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Designing for Mass Customization Housing through Generative Design

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DESIGNING FOR MASS CUSTOMIZATION HOUSING THROUGH GENERATIVE DESIGN

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ABSTRACT

This research proposal aims to investigate computational design strategies for sustainable, affordable, and more equitable housing. The study will focus on the use of generative design tools, such as parametric modeling, rule-based modeling, and optimization, to aid architects and designers in creating custom housing complexes for single families in small and medium urban lots. The goal is to develop a computational method that considers sustainability, affordability, and long-term usage parameters to create housing designs that meet the desired spatial qualities. The research question asks how generative design tools can support designers in approaching affordable housing given the increasing demand for it. The study will explore a modular grid-based design approach to ensure consistency and alignment and establish connections between individual spaces to form a complete house floor plan. The proposed research will consider site constraints and analyze existing buildings, trees, and zoning regulations to tailor the aggregation system. The stochastic aggregation component will generate numerous floor plans, and the optimization component will search for specific floor plans based on the requirements to evaluate the most suitable floor plans for any given scenario.

INTRODUCTION

This research proposal addresses computational design strategies for sustainable, more equitable, and more affordable housing. It investigates the use of parametric modeling, rule-based modeling, and optimization for the design of housing complexes for single families in small and medium urban lots, with a focus on construction metrics, such as cost, and general sustainability metrics, such as accessibility, and daylight saving. The goal is to design, implement, and test a computational method that aids architects and designers in approaching housing that takes into consideration parameters related to sustainability, affordability, and long-term usage.

This research is motivated by the ongoing global urban housing affordability crisis, which continues to grow increasing displacement and homelessness rates. In 2005 it was estimated 100 million people were homeless, and 1.6 billion people lacked adequate housing ("Global Poverty & Homelessness Statistics 2021" 2021). Expenses are growing at faster rates than salary and wage rates in many countries which continuously feeds into the lack of affordability crisis. Many people end up living in overcrowded or uninhabitable conditions, others stay in a compromised situation as food, health care, and educational purposes eat most of their salary. The housing crisis is fed by unsubstantial economic situations and political conflicts such as environmental crisis and war. Many citizens are being displaced, increasing the demand in a housing market already in shortage. Although the population of many places, such as Rio de Janeiro, Brazil, and La Paz, Bolivia, finds ways to "solve" the housing problem, without the support of designers and engineers, the results end up with poor unlivable conditions and often without infrastructure.

This leads to the following research question: how can available generative design tools and techniques enable the quick exploration of custom designs in the face of an increasing demand for affordable housing?

This research approaches this question from a constructive perspective, by designing, implementing, and testing a computational method for the problem of affordable and sustainable housing. The resulting prototype will be tested by addressing

specific housing design cases in real sites. The aim is to assess the potential of the generative design tool to create designs supporting designers to create designs that meet the requirements of affordability and sustainability, while also achieving desired spatial qualities.

