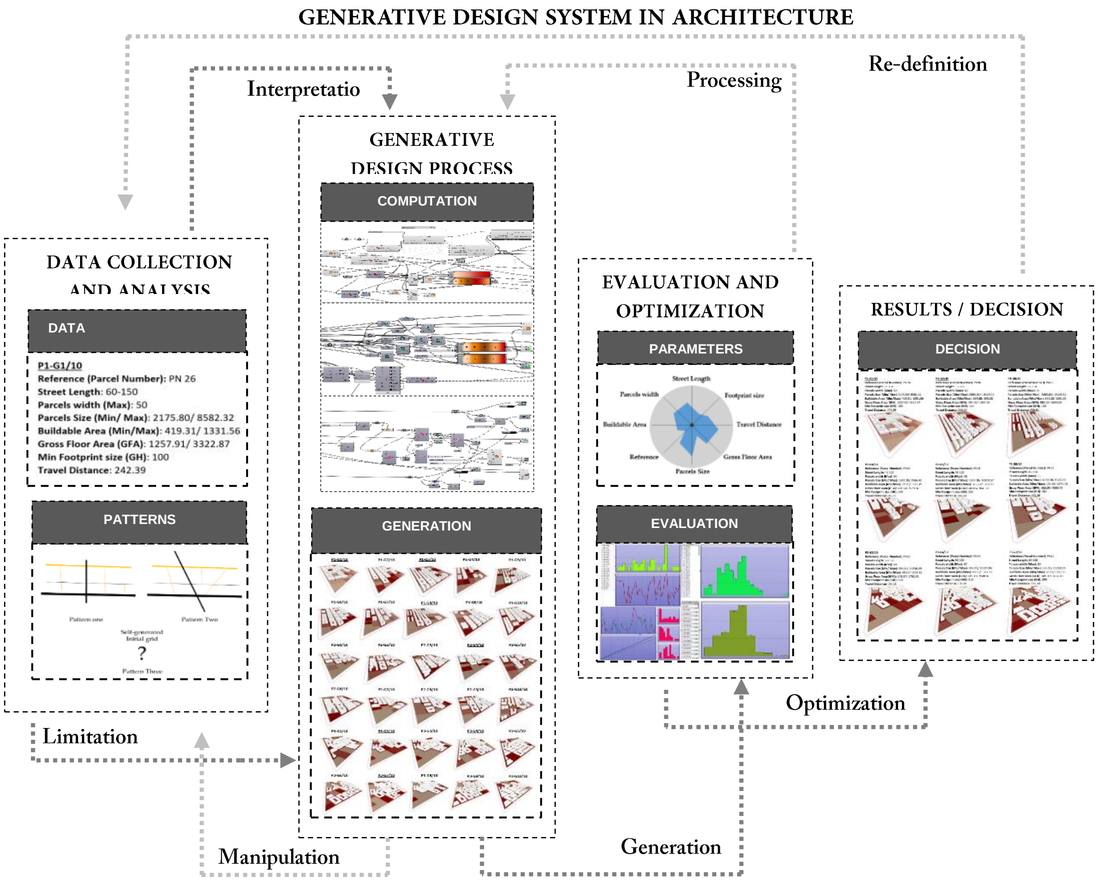


Figure 4.45. The generative design system implementation phases. (Source: by the author).

The chosen design possibilities are characterized by efficient accessibility, optimized division of the parcels and different extrusion of the building according to the design pattern of the university campus. Considering all the aspects of sustainable design the proposals are responding to many issues discussed within the data analysis section.

On account of time limitations and computer capacities, many techniques and approaches could be used to improve the optimization and evaluation phase of the generative design system. One of these approaches referring to the “Objective-Based Optimization Methods” is the design space exploration framework proposed by Fuchkina et al. (2018). It facilitates the selection, simplification, and aggregation of design possibilities with more deep applications. It also allows for the evaluation of multiple design alternatives by uploading simulations to the web application and the online exploring tool using “DeCoding Spaces” Grasshopper components. When the designs are uploaded, the input parameters could be saved, and the assessment outcomes may be categorized and customized. Matching alternatives grouped and the behavior of possibilities are visually presented in the self-organized map. “Wallacei” is a program in Rhino's Grasshopper that also performs in "Multiple Data-Driven Optimization" and employs evolutionary computing as a problem-solving technique for design challenges. It is mainly concerned with the synthesis of the design issue, the analysis of the outputted findings, and the selection of the best alternatives (Petrov and Walker, 2020).

The generative design conceptualization and application formed the basis of this research, where a generative design system is developed and involved to respond to the design problems and context requirement using computational tooling for both analysis and generation of the design possibilities. Many other parameters such as the prediction of future users comprise the number of students, academic staff and administrative staff that could be integrated into the system. In consequence, the parameters manipulation offers the potential to adapt the design process according to future user requirements. The system is used to seek better design growth possibilities and alternatives to effectively exploit the area proposed for university campus expansion, but it was not possible to solve all the resulting problems from data collection and analysis research part due to time limitation and tooling capacities. This generative design system is created for the specific case study of ESTU campus expansion. However, it could be applied for other case studies with the same design requirements and spatial conditions. Some other computational components and definitions could be needed to achieve further results and possibilities.

5. CONCLUSION

The conclusion addresses the findings of this study, including research conceptualization, methodology, and several comprehensive parts of the development and implementation of the generative design system. It highlights the research’s initial contributions, limitations, applicability and potential future advancements (Figure 5.1.). The research has outlined efforts to generative design techniques in architecture and spatial planning. It is based on the expectation that will be more required for buildings with rapidly developing needs because of various characteristics and measurements of design, and on the evolving complexity of applications, amounts of data and technological advances.

The study aimed to develop a complete methodology for generative design application. It takes into account both general concerns about the design process and particular algorithmic issues concerning the implementation of the system. The conceptual framework is based on existing design approaches and systems while also introducing new capabilities. The purpose of designing such a system is to help the development of a realistic generative design process. This methodology is intended to serve as a foundation for researchers to develop other evolutionary design systems. The method of establishing and implementing approaches based on generative design systems has shown a range of capabilities and implications, therefore encouraging consideration of the challenges. The possibility of integrating generative methods in architectural design stayed a focal point of the study. Since there is no conclusive answer to the experimental problems, this research offers different analytical methods. In a university campus master plan, the methodology is also examined regarding advancing the field of generative design processes and algorithmic model representation.

Unless the concepts reviewed and the designs considered are comprehended; generative design, as a result of digital design processes; it is indicated that architecture evolves into circumstances that serve as the foundation of the abstraction such as design methods and strategies, patterns processing and relationships between form and area configuration. The conclusion emphasizes the major contribution, design limitation and context requirement and even future research recommendations. It highlights the qualitative experience of interconnecting different parts of the design process rather than just concentrating on the outcomes composition. This, in turn, enables the resulted alternatives to be guided by multiple evolutionary systems and approaches even if they present different possibilities. However, those methods constrain the capacity of the designer thinking and limit their involvement in the improvement of design efficacy.

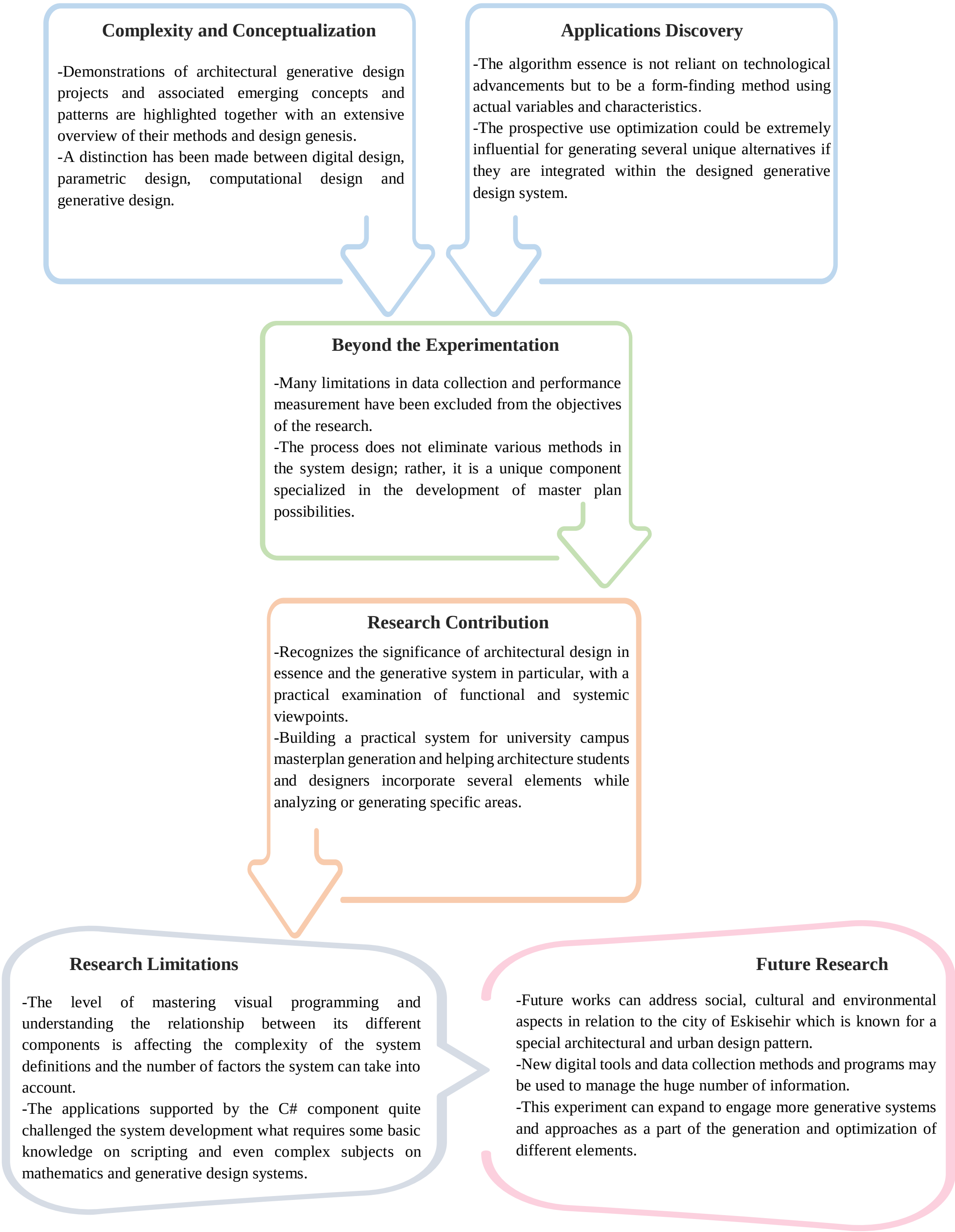


Figure 5.1. *General summarization of the conclusion chapter. (Source: By the author).*

5.1. Complexity and Conceptualization

This research introduces inclusive conceptualizations and classifications of the generative design concept to the current body of knowledge. This, in particular, gives a complete comprehension of the subject through the contemporary integration of many systems and approaches. In addition, some demonstrations of architectural generative design projects and associated emerging concepts and patterns are highlighted, together with an extensive overview of their methods and design genesis. Such contemporary instances, on the other hand, are exceptional in generative university master plan design theory and practice. The conceptualization began by forming the interconnections between the genesis of the generative design concept in architecture and different design systems and approaches engaged in the domain. To classify those early applications, each section of the research worked on identifying the particularity of each method. A hypothetical organization for using these methods in the early stages of architectural design is provided, along with possibilities and constraints, as well as a perspective on how these methods connect to existing design processes. The discussed projects are descriptive and conceptual in origin, and they investigate one potential future approach of architectural design strategy. As a result, a considerable selection of case studies provides a clear perception of the importance and implications of search in architectural design.

Throughout this investigation, generative design systems and approaches are researched, and interconnection is discussed to address the complexity of extensive problem settings. The main purpose of this research was to examine and appreciate generative design methods, and their components are defined hypothetically. The challenge of generative design composition and design project interpretation evolves from traditional design knowledge. The designer’s involvement strategy of dealing with projects has resulted in the emergence of the transformation in the knowledge of the creative generation process. As the output of design solutions can get automated, the designer's contributions, assessment, and direct interaction with the design area are decreased. Regarding generative design methods, the decisions must be emphasized because the design is an interpretive exploration and visual assessment activity. Since the design exploration area evolves, there is a necessity for further precise ways to boost the designer's advancement through the effective alternative.

According to the outcomes of this research, generative design in architecture is comprised of a wide range of cutting-edge innovations, architectural theories, and cognitive shifts that extended the typical usage of tools for design. Numerous choices are accessible in terms of hardware and software for the current digital revolution; conventional usage of programs for design is now transforming towards design generation, which employs algorithms, natural simulations, and evolutionary computation for architectural design. All of the attributes listed previously allow for the formation of dynamic architectural forms depending on morphogenetic processes. Visual programming allows users to develop designs by changing creative perspectives with the assistance of digital tools. There is already scripting-based software offered to assist designers in reasoning beyond standard architectural design principles, conceptualizing better ideas, improving contemporary theories, doing complicated computations, and evaluating possibilities.

A distinction has been made between digital design, parametric design, computational design and generative design. Digital design is defined as an engagement of different digital tools CAD, CAAD, CAM in design. A parametric design predefines a computational design framework and a programming process is utilized to develop several variables. The computational design represents the usage of relevant design applications and computer capacities in specific visualization and representation. A procedure of evolution, generating different designs and developing an adaptive system, is specified with generative design to develop a subset of features or any other adjustments in this generative process of development.

Alternatively, architectural design generations present two challenges in particular. To begin with, the search areas for alternatives are considerably too extensive, if designers consider all potential design variants. For example, even with limited configurations and constraints, there are many alternatives to consider when planning an extension of a master plan. This is especially evident when a variety of variables are considered together. Secondly, several architectural design problems are multifunctional, and these purposes frequently intersect. For instance, implementing a responsive density master plan with directed and decreased open space requirements, are two competing priorities. Multiple interests in conflict with one another can cause non-linear challenges.

Personalized modern processing techniques, which integrate power generation technology with user preferences are frequently utilized in other fields, cannot be fully investigated. Moreover, it is believed that the opportunities presented by digital design tools, which have appeared with the progression of technology in the latest years and whose performance has enhanced, may have a specified potential in managing one such challenge if assessed with a design technique appropriate to the context. In the conceptualization, a model centered on a revolutionary design method that is accompanied by digital design tools and allows performative interaction has been designed for this reason. A comprehensive investigation for a specialized large-scale method and computational design tool was first performed throughout the model development. According to the test results of the experiments, a design intervention focused on collaborative interaction with the designer would be sustainable.

5.2. Applications Discovery

The significance of designers and associated methods to design, as well as research into the function of revolutionary design tools in the generative arena, explain certain changes in the substance of decision making from one component to another. While decision making maintains to provide an important aspect in generative design, its relevance is now largely oriented on being a tool for collaborations than conceptualization. Consequently, the significance of sophisticated computer programs is getting increasingly crucial in today's architectural fields of study, since several advanced software applications such as Grasshopper are widely acknowledged as generative tools. Additionally, some constraints, such as design length or scale, may require designers to engage generative algorithms regularly. Therefore, performing generative design outside programming is mostly unpractical and challenging. Algorithms are creating components in this regard since they generate shapes and morphologies. Nonetheless, the algorithm essence is not reliant on technological advancements. It has been noted that for certain architects, such as Le Corbusier, Otto, and Moretti generative design was intended to be a form-finding method using many variables and characteristics instead of software. Data processing, on the other hand, is often associated with automated systems among today's designers. Looking evidently around the design process demonstrated that, while the generative design is supposed to be an innovative approach to design by several more designers, it can transform the principle intentions of every scope proposal, since these processes have distinctive properties, such as the approach and the users' identification.

The generative design system framed within this research sets the interrelationships between visual scripting which represents the generative tools and the visualization of the outcomes in the geometrically interpreted models of the same concerns. The challenge is making designers and architects understand in-depth not just the mechanisms of growth, but also the techniques of generation through computational tools. At the same time computation poses challenges when it comes to tool choosing and involvement of design knowledge in an appropriate way. This is what makes research on the domain of architecture and spatial planning critical. By discussing the generative design process and optimizations methods, this research presented a specific standpoint that brings algorithmic representation to architectural design into understandable practice.

The generative design system uses components to explain and express the geometry or design, and it allows the algorithm to generate new patterns. The importance of creating a generative system by engaging some methods involves the process of forming output that has been implicitly classified in the input. Systems in which convenient and different representations and principles are utilized to express extremely complex structures. Methods for developing complex structures by repeatedly employing simple approaches such as self-generation and simple algorithms. Techniques for selecting the most appropriate interpretation from a list of created possibilities are generating a solution variation to sustain the requirements. Throughout the early stages of design, these methodologies can assist designers considerably enhance building productivity without restricting their flexibility or implementing specific alternatives. The designer's significance is determined by the instruments used, whether they are preconfigured, generative tools, equipment developed by the designer, or outlines generated traditionally. The design outcome is determined by the amount of data complexity, which may be manipulated to meet particular requirements. An appropriate technique of planning is achieved since many generation phases may be managed to reflect the use of iteration capabilities.

In recent years, there has been a lot of discussion about design optimization in the initial phases of architectural design. This research offers an algorithmic system for generating and enhancing a four-loop design optimization and capability exploration in architecture, to solve certain of the limitations of traditional design optimization. Such design optimization, according to arguments, disconnects the architectural output from its surroundings and users, resulting in an impairment in spatial dimension and a building's integration into the contemporary context. Furthermore, others believe that completely automated optimization disconnects from physical modeling and design processes, which were previously important fundamental elements of architectural academic progress, and therefore concerns the elimination of parameter characteristics, impacts, and attributes.

Accordingly, the notions of “Multiple Data-Driven Optimization,” can be highly effective when exploring out suggestions to challenging aspects, but they do not ensure that an appropriate alternative is found. In the study project of several pattern generations, it can be demonstrated that the layouts evolve responding to the requirements over time. The suggested alternatives of the “Objective-Based Optimization Methods” might be considerably improved than the results of previous subjective testing of diverse parameters, demonstrating that the optimization process boosts the usage of generative design through extensive evaluation and development. The resultant provides a coherent illustration of the best entities and allows the designer to easily appreciate the trade-offs among optimal various objectives to make experienced decisions. As an outcome of the research, it can be concluded that the prospective use of “Evolutionary Optimization” and “Multi-Objective Optimization” could be extremely influential for generating several unique alternatives to dynamic freeform architectural challenges if they are integrated within the designed generative design system. Meanwhile, when it refers to assessing the outcome and determining a design concerned with qualitative objectives, the designer's involvement remains essential.

5.3. Beyond the Experimentation

Developing and implementing a generative system into the university campus master plan was explored as a challenge with the given context requirements and design problems. Modeling spatial development and predicting several possibilities and alternatives using generative methods demand quantitative characteristics. After all of the provided outcomes, the research gap is still vast to reach a well-organized generative system that responds autonomously to the variation of parameters. Among the research questions, the one asked “How can the generative design method interpret different constraints and requirements while respecting design patterns?" was intended to identify the limitation and conditions that may shortcut design applications when using computational techniques in architecture. This highlights that the computational tools can only serve a part but not formulate the whole design process, and the most challenging aspects rely on the use of scripting and programming rather than other design tasks.

The aim of the experiment section in this research was to interconnect three main elements of the university campus master plan to set a generative design system capable of providing design possibilities and alternatives at a different scale. The three main elements of the system lay in functional connectivity, responsive density and design pattern where every one of them tends to solve different design problems with several design limitations and requirements. The result was a combined computational system capable of generating master plan possibilities based on various measures and differentiating input parameters. In addition, different generative design systems and approaches such as algorithmic systems, genetic algorithms systems and parametric approaches have been integrated as a logic to perform the design application. The main advantage of the research lies in this combination between data collection part and analysis and the computational system developed. It illustrates the strength of the generative design system in providing many proposals and alternatives responding to different conditions and requirements. The contribution is not only lied on the experimentation part of the system however it can be involved in several domains of spatial analysis and design empowerment or even extend its practice by evolving new capacities and parameters.

To explain how the system is applicable in real practices, this research focused on three trials with different design patterns. All the trials are based on the same system process which is illustrated in the figure (4.45. page 203). The research reflects on the generative design of the university campus master plan across different steps of data collection and analysis, design process, evaluation and decision making. The system could be developed in the future by engaging analytical applications that could benefit the analysis part of the research. This is by focusing on the environmental-related performance of the university campus and its structural patterns. This type of design could also study different factors such as climate effects, energy consumption and geography characteristics. However, many limitations in data collection and performance measurement that several generative design software faces have made these applications somehow excluded from the objectives of the research. At the present, there is no holistic generative design system that unifies all modeling applications in one single software or design tool. Each system varied from another according to the problems intended to be solved as well as different spatial requirements and design limitations presented in every step of the system. Thus, the interconnection of different university campus design elements makes this system respond to some problems that the architecture research domain faces in the present.

The presentation of the campus area to be as beneficial as possible for our research is provided in form of maps. Many information are included such as density, zoning, build non-build, and pattern characteristics to describe explicitly the university campus typology. Some details such as scale, area limits, and locations are easy to describe, whereas many other attributes like design quality, walkability, accessibility need different types of data to be calculated. The data collected from contextual data analysis, including the use of an algorithmic tool to assist the programming methodology of the computational analysis engaged in the data collection phase, are regarded as empirical representations that demonstrate the studio-based experiment outcomes toward integrating design limitations in the master plan design phase.

The generative design system allows us to create a limitless number of possibilities by adding new parameters or by manipulating the existed ones in any stage of the design. During that, all the calculations and geometry relationships will be updated automatically. During generations, some geometry changes could be done manually to support the whole process according to the results gotten from phases one and two of the analysis without any further applications. It is a combination of computation extension and human intention and intervention.

The scope of this research lies also in seeking an effective interconnection between the generic elements of the university campus master plan. The main focus is engaging generative systems to understand how could the relationship between responsive density, functional connectivity and design pattern of university campus master plan affect design possibilities as it develops over time. The design process involved different generative systems and approaches to understand the complexity of design problems resulted. The interconnection of three elements contributed to the formalization of the design system at three trails with different design patterns:

- **Pattern one:** The first trial of the system based on a simple grid which was resulted from the data collection part of the study. The spatial density was responsive to the same linear characteristics of the initial grid which later become the genesis of parcels division and footprint arrangements. The design pattern of final buildings is represented more on the height instead of block clustering and distribution variance. This trial could be useful for linear space generation and design analysis.
- **Pattern two:** The second trial of the system shows some differences in spatial density alternatives and street network interconnections which makes parcels generation result in different forms and characteristics (length and borders). Consequently, final design possibilities are better varied and clustered. This is because of the initial grid which is characterized by nonlinear axes and sub-axes. This trial is particularly capable of solving problems with specific spatial conditions and space generation.
- **Pattern Three:** The third trial of the system is an evolutionary process that is not based on any genesis grid or input parameters in its early generation. Self-evolutional propositions provided by the decoding space plugin are taken as input parameters for later application of functional connectivity. Therefore, this system helped in generating very sophisticated spatial morphologies and building patterns of the university campus master plan. In addition to that, final buildings design patterns have a convenient range for generations with fewer limitation and conditions.

The methodology expanded on the generative design system's parts involved in all the trials, showing examples of how it can be used in real problem-solving design processes. The data collected from the analysis part of the methodology were interpreted and represented computationally to use them as parameters within the application such as spatial density (built/ Non-built and open space), functional connectivity (Street network and parcel division) and design pattern (Buildings cluster and heights). These data were extracted through the study of 2005/2020 maps expansion besides the students' works during the design-studio experiment and then encoded as input parameters based on different generative tools and plugins inside Grasshopper/Rhino. Feedbacks from the three elements of the process was a fundamental part of the design process. The generated possibilities were analyzed based on confirmed generative design systems and approaches, in the case of spatial density, functions proportions and spatial data as well as main axes and sub-axes. Functional connectivity involved street network relationship and main entrance location's calculation and decision making along with the division logic of the parcels. Design pattern mainly engages all the resulting outcomes and uses the footprints to generate buildings patterns, clusters and compute the volume height of each of the buildings according to the other ones. All data collected were integrated as a part of the generative system to increase the interconnection between system parts and to reach more varied design possibilities based on the same input parameters. The final decisions were encoded computationally giving the chance for high-level generation capabilities during generation.

In any attempt to apply the same system for the generation of other areas of the university campus, some input parameters have to be changed and others to be identified. In this context, there is a trade-off to perceive regarding efficiency (moderate degree of morphologic features) and ease of interconnectivity (comprehensive specification) of the pattern's outcomes, depending on the reason for which the categorization (segmentation) is to be used (application concern). Therefore, when the generative process can be employed in its entirety (as in certain urbanization analysis and simulation projects), this evolving system may be quite beneficial. Even if it is a quantitative and properly dined measure, there are still problems to use it properly.

This research offers a conceptual framework for designers to use in the formulation of several university campus master plan expansions. It suggests a generative system that resolves the constraints of existing mechanisms. The system is developed out by a combination of operational systems and approaches, and the actual application was done with the Rhino/Grasshopper software, which allows for further investigation at multiple dimensions with many additional plugins and libraries. The process does not eliminate various methods in the system design; rather, it is a unique component specialized in the development of master plan possibilities. However, it enables the architect to explore deeper into the examination of many design strategies to apply, such as challenging interconnection, specialized functions, and diversified patterns.

5.4. Research Contribution

This dissertation provides contributions in several aspects. On a theoretical level, it investigates the paradigm of generative design from the perspective of design and architecture. As a result, it is explored from both practical and theoretical perspectives, with conceptual classifications of projects, systems, and approaches depending on architectural challenges specified. This uncovers generative possibilities from the standpoint of architecture rather than computing capability. The research also recognizes the significance of architectural design in essence and the generative system in particular, with an experiential examination of functional and systemic viewpoints offering various frames of reference about the generative design domain. Components (in the combination of patterns) can maintain conventional architectural designs without the requirement for codified rules. However, unlike traditional building processes, the generative process is restricted by technology and data analysis. Considering the circumstance of each transformation, the restrictions control expansion. The rational perspective, on the other hand, integrates the use of several processing parameters. The more elements that are connected with a pattern, the more cohesive the layout emerges. This contributed to the architectural design literature by offering a unified indicator and qualitative definitions for the basic features of various systems and approaches. Scholars and practitioners may examine the contributions of diverse approaches that impact design form, such as rules, patterns, and codes, using these measures and algorithms. It also suggests a strategy for analyzing a university campus master plan. A group of components is a description of a particular element. The further components a pattern contains, the profound significance of its geometrical interpretation occurs. The proportion of parameters for each pattern in a generative process suggests the generative system's integrity.

This dissertation also contributes to the architectural design domain aiming to build a practical system for university campus masterplan generation and help architecture students and designers incorporate several elements while analyzing or generating specific areas. The researchers claim that the data collection and analysis part is a very important step in any generative design system formulation, and engaging different phases such as traditional growth spatial and computational analysis and design studio-based experiments could give better problem-driven design applications. Hopefully, the research will be developed in the future to demonstrate many other contributions by seeking more solutions to the university campus master plan expansion mechanisms.

Another crucial contribution of the research lies in the interconnection of the algorithmic definitions of the generative design system provided for university campus master plan. Three design elements have been focused on. The first design element of the system is functional connectivity that tends to place the functional location of the main entrances for parcels and buildings and equilibrates street networks responding to all mobility types (Car/bus, bicycle, Pedestrian). In addition to that, it aimed to build an interconnection between parcels, street network and building footprint. The integration of this part in the generative system required managing some components including main entrance location calculation, interconnection with street networks, and parcels division logic in advanced Grasshopper canvas to compute data and eliminate overload calculation.

The second design element is based on responsive density evolution by creating significant main axes connecting the principal roads and the university campus and set parcels division logic that responds to all spatial requirements and design conditions as well as managing density of land-use according to open space proportion. The system engaged computational design tools and practices related to generative design systems and approaches. The visual programming has been performed and optimized to generate possibilities and alternatives. The integration of the model gives the chance for any other application in different areas and for different design problems to be done just with some further adjustment of data and input parameters. The developed generative design system can calculate characteristics of the resulted alternatives and provide them in values. Multiple samples were illustrated in chapter four (see page 177) with sufficient details. The system retains all the data collection and analysis phases' outcomes into consideration to avoid any isolation during computation and generation.

The third element was the design pattern of the buildings which focused on preserving the simplified characteristics of the main campus patterns and making buildings clustered together respecting the build and non-built areas and also providing buildings' relations regarding volume height. The system engaged an advanced plugin in evolving several solutions. The system is a complete process that responds to all data collected from the three steps as a unified model which provides the generation of a complete university campus masterplan. Most systems optimize responding to a single design problem or research objective; the integration of many computational tools together allow multiple spatial conditions, context requirement and design problems to be incorporated as a combined system and provide a variety of possibilities fit to many experiments.

5.5. Research Limitations

Fundamentally, it is important to mention that there is a lot of potentials that could be searched and explored with the use of this system. It is based on creating a new generative design process and space analysis in architecture which is applied within a university campus master plan expansion. Additionally, plenty of other limitations could be experienced under the relationship computer-designer. In addition to space needs, the site circumstances, sociological aspects of the community must be included in the process, a generative design system also incorporates many determining variables. This may take place in a layout design or variable parameters of the computational model.

The practical constraints of this research were primarily focused on the limitations of the intrinsic generative tools oriented by Rhinoceros and Grasshopper, which were restricted in their convergence during the early stages of the process. This tool was considered as the canvas for the suggested generative system because of its connectivity and adaptability, as well as the large range of plugins available as a toolbox for solving numerous design constraints. The level of mastering visual programming and understanding the relationship between its different components is affecting the complexity of the system definitions and the number of factors the system can take into account. Each part of the system formulation requires a significant period of time for interconnecting each component with the other parts without facing any bugs and computational failures. Currently, the system is limited to three main elements, each of them is focusing on a specific number of problems and limitations. The final step of the system which is concerned with the design pattern is only generated if the two first steps have effectively occurred and the 2D results gotten from them will be extruded into a 3D design that represents the buildings of the university campus. The design pattern is also limited to just the type of clustering and volume heights where many other characteristics could also be implemented if the system will be further developed. Whereas this demands many other computational tools and techniques incorporated correlating to the design context.