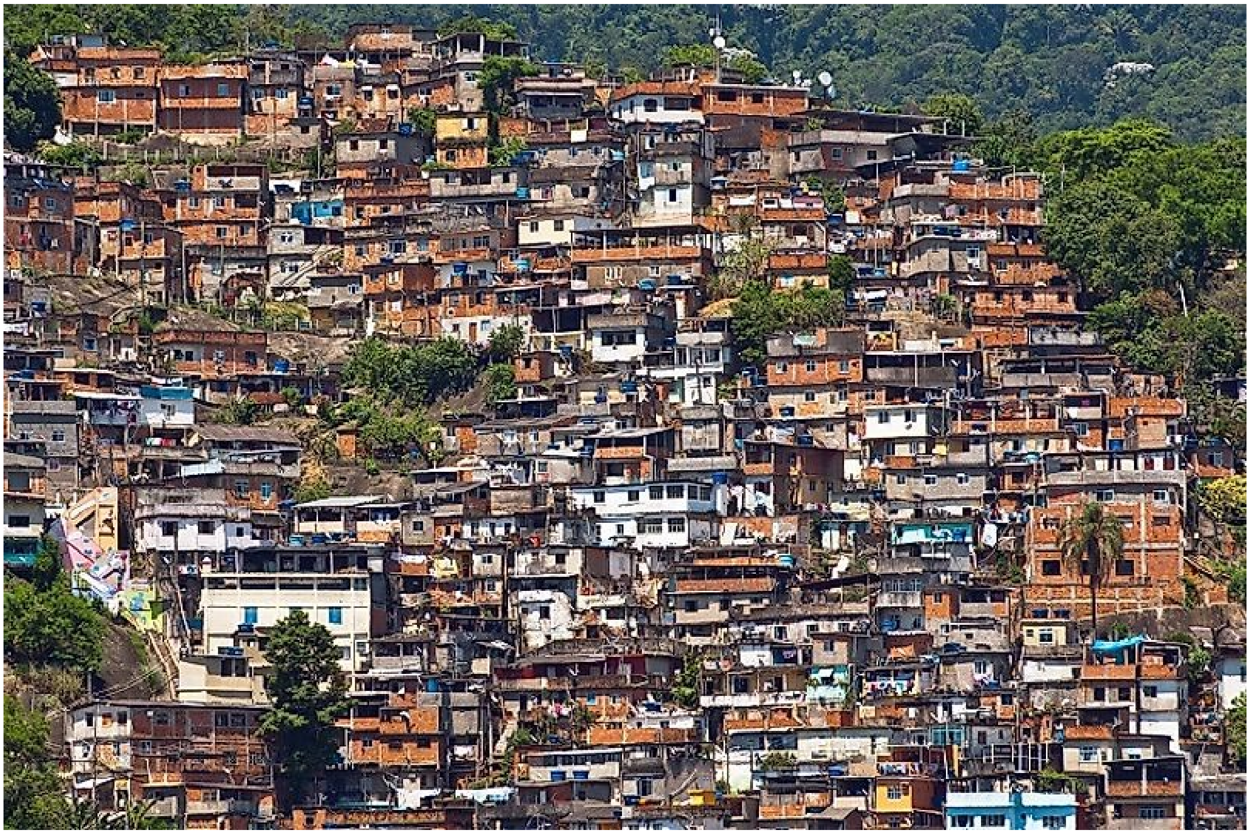


Figure 1 A crowded favela on the outskirts of Rio de Janeiro. Image from (Sheth 2017)

Figure 2 Poverty Homes in La Paz, Bolivia. Images from ("TECHO Bolivia," n.d.)

Figure 3 Poverty Homes in La Paz, Bolivia. Images from ("TECHO Bolivia," n.d.)

Figure 2 Ukrainian citizens fleeing their country. Images from (Corbett 2022)

PROJECT BACKGROUND

As mentioned before, the rapid urbanization and ongoing housing crisis are the motivations behind the investigation of a computational method to make decisions related to sustainability and affordability more accessible to designers and clients. Affordable and sustainable housing has extensive meaning, but we will focus on the affordability of the modular design allowing for prefabricated panels to be determined and specific environmental qualities of the building configurations. The use of generative design can also provide a tool to create low-rise densification without compromising living conditions. The following section is organized into topics that will be implemented through the research.

2.1 Low-rise high-density house types

Densification is an ongoing process, what we aim for is low-rise density development which achieves higher density avoiding increased heights and maximizing

unbuilt surface area. Low-rise densification provides residents with spacious and private outdoor areas. The horizontal density has been developed with a compositional logic with no dominant hierarchy. The compositional logic is composed of either repetitive or varied modules creating pattern-like configurations. An important aspect of the configurations is patios or terraces which are necessary for healthy living providing better lighting conditions and ventilation. Another great influence in creating successful low-rise density is the need to organize circulation areas with low hierarchy. Horizontal circulation solutions systems to aim for are alleyways, connecting courtyards, or partially open ground levels.

2.2 Sustainable Design

Our focus on sustainability consists of optimization of the spaces based on direct sun hours exposure. The user will be able to analyze window surface exposure with respect to the amount of radiation absorbed. According to Marilyne Andersen of MIT's Department of Architecture (2006) lighting accounts for 25 to 40 percent of energy consumption. By providing the designer with a daylight optimization tool, we can have considerable financial savings and provide a healthier environment for mental acuity with natural illumination.