The measures involved in the experiment part of the research area at a basic level compared to capacities that visual programing techniques could perform. The system needs to be developed to search for more performative possibilities with variance in characteristics and design patterns results. The feedback loops create some limitations to how input parameters should be integrated and to what extent the system could be self-generating. The different systems and approaches such as algorithmic system, genetic algorithms system and parametric approach have been applied with the help of computational tools and plugins. These techniques challenged the system application because of the complexity level they force across all parts of the system. The application of the system on any other university campus plan should not be limited to just elements like spatial density, functional connectivity and design pattern, but more parameters of Eskisehir city have to be exerted to the urban pattern. The applications supported by the script components quite challenged the system development because it is not a familiar thing for an architect or urban designer. This is what requires some basic knowledge of scripting and even complex subjects on mathematics and generative design systems. The applied nature of the research may be a challenge and perhaps a struggle for most architects and urban designers, however, the near future will force them to go deeper into similar topics and experiences because of the technological advancement that the architectural design domain will be living.

5.6. Future Research

The presented generative design system for a university campus master plan expansion is based on available tools, software and methods, and integrating some other applications by using extra script's components to perform some optimizations methods within the design process development. This system could be developed by engaging artificial intelligence and machine learning processes to seek more design possibilities. The generative design system could be also redesigned in a script and presented as a plugin or software to solve similar spatial planning problems and architectural design applications. This system would be more efficient by counting more requirements and conditions of the users inside the university campus and even interaction and accessibility with the city center. Because of time and data limitations, this research focused just on design challenges and spatial requirements inside the university campus. However, future works can address social and cultural aspects of the city of Eskisehir which is known for a special architectural and urban design pattern. The citizens of the city could be engaged within the study by doing a wide studied survey. New digital tools and data collection methods and programs may be used to manage the huge number of information.

With the existence of novel computational tools within urban planning and spatial analysis, searching for free tools which have online platforms for visualization and representations will benefit the work. Besides that, engaging different social, institutional, and administrative decision-making parts will give better solutions that could be applicable in real-time. Future research on the generative expansion of the university campus master plan should be incorporated with the quantitative limitation of the final output. The experiment focused only on the final results of the generative system while research into the mechanisms and behavioral interaction of the morphologies would give more cohesion to the design process. This experiment can expand to engage more generative systems and approaches as a part of the generation of different elements.

More research on buildings clusters and facades characteristics will implicate a better comprehension of the steps and how they can be involved as a part of the system to respond to energy and climate requirements. Experiments will also need other refinements of the footprints and buildings' non-rectangular shapes to search for better-sophisticated form possibilities to achieve relevant design objectives. The experiments will contribute to both university campus master plan and urban design domains. Finally, the research will search to widen the domain of science by contributing to the existing generative design systems presented universally and seek further into the practices of data collection, space planning and form generation. Significantly, the modularization of generative design system through algorithmic representation needs to be performed using as few data types as possible in its early experiments. This allows for the complete abbreviation of data and to define the particular component for the design purpose. This also offers a greater interconnection of the system parts and afford effective flexibility to control the mechanism of system behavior.

The process developed through this generative design system is not meant to be a decisive set of propositions for university masterplan design development. Instead, it is considered as an investigation where several tools and behaviors are chosen for the benefits of research intents. There is still a long way of work to interpret other design methods and spatial experiences into generative systems. But, as it's highlighted in earlier sections of the research, the success of future techniques and processes becomes effective if the model will present a greater level of interconnection with other standards of computational design methods. By increasing the ratio of design concerns and data variation, this system might be expanded and developed. The focus here was just on resolving each problem in relation to the other ones. Future research could expand the number of problems and involve more generative methods that could play important roles in decoding data and testing new scenarios in further detail. The usage of such a method is related to the challenges faced in the design process and analysis stage. The chance of variety platform availability could make architects derive inspiration and innovate tools that could respond to multiple design problems and context requirements.

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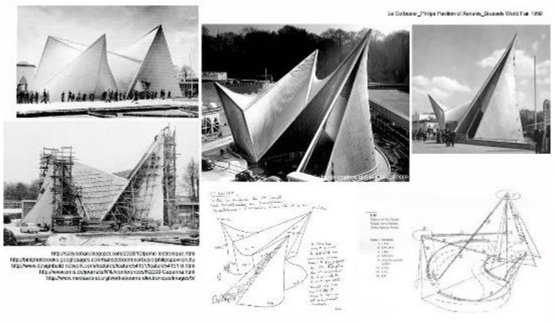
APPENDIX

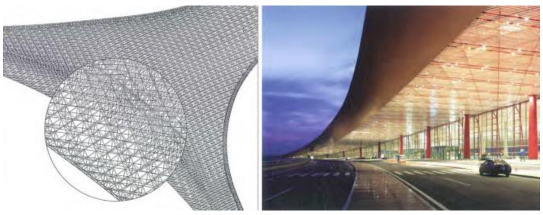
APPX- 1. Architectural Projects

Applied Generative Design Methods

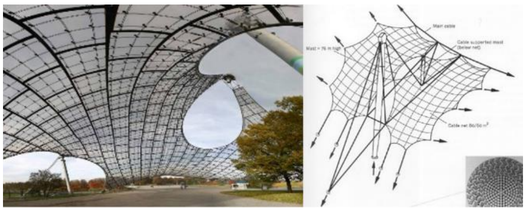
Sagrada Familia Barcelona, Spain / Antoni Gaudi / 1882. Source: Kevin Jan Mazanek, 2016.



The Philips Pavilion for the Brussels World´s Fair / 1958 / Le Corbusier and Iannis Xenakis. Source: https://tr.pinterest.com/pin/758997343420367826/?lp=true

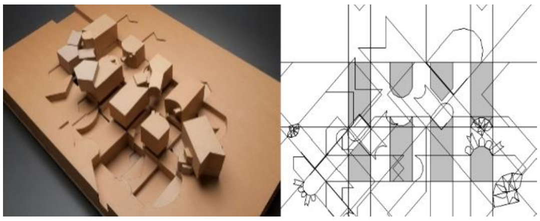


Beijing International Airport Beijing, China / 1958. Source: Cecil Balmond , informal (New York, 2007), p363.

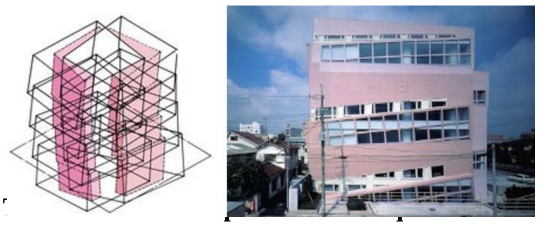


Olympic Stadium in Munich / 1968 / Frei Otto and Frederick Kiesler. Source: Agkathidis, 2015.

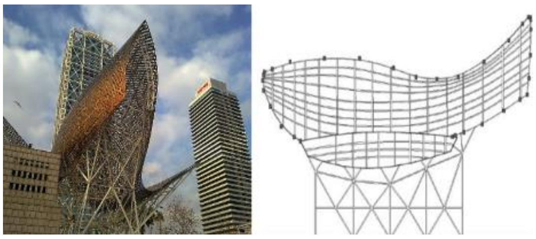
Multihalle Mannheim / Frei Otto / 1968. Source: Frei Otto, 1995.



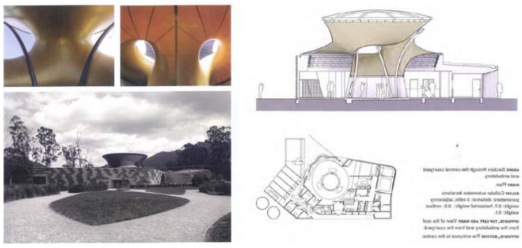
Biocentrum in Frankfurt /1987 / Peter Eisenman. Source: Eisenman 2004.



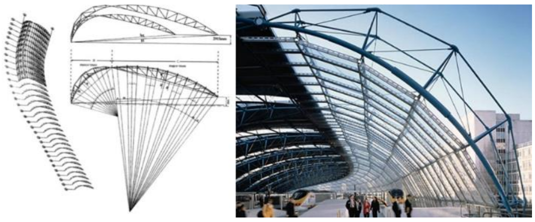
Tokyo / 1990 /Peter Eisenman. Source: Eisenman, 2004.



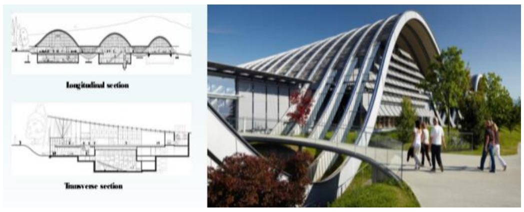
Golden Fish (The Olympic Village in Barcelona) /1992 / Frank Gehry. Source: Nicholas Socrates, 2008.



Australian Wildlife Health Centre Healesville Sanctuary, Australia / 2003 Minifie Nixon Company. Source: Jane burry and mark burry, 2010.

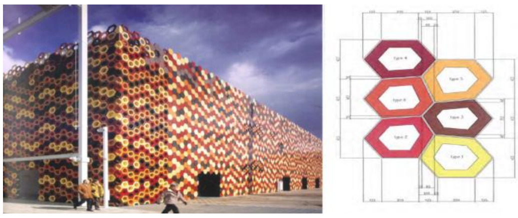


The Waterloo Terminal in London / 1994 / Nicholas Grimshaw. Source: Grimshaw and Partners, 1993.

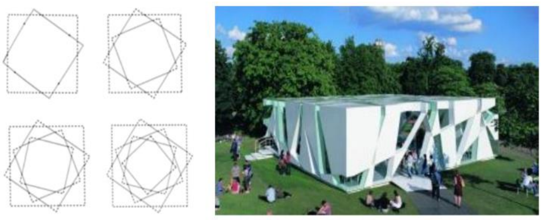


Zentrum Paul Klee Berne, Switzerland / Renzo Piano / 2005. Source: designrulz, 2017. https://www.designrulz.com/?s=Zentrum+Paul+Klee++Renzo+Piano

British Museum Great Court London, Uk / Foster + Partners/ 2000. Source: Jane burry and mark burry, 2010.

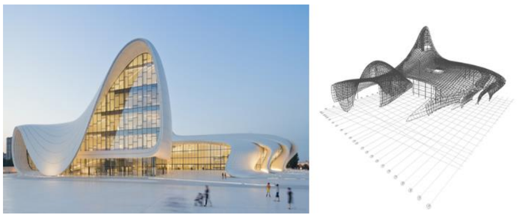


Spanish Pavilion Expo 2005, Aichi, Japan / Foreign Office Architects. Source: Jane burry and mark burry, 2010.

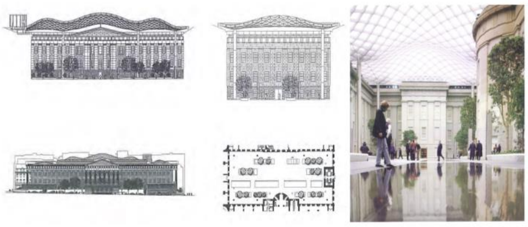


Serpentine Gallery Pavilion in London / 2002 / Toyo Ito. Source: Deuling, 2001.

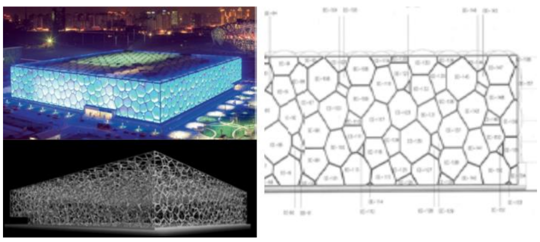
Island City Central Park Fukuoka, Japan / Toyo Ito / 2005. Source: Jane burry and mark burry, 2010.



Heydar Aliyev Centre, Azerbaijan / 2007 / Zaha Hadid Architects. Source: Kristin Dispenza, 2011. http://buildipedia.com/aec-pros/from-the-job-site/zaha-hadids-heydar-aliyev-cultural-centre-turning-a-vision-into-reality.

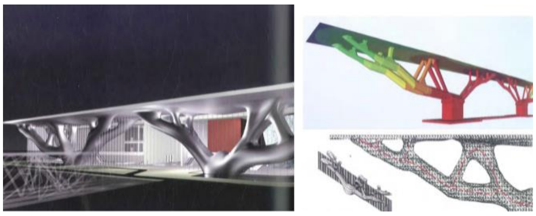


Smithsonian Institution Courtyard Washington, DC, USA / Foster + Partners / 2007. Source: Jane burry and mark burry, 2010.

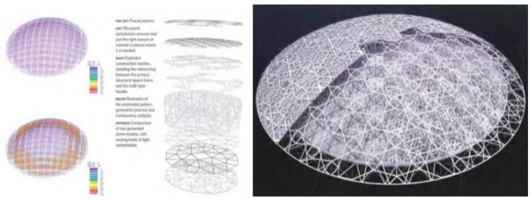


Water cube Beijing / PTW Architects and Arup / 2008. Source: Peddle Thorp and Walker, 2014. https://www.e-architect.com/beijing/watercube-beijing.

Melbourne Rectangular Stadium Melbourne, Australia / Cox Architects / 2010. Source: Jane burry and mark burry, 2010.

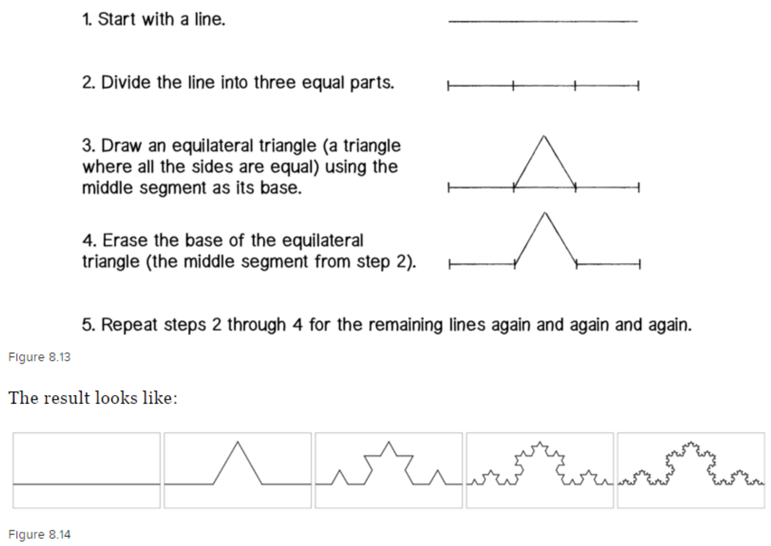


Qatar Education City Convention Centre Doha, Qatar/ Arata Isozaki / 2011. Source: Jane burry and mark burry, 2010.

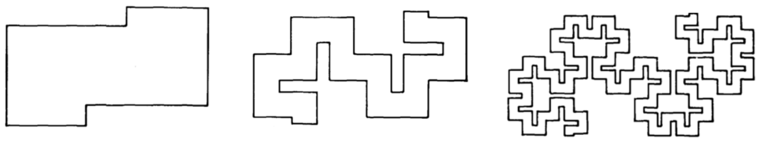


Louvre Abu Dhabi Abu Dhabi, UAE / Ateliers Jean Nouvel / 2017. Source: Jane burry and mark burry, 2010.

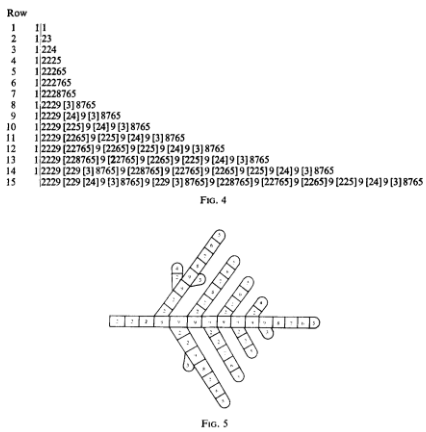
APPX-2. Generative Design Systems and Approaches Examples and Illustrations from Different Researches

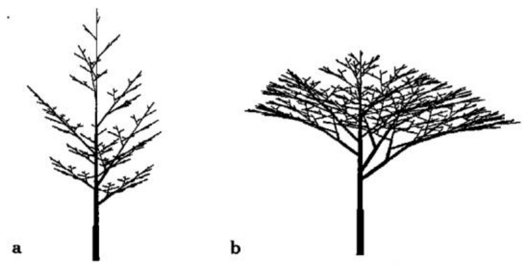


Explanation of Koch Curve. From Daniel Shiffman, *The Nature Of Code* (2012)

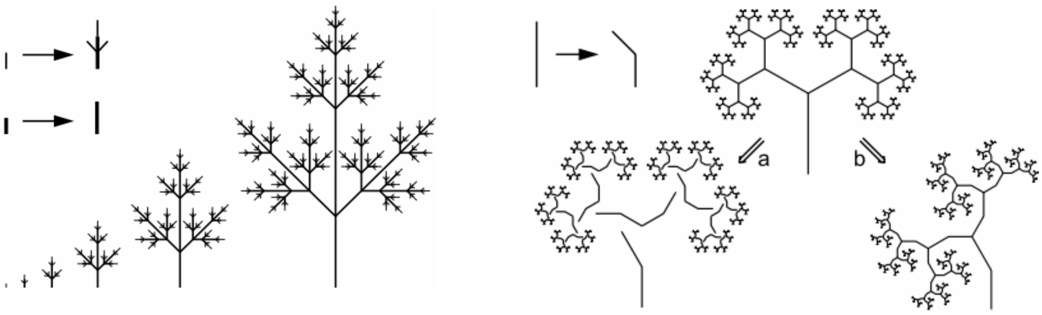


Shape grammar generated of the repeated use (a,b,c) (Stiny & Gips, 1971, p.132)

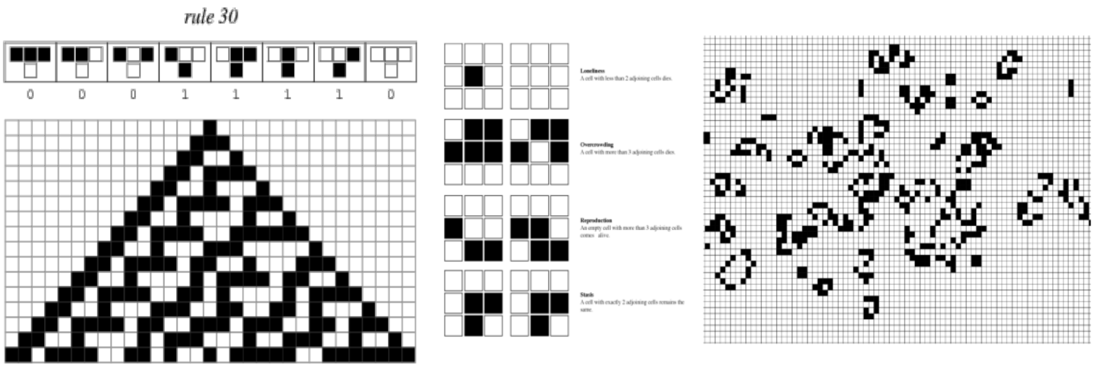




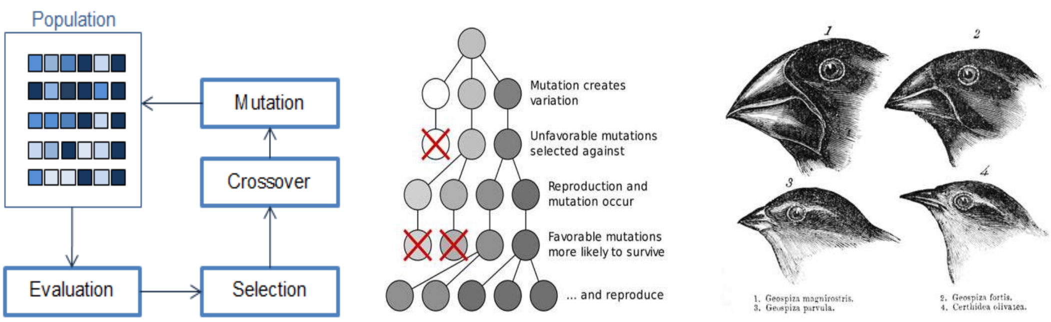
Aristid Lindenmayer, Mathematical models for cellular interaction in development (1968)



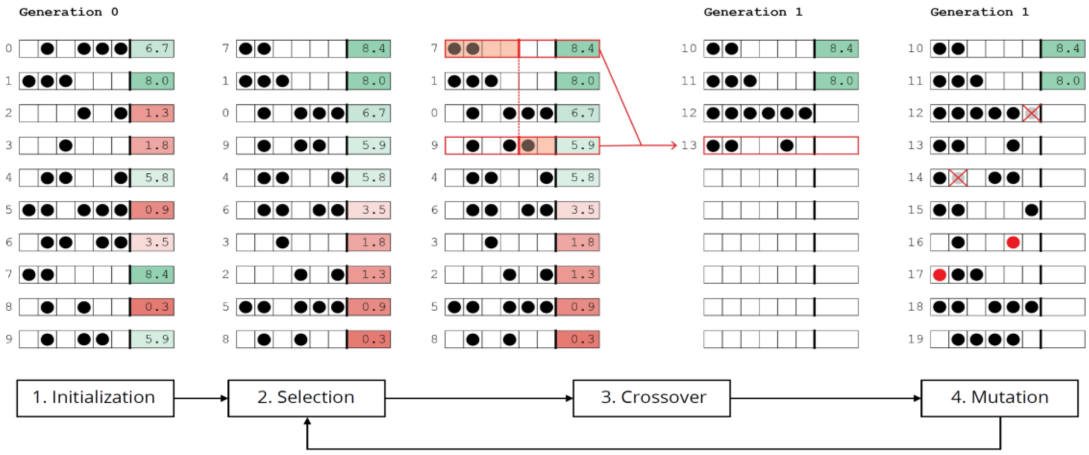
Plant development as a rewriting process. (Left) Developmental model of a compound leaf; (right) comparison of the construction (Prusinkiewicz et al., 1996, p. 2).



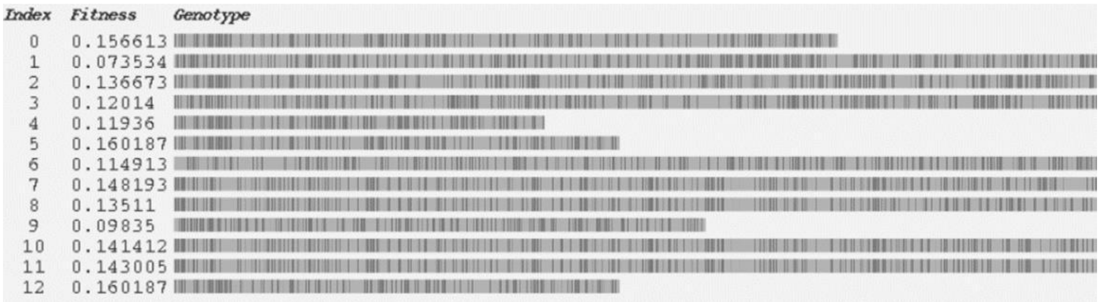
(left) Statistical Mechanics of Cellular Automata (Wolfram, S. 1983). (Right) From Math World-A Wolfram Web Resource (John Conway's Game of Life, 1970).



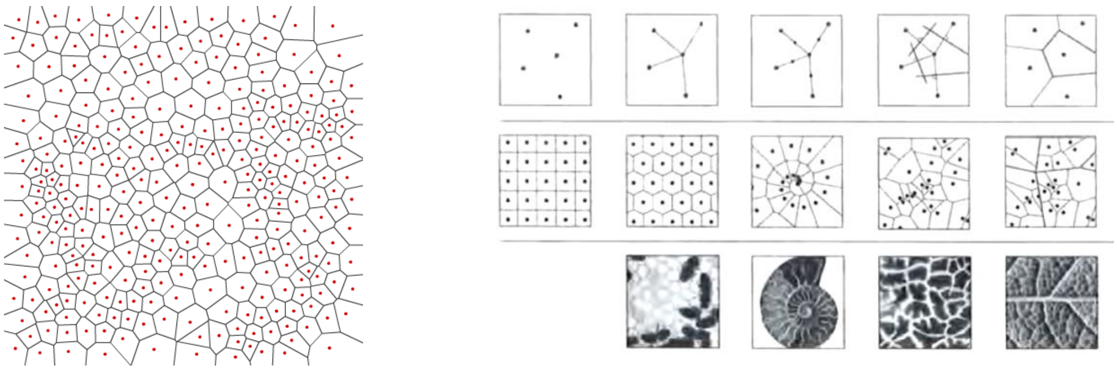
(left) Genetic Algorithms explanation. (Right) Natural evolution process (Source:https://www.fontenay-ronan.fr/unrelated-parallel-machine-scheduling-problem-heuristic-genetic-algorithm/)



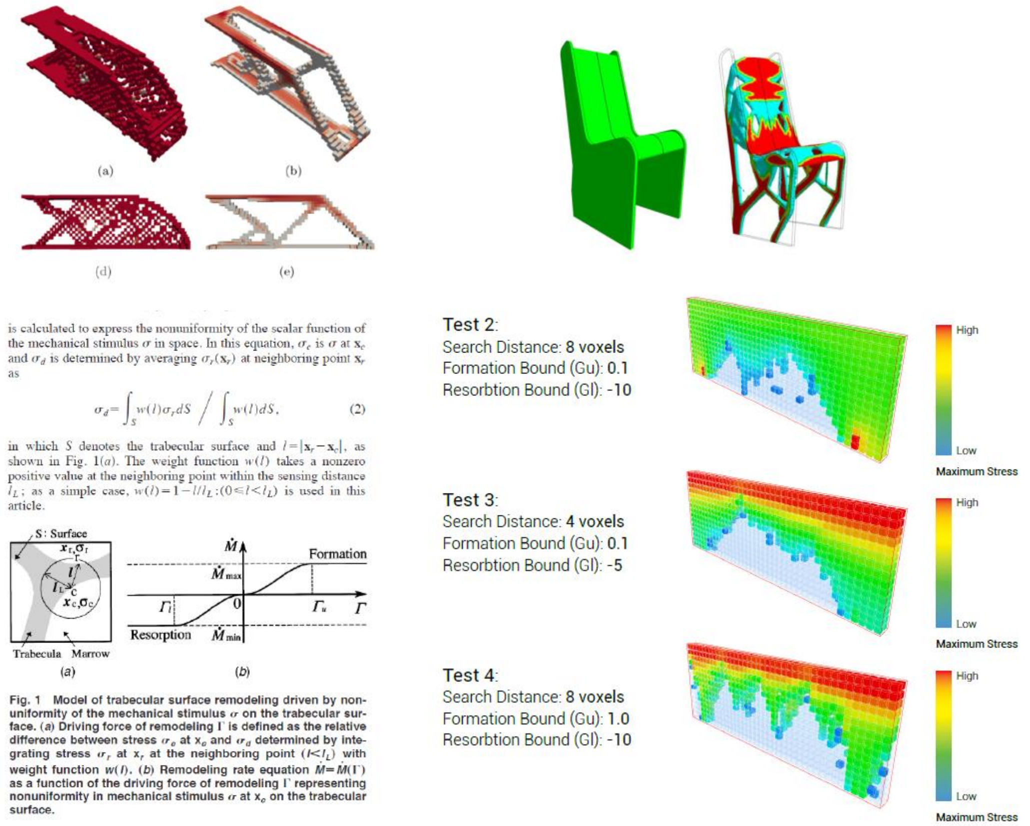
Genetic algorithm steps illustration (Source: Danil Nagy ,2019)



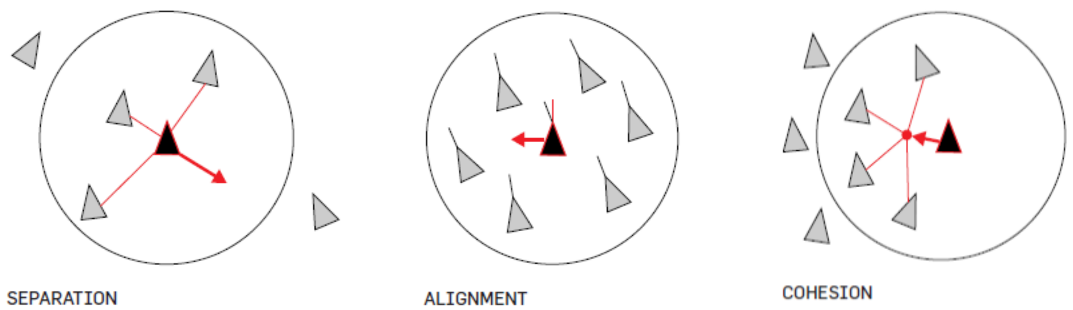
Representation of Genomes (Source: Visual analysis of evolutionary algorithms, 1999).



Voronoi Diagram representations and applications. (Left) source: Nowak, 2015. (Right) Source: Jane Burry and Mark Burry, 2010.

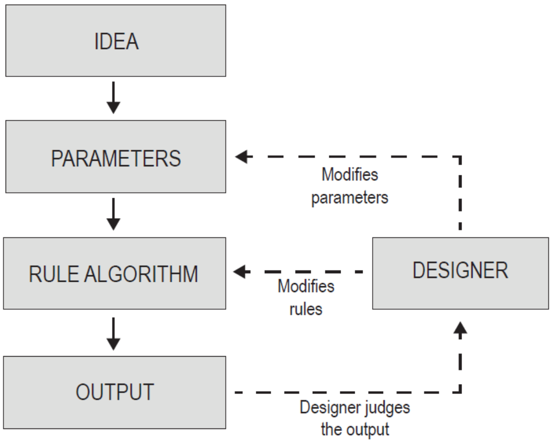


Application example of topology optimization in the field of structural analysis. Source: Danil Nagy and David Benjamin, Trabecular bone growth optimization (2013).