2.3 Modular design

The modular design consists of constructing prefabricated structures in sections that are transported to a site and assembled to the foundation. This approach has many benefits in reducing costs, allowing for quick replication, and creating a controlled environment. It saves time by preventing any weather interference or delay. The inventory is more controlled as there is no risk weather can cause material damage and prevents theft. Materials and appliances used in the modules are bought in bulk allowing additional savings. Many industries now provide products where customers can choose what color or configurations they need. We are going to address the same style of mass customization known as assembled-to-stock. ATS provides a range of customization but within set designs and attributes. “Customers can request variations within the set system of form and relationship of elements to one another.”(Smith 2019). Thanks to the evolving technology we can easily create a more customizable process

for units, this will allow us to fulfill the needs of different ways of living and not impose a way of living on owners.

2.4 Generative Design

Generative design incorporates computational techniques to generate design alternatives that meet certain constraints or parameters defined by the designers. This method typically goes through a clear set of steps that are divided into two stages, formulation of the generator as a program or computational model, and execution of the generator during the design to produce a desired output. The generator needs a set of defined inputs as guidance for design exploration and generation.

The two main generative modeling processes that will be adopted are parametric modeling and rule-based modeling. These processes are essential elements to generate custom housing configurations.

> *1. Parametric modeling: is a modeling technique where the design is explicitly modeled from parameters, geometric entities, relationships, and operations. By controlling parameters, such as dimensions or numbers, the resulting geometry of the design is automatically updated by the propagation of the new data over the model.*
>
> *2. Rule-based modeling: This computational design approach uses predefined rules or algorithms based on mathematical and logical expressions to generate designs. It is widely used in fields such as architecture, engineering, and product design to optimize designs based on factors like structural integrity, energy efficiency, manufacturability, usability, and cost. Rule-based modeling helps to automate the design process and explore a wide range of design options, enabling designers to identify effective solutions based on predefined criteria.The rule-based process we are going to use is " Stochastic aggregation, where at each step one rule is randomly selected from the provided rule set. This allows an open growth process, but highly reduces the user's control on the outcome, limited to defining the rule set and a selection probability for each rule.".* (*Rossi, Andrea & Tessmann, Oliver. (2017))*

This work also relies on optimization, which focuses on using algorithms that search for the most effective solutions concerning an objective function/fitness function. This search can look for solutions in the space of the parameters or of the sequence of transformational rules applied to an initial solution. A fitness function "takes an individual and determines how well it fulfills whatever criteria the algorithm is optimizing for." (Kiely, P. (2020, May 25). Introduction to genetic algorithms. FloydHub Blog. https://blog.floydhub.com/introduction-to-genetic-algorithms/)

In this context, the execution of the generator can benefit from fitness functions based on climate, daylight, or geometric properties, such as surface area. "The parameters can represent a way to select the initial state" before the implementation of fitness function optimization. The execution stage reaches an end by synthesizing the alternative solutions given by the optimization process. In a way, Generative design helps us provide a more solutions in a shorter amount of time with clean and set parameters to the design.

Table 1 Grasshopper Plug-Ins

Name	***Category***	***Description***	***Link***
Galapagos	*Optimization*	*Galapagos is a feature embedded in Grasshopper that enables users to optimize shapes to achieve their desired goal.*	*https://grasshopperdocs.com/addons/galapagos.html*
Ladybug	*Environmental Analysis*	*Ladybug is a Grasshopper plug-in that enables visualization and analysis of weather data, including diagrams like sun path and wind rose,*	*https://www.food4rhino.com/en/app/ladybug-tools*

		as well as geometry studies such as radiation analysis, shadow studies, and view analysis.	
Wasp	*Stochastic Aggregation*	*Wasp is a Grasshopper plug-in developed in Python that offers combinatorial design tools for discrete elements and provides aggregation procedures, constraint tools, and visualization utilities.*	*https://www.food4rhino.com/en/app/wasp*

METHOD

We are currently investigating a process that aims to explore the potential of generative design in aiding designers. Our approach involves considering the design of spaces with a modular system, while keeping in mind that these spaces need to work cohesively within a larger system for seamless transitions. To achieve this, we utilize a grid-based design approach to ensure consistency and alignment.

Once the individual spaces are designed, we carefully establish connections between them, taking into consideration how these spaces complement and flow into one another. This phase is called "unit aggregation," where each space is joined together to form a complete house floor plan or "unit." Throughout the research, we have considered multiple steps to ensure the composition and adaptability of the unit aggregation.