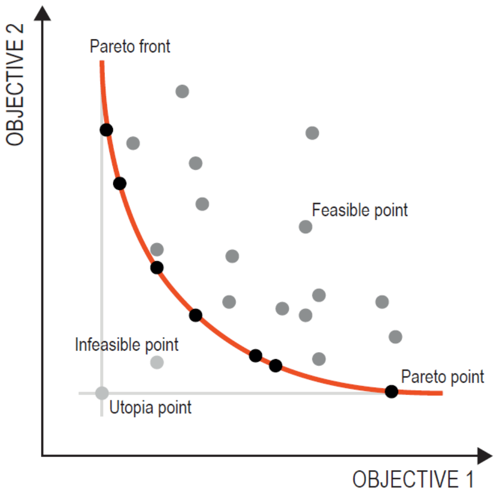


Mathematical models to simulate and understand the swarm behavior. source: Reynolds CW (1987).

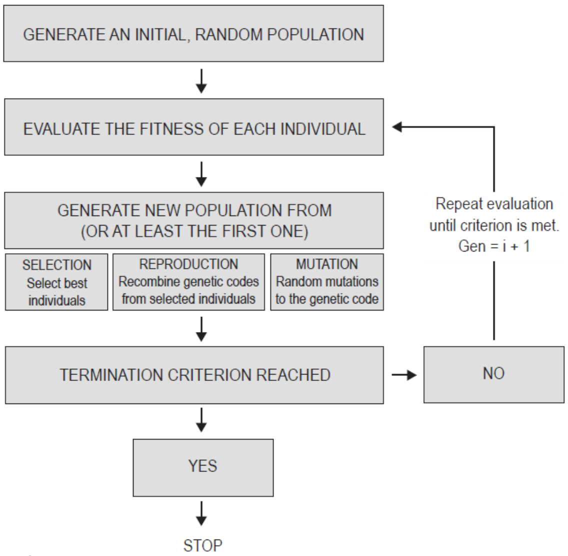
APPX-3. Generative Design Optimization and Applications Methods



Flow chart over a design process. source: Henriksson & Hult (2015)

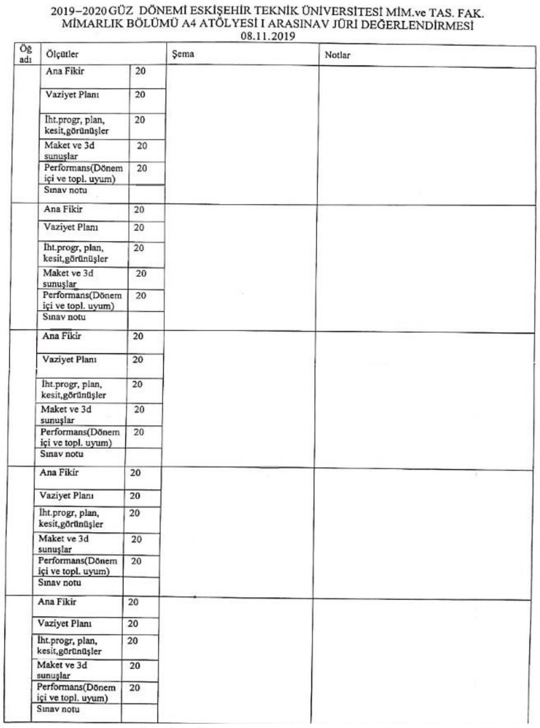


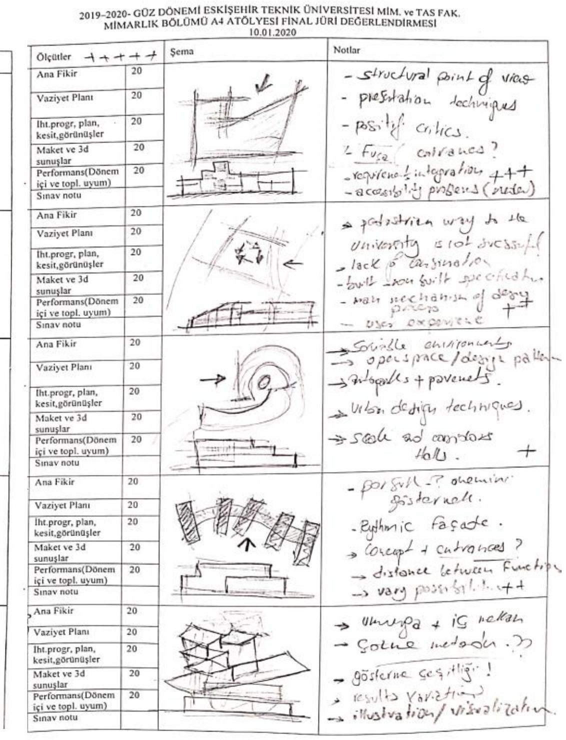
Pareto front for a bi-objective optimization problem. Source: Henriksson & Hult (2015)

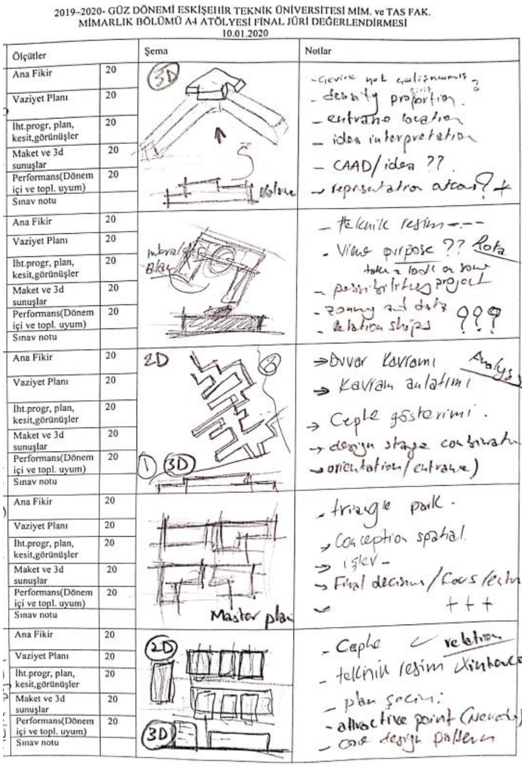


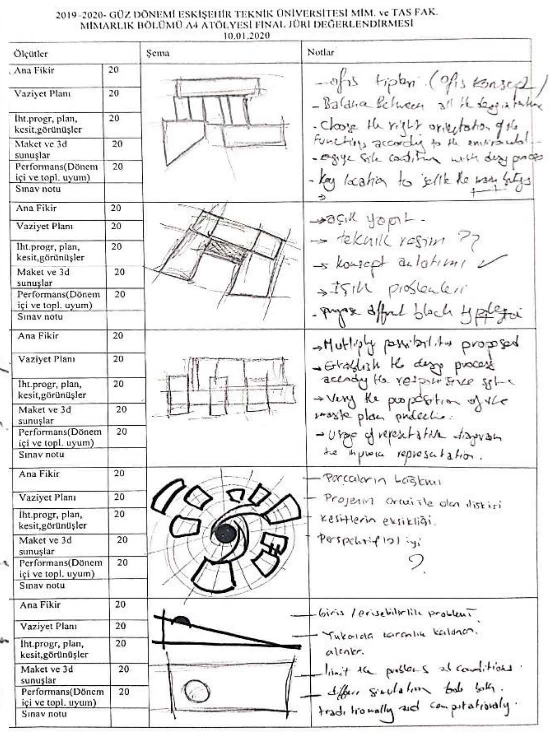
Flow chart of genetic algorithm optimization. Source: Henriksson & Hult (2015)

APPEX-4. Design Studio-Based Experiment Assessment Tool (Examples)

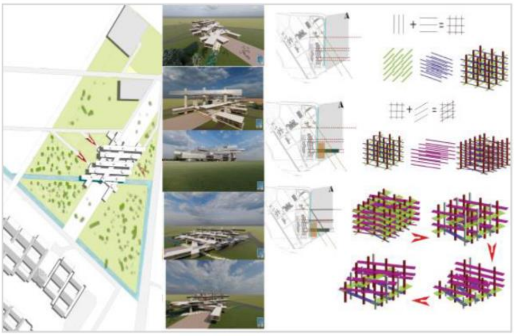


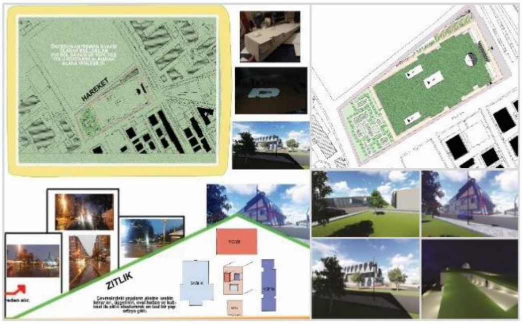


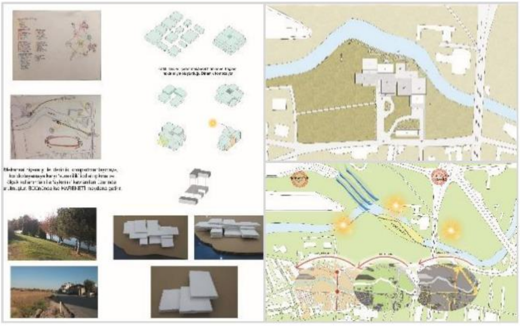


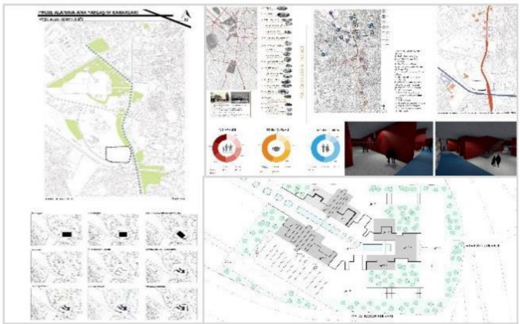


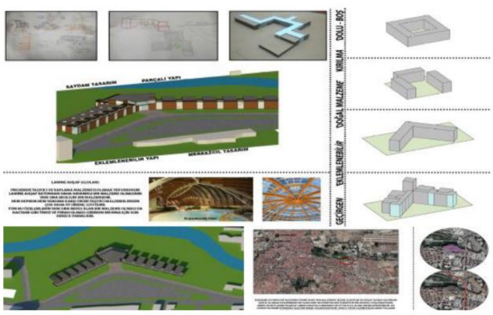
APPEX-5. Some of the Students Works During Studio-Based Experiments

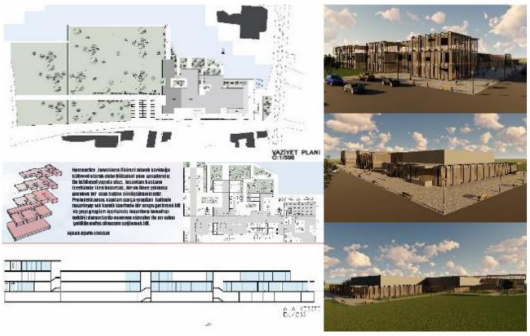




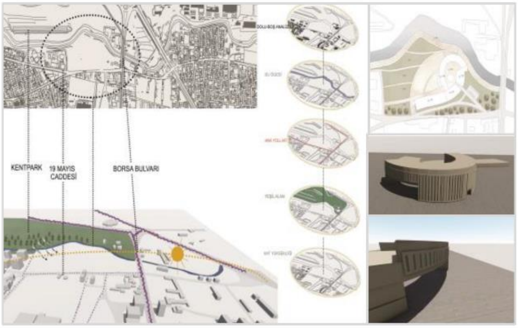


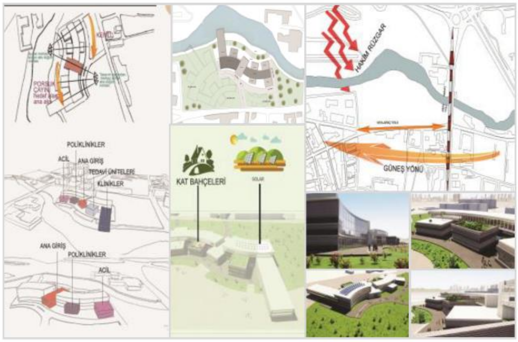


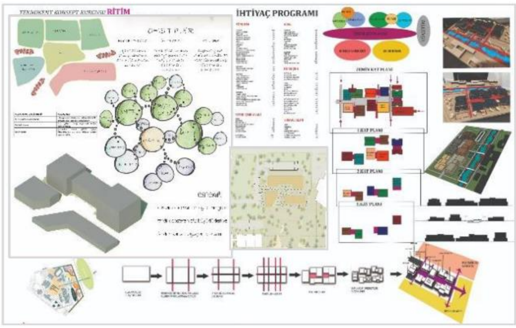


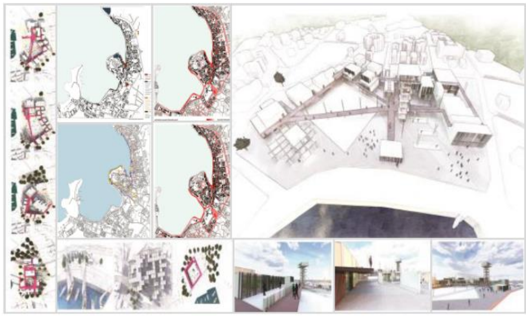

VAZİYET PLANI

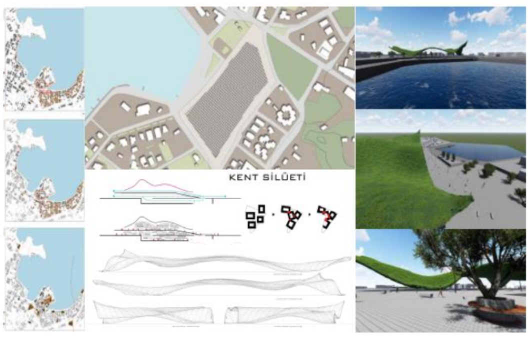

A-A KESİTİ


KENTPARK
19 MAYIS CADDESİ
BORSA BULVARI


POLİKLİNİKLER
ACİL
ANA GİRİŞ
TEDAVİ ÜNİTELERİ
KLİNİKLER
KAT BAHÇELERİ
HAKİM RÜZGAR
GÜNEŞ YÖNÜ


RİTİM
İHTİYAÇ PROGRAMI

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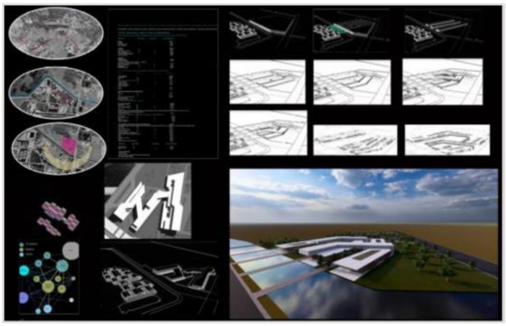
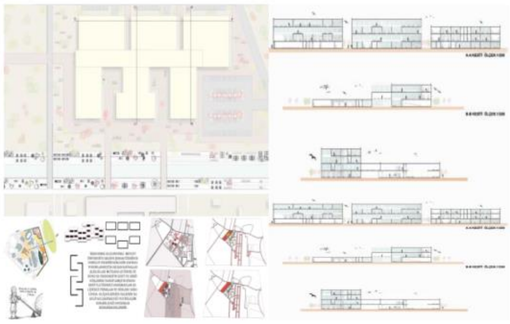
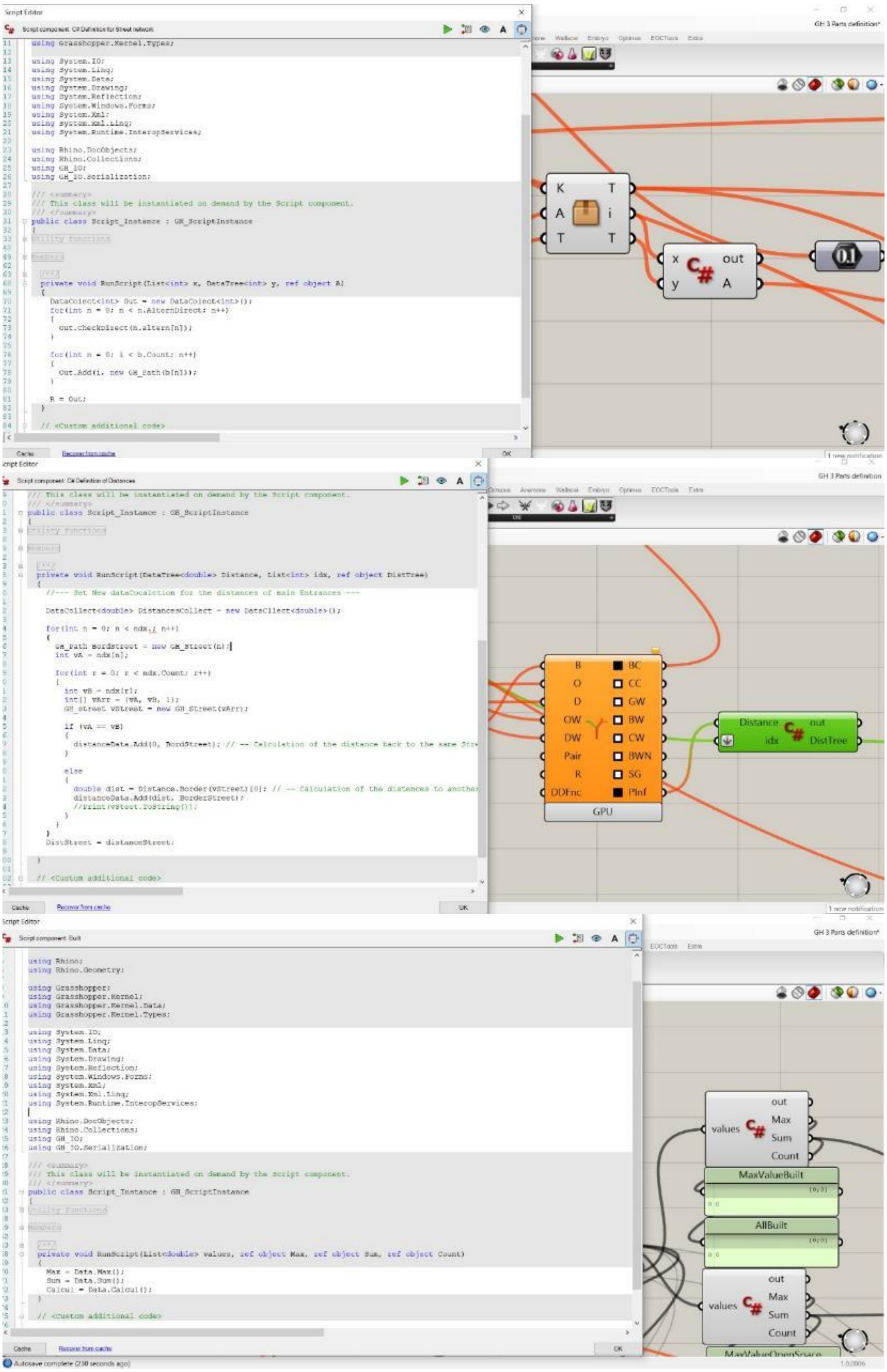




APPX-6. C# Scripts Examples Used for GH Generative Design System



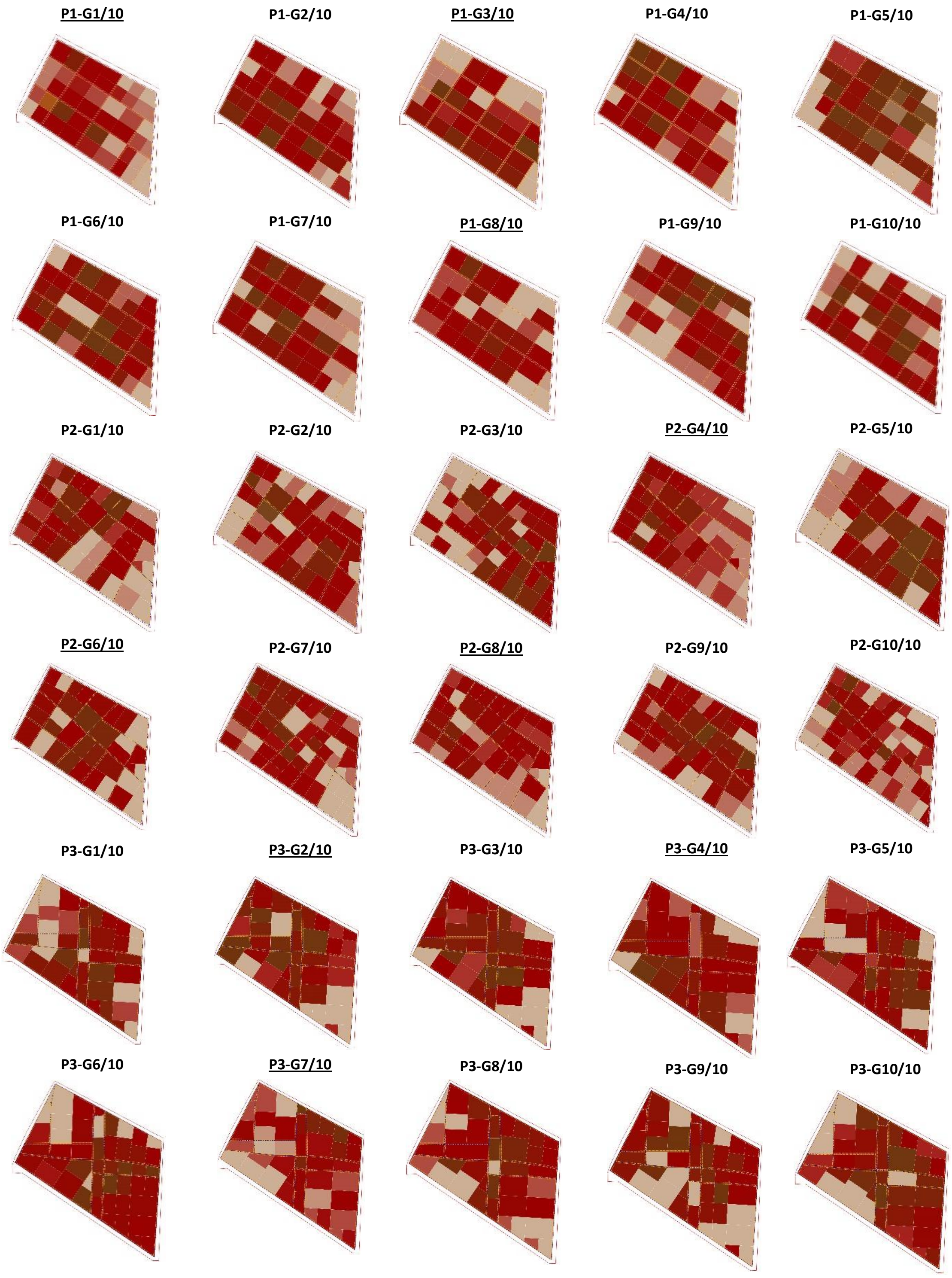
APPX- 7 Unscaled (Real) Numerical Data Both Inserted and Resulted (GDS)

	Possibilities	Generation	Iteration (loop)	Reference (Parcel Number)	Parcels width (Max) GH	Parcels Size (Min/ Max) m2	Dense Area (Min/ Max)%	Buildable area (Min/ Max)%	Gross Floor Area GFA (Min/ Max)m2	Travel Distance (Min)m
Pattern 01	**P 1**	**P1-G1/10**	**3**	**PN 26**	**50**	**483.52/ 1907.19**	**53.07/ 82.55**	**93.18/ 295.91**	**279.57/ 738.42**	**53.87**
	P 2	P1-G2/10	5	PN14	55	640.68/ 2065.41	52.62/ 86.01	76.53/ 284.69	136.29/ 637.99	58.09
	P 3	**P1-G3/10**	**7**	**PN36**	**60**	**640.68/ 2984.32**	**52.93/ 82.01**	**36.59/ 201.17**	**109.79/ 437.26**	**56.97**
	P 4	P1-G4/10	9	PN35	60	640.68/ 2984.32	57.52/ 82.55	55.39/ 223.55	166.17/ 538.33	63.37
	P 5	P1-G5/10	12	PN46	56	640.67/ 2065.42	49.28/ 86.01	35.65/ 284.69	106.98/ 53.81	57.84
	P 6	P1-G6/10	1	PN16	55	640.67/ 2065.42	52.71/ 86.01	77.27/ 284.69	172.50/ 637.99	57.89
	P 7	P1-G7/10	4	PN06	55	640.67/ 2065.42	52.61/ 86.01	60.94/ 254.22	182.85/ 591.88	57.62
	P 8	**P1-G8/10**	**3**	**PN01**	**60**	**640.68/ 2984.32**	**59.40/ 86.01**	**73.69/ 235.84**	**200.57/ 586.68**	**56.84**
	P 9	P1-G9/10	15	PN44	48	479.12/ 1907.19	49.25/ 82.55	31.93/ 237.57	95.79/ 664.95	60.61
	P 10	P1-G10/10	10	PN28	49	479.12/ 1907.19	47.79/ 82.55	21.43/ 238.79	85.73/ 546.13	58.60
Pattern 02	P1	P2-G1/10	4	PN42	55	362.76/ 2214.76	48.69/ 90.07	37.53/ 237.32	150.10/ 724.64	50.96
	P 2	P2-G2/10	7	PN29	55	362.76/ 2214.76	38.45/ 90.07	37.52/ 227.16	112.58/ 559.28	51.5
	P 3	P2-G3/10	11	PN35	52	362.76/ 2029.69	38.46/ 85.03	19.15/ 250.60	95.72/ 691.48	53.64
	P 4	**P2-G4/10**	**14**	**PN12**	**54**	**362.76/ 2214.76**	**38.46/ 90.07**	**6.26/ 247.22**	**46.34/ 573.13**	**54.59**
	P 5	P2-G5/10	3	PN08	60	622.17/ 2435.54	53.63/ 93.89	33.08/ 277.2	99.23/ 550.96	50.98
	P 6	**P2-G6/10**	**12**	**PN01**	**58**	**362.76/ 2405.24**	**53.88/ 93.09**	**72.38/ 286.21**	**144.15/ 453.62**	**54.50**
	P 7	P2-G7/10	5	PN27	51	362.76/ 2207.49	44.13/ 85.03	71.91/ 316.32	143.81/ 743.60	54.50
	P 8	**P2-G8/10**	**13**	**PN32**	**53**	**362.76/ 2207.49**	**48.08/ 85.03**	**37.90/ 283.2**	**122.68/ 684.61**	**56.08**
	P 9	P2-G9/10	2	PN20	55	362.76/ 2214.76	38.46/ 90.07	30.83/ 267.83	92.50/ 577.03	58.67
	P10	P2-G10/10	8	PN49	51	362.76/ 2207.49	44.13/ 85.02	4.96/ 272.97	34.67/ 1211.59	54.74
Pattern 03	P 1	P3-G1/10	6	PN12	60	212.51/ 2500.07	42.69/ 94.83	8.75/ 295.83	34.82/ 389.45	165.35
	P 2	**P3-G2/10**	**13**	**PN26**	**60**	**212.51/ 2500.07**	**34.76/ 49.83**	**8.71/ 295.83**	**33.20/ 389.45**	**36.75**
	P 3	P3-G3/10	9	PN04	65	212.51/ 2500.07	34.76/ 94.83	5.01/ 279.65	34.15/ 447.44	34.17
	P 4	**P3-G4/10**	**12**	**PN08**	**67**	**212.51/ 2212.39**	**42.69/ 127.66**	**9.11/ 295.83**	**33.20/ 423.89**	**30.05**
	P 5	P3-G5/10	11	PN46	55	212.51/ 2212.39	46.27/ 89.91	20.97/ 242.67	41.93/ 366.67	38.74
	P 6	P3-G6/10	4	PN38	75	212.51/ 2212.39	34.76/ 89.91	8.70/ 295.83	34.82/ 368.05	36.97
	P 7	**P3-G7/10**	**14**	**PN15**	**60**	**212.51/ 2500.07**	**34.76/ 94.83**	**8.70/ 295.83**	**33.20/ 368.05**	**30.07**
	P 8	P3-G8/10	9	PN32	61	212.51/ 2500.07	34.76/ 94.83	4.75/ 274.10	85.47/ 378.46	36.67
	P 9	P3-G9/10	2	PN24	57	212.51/ 2212.39	34.76/ 89.27	16.14/ 250.83	45.06/ 387.06	39.23
	P10	P3-G10/10	9	PN52	60	212.51/ 2500.07	34.76/ 94.83	8.70/ 295.83	34.82/ 389.45	36.61