In order to provide a comprehensive understanding of the generative process developed for this capstone project, we will focus on a specific design scenario, which is described as follows: The site is an MF-12 multifamily district established to provide more compact residential development, promoting the more efficient use of land at a less expensive cost in smaller lots.

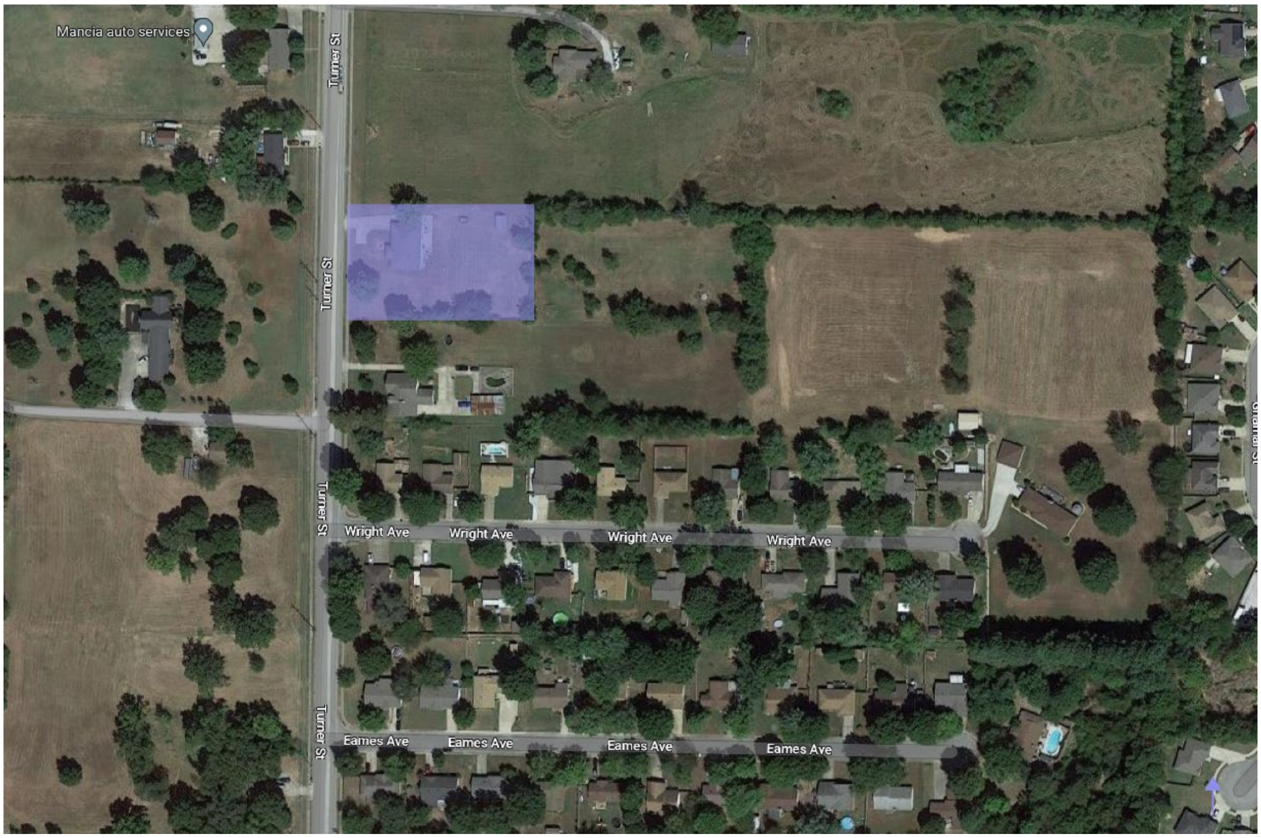


Figure 3 SITE IN CONTEXT

2501 Turner St. Springdale, AR.

Climate and weather: We use a weather file to extract meteorological variables, such as temperature, humidity, and wind from Springdale AR. Program requirements are based on the household's needs. The tool allows for a selection of spaces needed such as two bedrooms or two bathrooms, a big kitchen area, or a small kitchen area. The designer may change the program requirements. Potential requirements based on performance, such as:

Increasing daylight availability of spaces

Reducing glare in internal spaces

Enabling a hierarchy of privacy in the open and internal spaces

Decreasing the surface area of the perimeter wall

Controlling visibility percentage on focus points

By creating a catalog portraying the different unit configurations according to their parameters and optimizations we can showcase the flexibility of the process and how it won't impose a way of living on residents but rather become home to their specific needs.