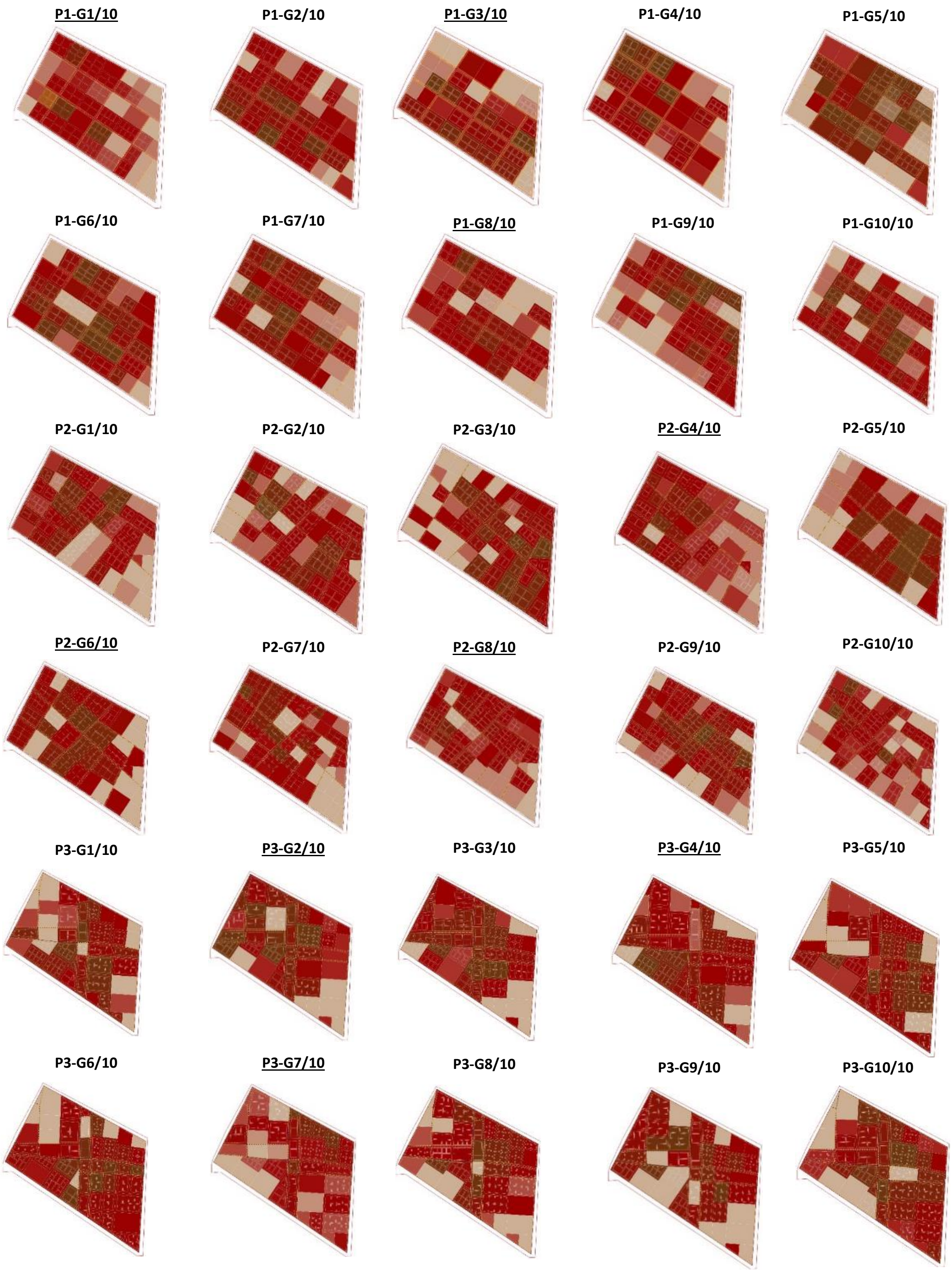
Results of the functions distributions after generation (GDS)

	Possibilities	Generation	Academic Units	Social Units	Administrative units	Technical Units	OSR	GSI	FAR
Pattern 01	**P 1**	**P1-G1/10**	**≤**	**≤**	**≈ 2.6%**	**≈ 2.2%**	**12**	**≤**	**0.48**
	P 2	P1-G2/10	≈ 35.5%	≤	≤	≤	12	≤	≤
	P 3	**P1-G3/10**	**≤**	**≈ 64%**	**≤**	**≈ 2%**	**12**	**0.30**	**≤**
	P 4	P1-G4/10	≤	≤	≤	≈ 2%	11	≤	≤
	P 5	P1-G5/10	≈ 37%	≤	≤	≤	10	≤	≤
	P 6	P1-G6/10	≈ 36.5%	≤	≤	≤	9	≤	≤
	P 7	P1-G7/10	≤	≤	≈ 2.5%	≤	11	≤	0.49
	P 8	**P1-G8/10**	**≤**	**≈ 63%**	**≤**	**≈ 2.1%**	**12**	**0.28**	**≤**
	P 9	P1-G9/10	≤	≈ 63%	≤	≤	15	≤	≤
	P 10	P1-G10/10	≤	≤	≈ 2.6%	≤	10	≤	0.47
Pattern 02	P1	P2-G1/10	≤	≈ 64.5%	≤	≈ 1.9%	10	≤	≤
	P 2	P2-G2/10	≤	≤	≈ 2.35%	≤	15	≤	0.48
	P 3	P2-G3/10	≈ 37%	≈ 63%	≤	≤	09	0.28	≤
	P 4	**P2-G4/10**	**≈ 37%**	**≤**	**≈ 2.6%**	**≤**	**13**	**≤**	**0.49**
	P 5	P2-G5/10	≤	≈ 63%	≤	≤	13	≤	≤
	P 6	**P2-G6/10**	**≤**	**≤**	**≈ 2.7%**	**≤**	**12**	**≤**	**0.47**
	P 7	P2-G7/10	≤	≤	≈ 2.15%	≤	12	≤	≤
	P 8	**P2-G8/10**	**≤**	**≤**	**≈ 2.6%**	**≈ 2.2%**	**13**	**0.28**	**≤**
	P 9	P2-G9/10	≤	≤	≈ 2%	≤	10	≤	0.49
	P10	P2-G10/10	≈ 36%	≈ 64%	≤	≤	12	0.26	≤
Pattern 03	P 1	P3-G1/10	≤	≈ 65%	≤	≈ 1.9%	12	≤	≤
	P 2	**P3-G2/10**	**≈ 37%**	**≈ 64%**	**≤**	**≤**	**10**	**≤**	**0.47**
	P 3	P3-G3/10	≤	≤	≈ 2.4%	≤	11	≤	0.49
	P 4	**P3-G4/10**	**≈ 38%**	**≈ 66%**	**≤**	**≤**	**14**	**0.30**	**≤**
	P 5	P3-G5/10	≤	≈ 64%	≤	≈ 1.95%	11	≤	≤
	P 6	P3-G6/10	≈ 36%	≤	≤	≤	09	≤	≤
	P 7	**P3-G7/10**	**≈ 36%**	**≈ 63%**	**≤**	**≤**	**12**	**0.29**	**≤**
	P 8	P3-G8/10	≤	≤	≤	≈ 2%	13	≤	≤
	P 9	P3-G9/10	≤	≈ 63.5%	≤	≤	10	≤	≤
	P10	P3-G10/10	≤	≤	≈ 2.2%	≤	10	≤	0.48

APPX-8 Outcomes of The 30 Generation Possibilities (Plans and Evaluation Diagrams)

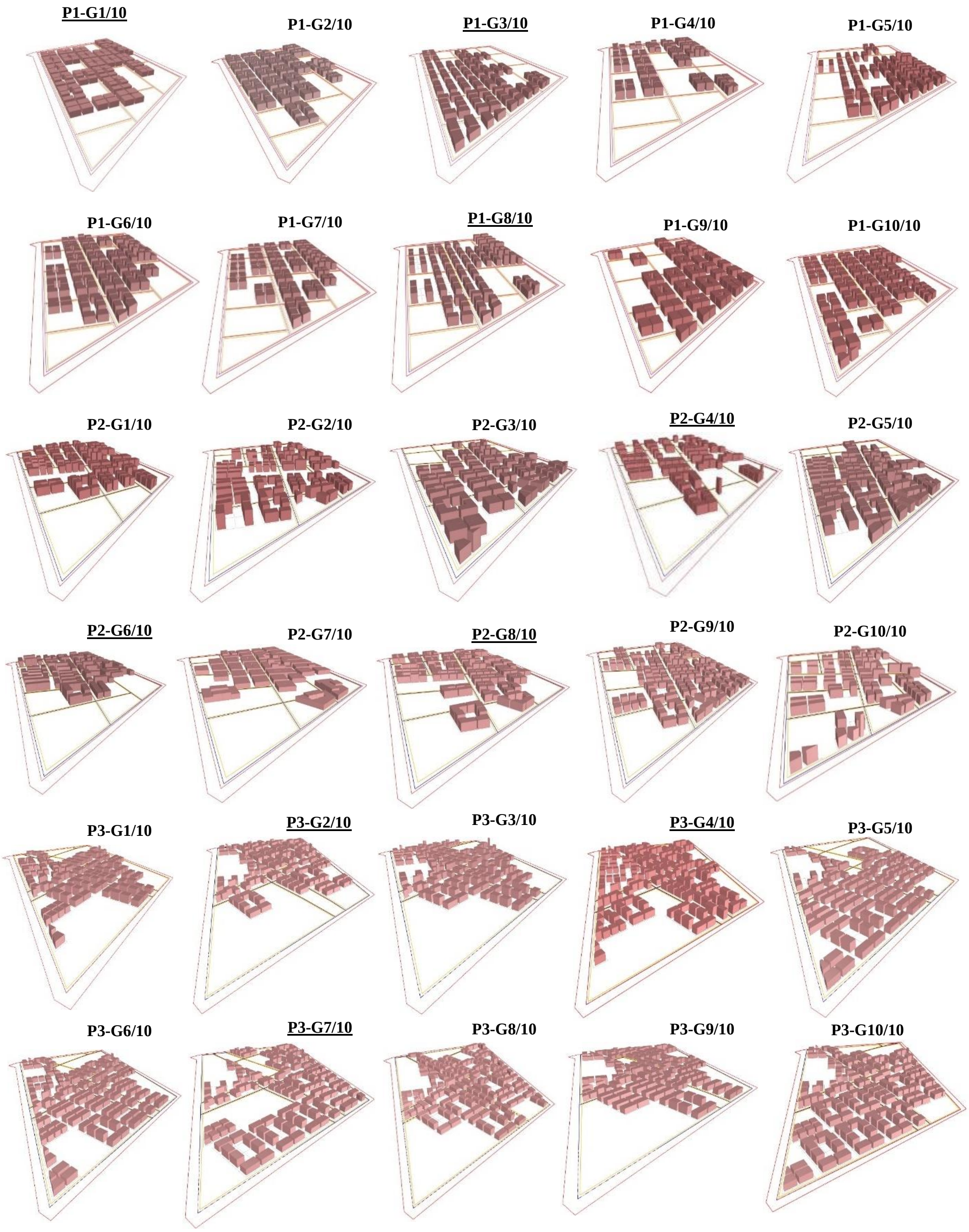


Buildings footprints



Built and Non-Built Ration

Volume Extrusion – View 01



Volume Extrusion – View 02

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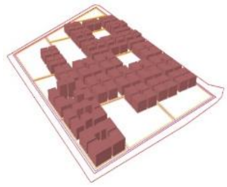
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P1-G3/10

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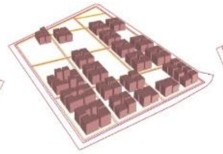
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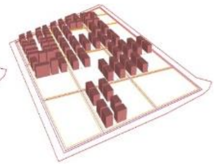

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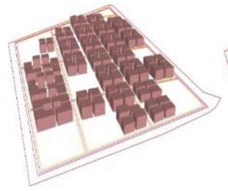
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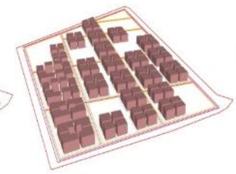
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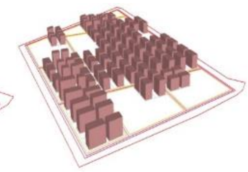
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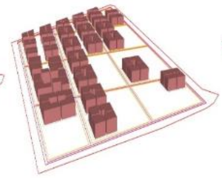
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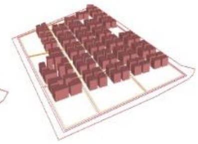

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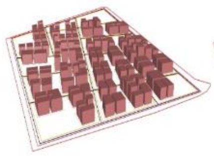
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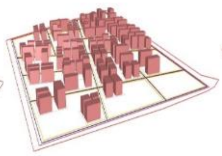
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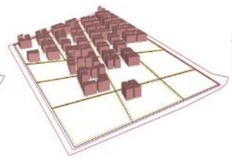
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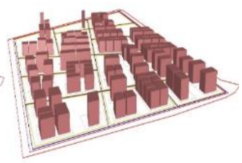
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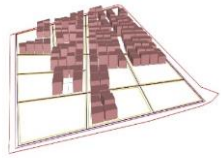

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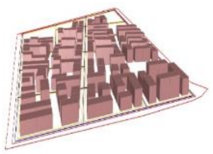
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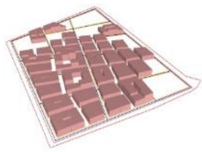
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P2-G9/10

P2-G10/10


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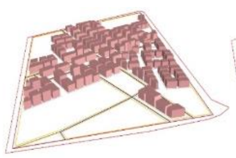
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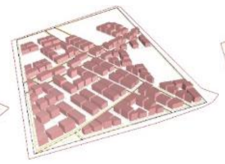
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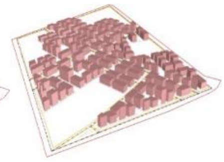
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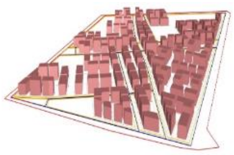
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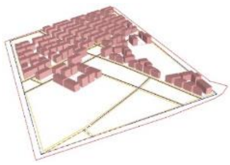

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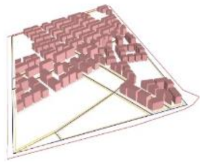
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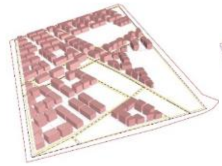
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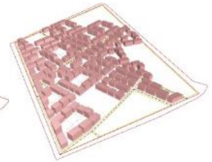
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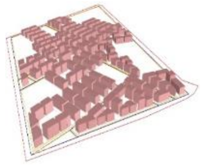
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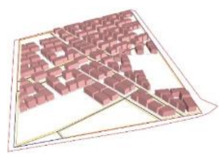

Functions Arrangements

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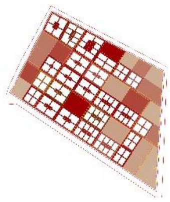
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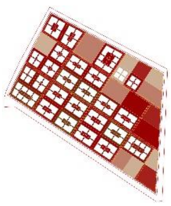
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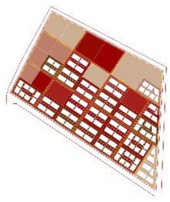
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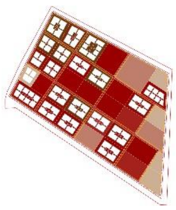
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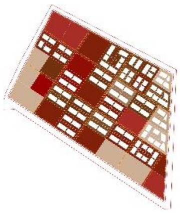
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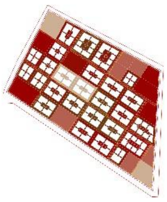
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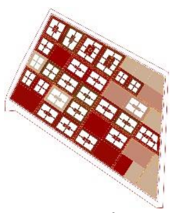
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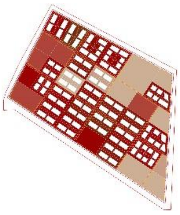
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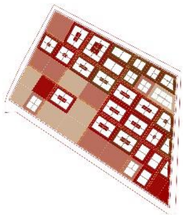
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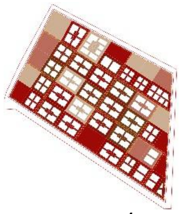
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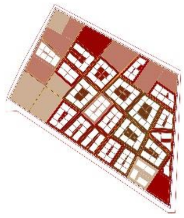
P2-G2/10