1. Design Housing Through a Modular System

To create a flexible and customizable housing solution, I carefully considered a set of essential spaces that would be part of the design. Each space was designed as a small or large module to ensure the greater feasibility of modular customization. The goal was to demonstrate how each unit could be easily adapted to meet users' needs, based on the available modules and desired space.

For example, in this design, we incorporated three types of bedrooms, three types of bathrooms, a laundry area, two living rooms, and two kitchens. Additionally, recognizing the importance of exterior spaces, we created three types of patio modules to allow for more variety and control in how the outdoor spaces connect with the units.

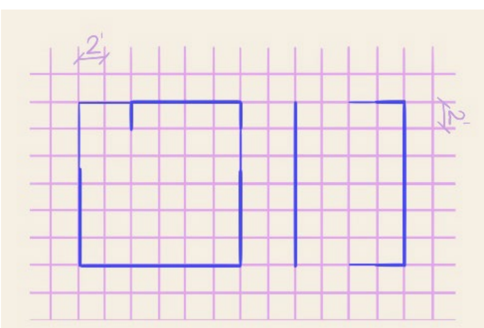


Figure 4 2' BY 2' GRID SYSTEM

To ensure seamless integration of the modules, I implemented a grid system that each space follows, avoiding overlapping or double walls during the aggregation process. This grid system also provides an organized set of parameters for future steps in the design process. Accessibility and circulation were carefully considered during the space design phase.

While testing various configurations for public spaces to provide more feasibility in unit creation, I concluded that having too many spaces could be inefficient for mass production and prefabrication. Therefore, I decided to limit the number of units for each

public space to two, allowing for a more controlled scenario of unit creation while still allowing for customization options.