P2-G3/10

P2-G4/10

P2-G5/10

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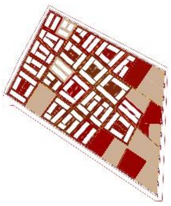
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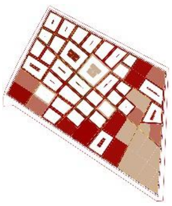
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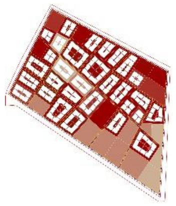
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P2-G10/10

P3-G1/10

P3-G2/10

P3-G3/10

P3-G4/10

P3-G5/10

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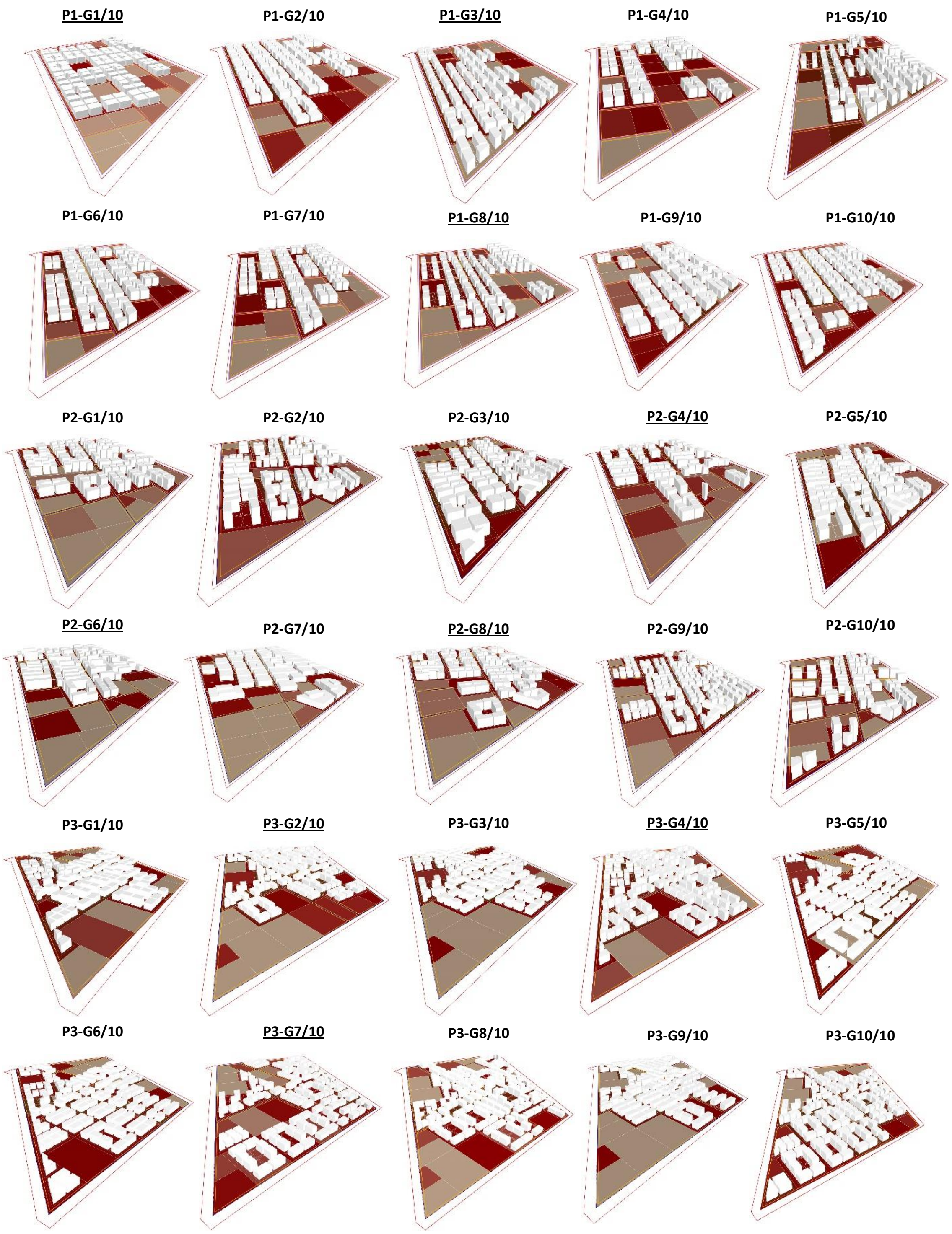
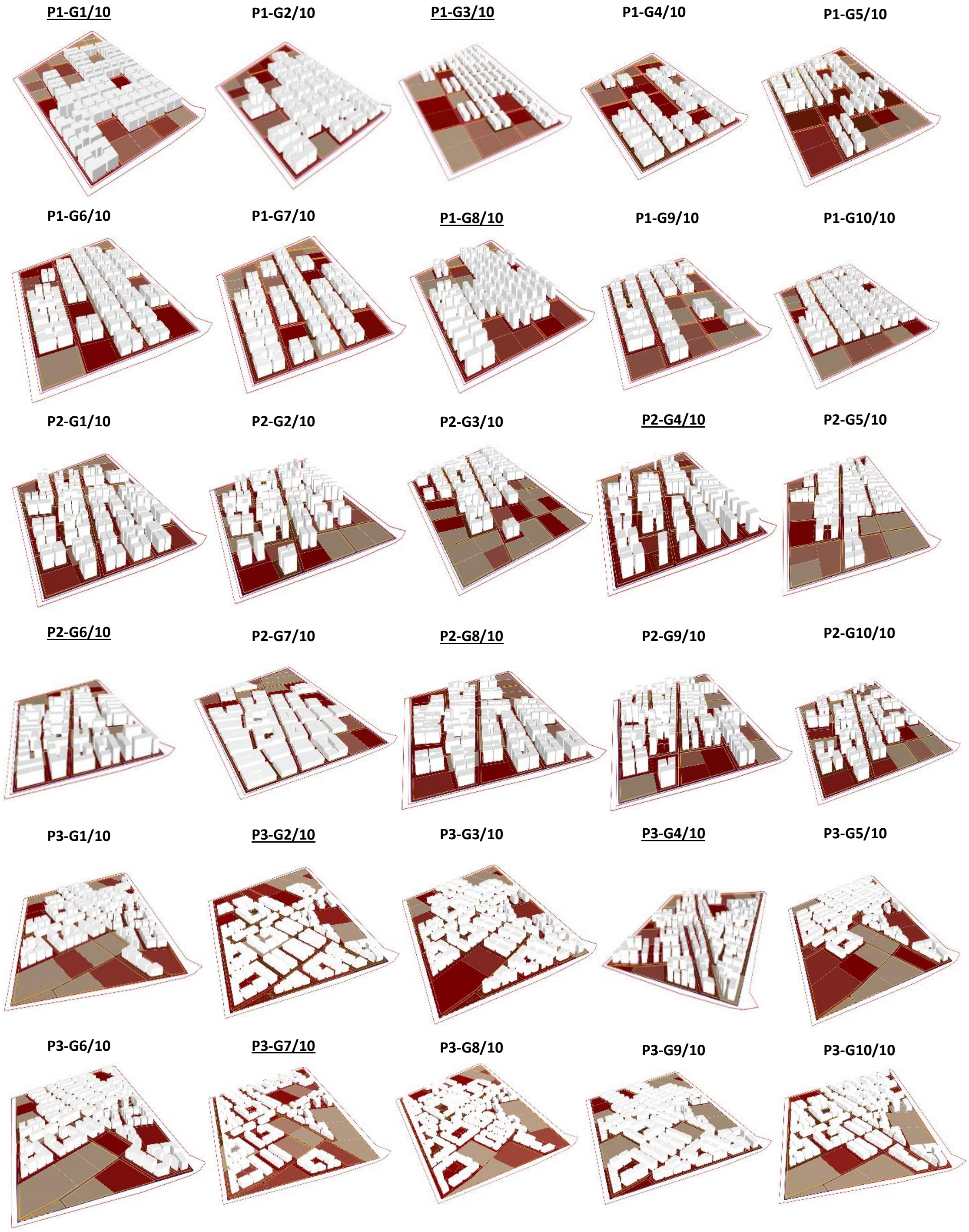
P3-G9/10

P3-G10/10


3D Visualization – View 01



3D Visualization – View 02



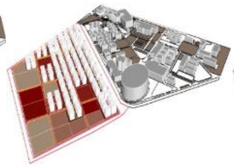
General Arrangement with ESTU Campus Master Plan

General View with ESTU Campus Master Plan and Extension Area - 01

General View with ESTU Campus Master Plan and Extension Area - 02

P1-G1/10

P1-G2/10

P1-G3/10

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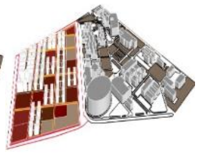

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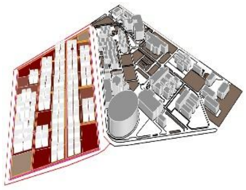
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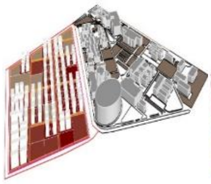
P1-G8/10

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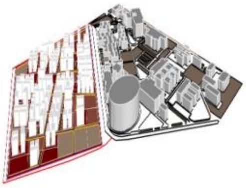
P1-G10/10


P2-G1/10

P2-G2/10

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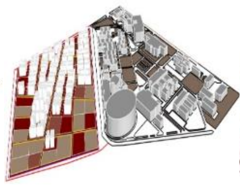
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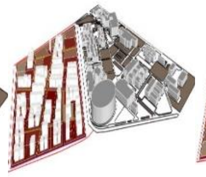
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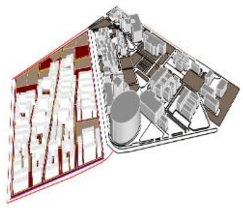
P2-G6/10

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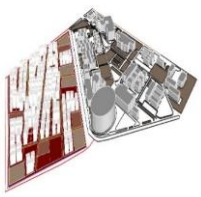
P2-G8/10

P2-G9/10

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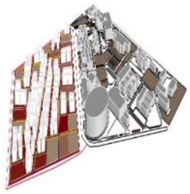

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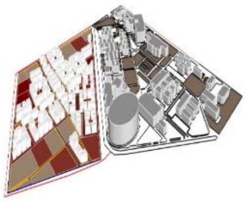
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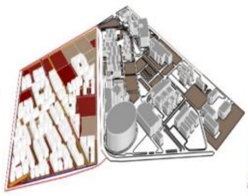
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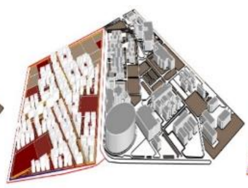
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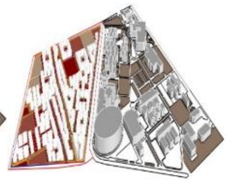
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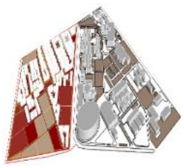

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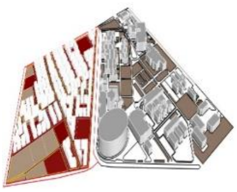
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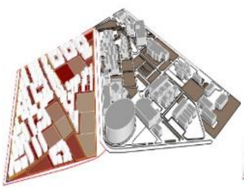
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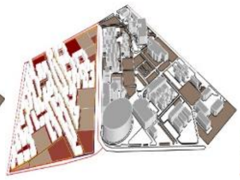
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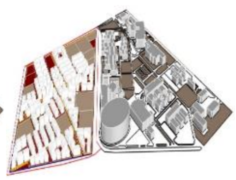
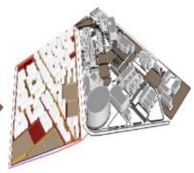
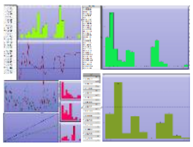

P3-G10/10


Evaluation And Optimization Data Collection Diagrams – 30 generations

P1-G1/10



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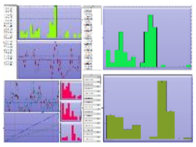

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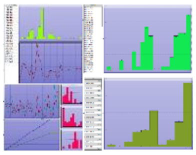

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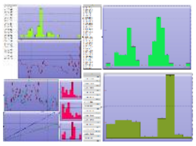

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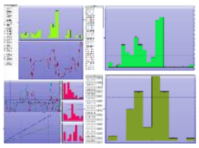

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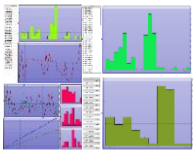

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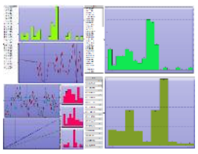

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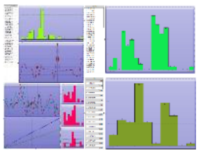

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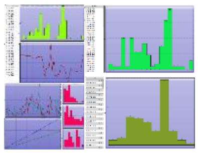

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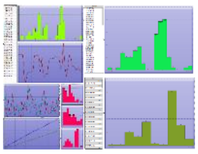

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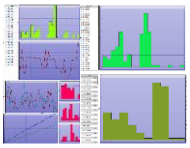

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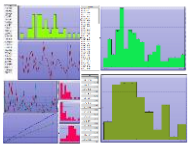

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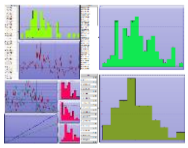

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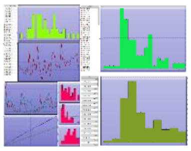

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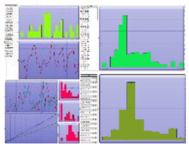

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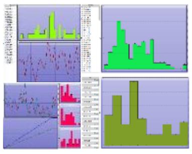

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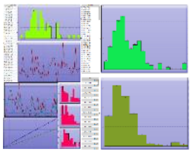

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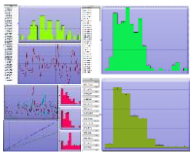

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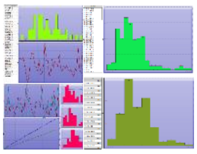

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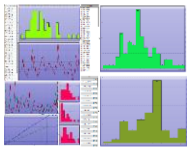

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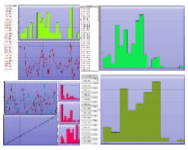

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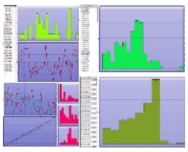

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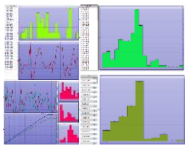

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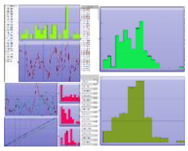

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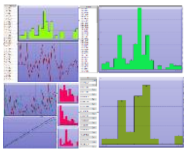

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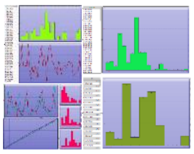

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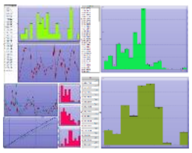

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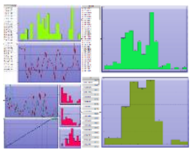

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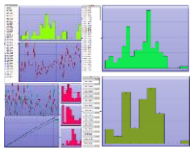

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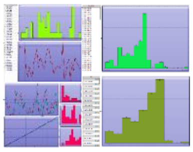

APPX-9. Final Visualization of the Generative Design System Outcomes (3 Patterns)

Pattern 01

Pattern 02




Pattern 03