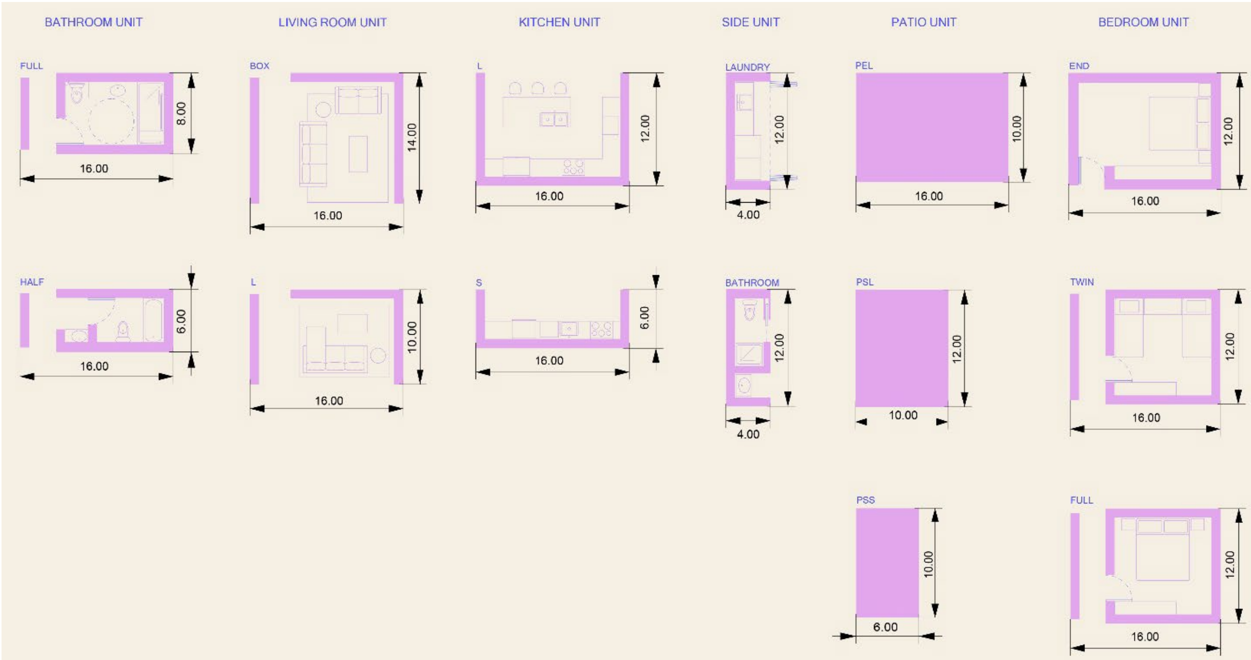


Figure 5 INDIVIDUAL SPACES FLOOR PLAN

A. Window Options

I incorporated three options for window styles during the module design process to optimize the window configurations for specific needs. Each option was designed with a specific focus in mind. Option one strikes a balance between visibility and daylight, option two prioritizes greater visibility, and option three emphasizes maximizing daylight. I conducted thorough investigations using climate studio daylight studies to arrive at these three options. The results of these studies were analyzed to identify areas with average daylight levels ranging between 200 to 500 lux, which are represented by blue tones in the figure below. This indicates better daylight availability in these areas.

The bedroom end unit in the figure displays three distinct window configurations, which were identified through extensive daylight studies. The floor plan incorporates these configurations to optimize window placement and orientation for maximum exposure to natural light. This approach involves leveraging climate studio daylight

studies that utilized weather information from Springdale, AR, with sensors positioned at a height of 4 feet above the ground. By offering three tailored window options, I was able to deliver optimized solutions that cater to specific needs, ensuring a well-lit and visually appealing interior environment.

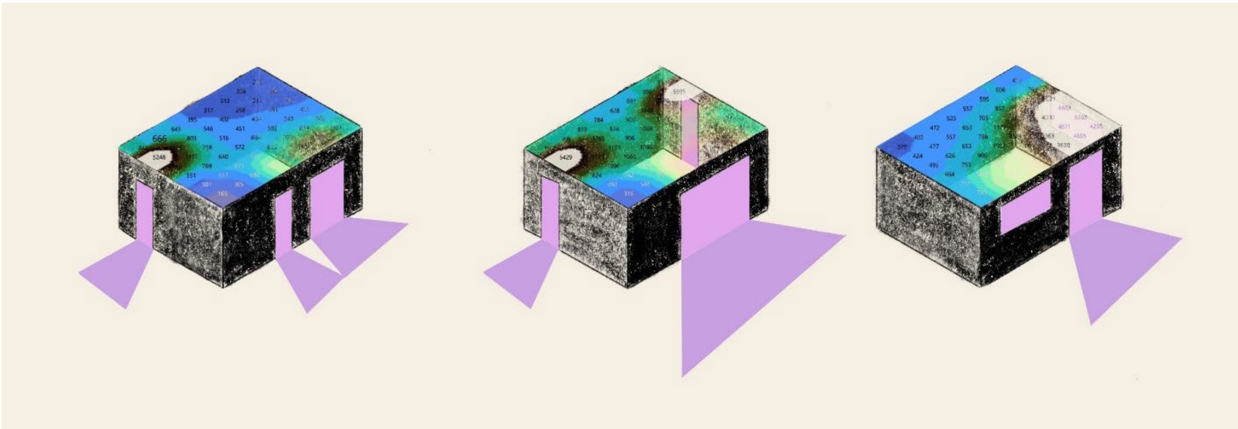


Figure 6 THREE TYPES OF WINDOW OPTIONS

B. Roof Design Studies

We carefully consider the design style we want for the overall composition of our project when it comes to roofs coming together. Specifically, we aim to create a cohesive and visually appealing look for public spaces such as the kitchen and living rooms, where the roof design should enhance the interior experience and help with light control.

To promote modularity, we have decided to stylize the bedrooms and bathrooms with a consistent roof design that enhances the interior spaces. This is achieved by incentivizing transitions through compression and expansion, creating a sense of openness by slanting the roof towards the outside wall. The standard roof pieces are defined for each module independently to provide more control during the aggregation process, allowing the designer to adjust the roof's angle and direction based on the chosen floor plan for each unit. This approach helps create a cohesive mass composition for the overall design.

In contrast, we created a unique roof design for the living room and kitchen that fuses the two spaces. The process begins by creating a rectangle around each space,

representing the area that the roof will cover. This information will be used later to create the roof panels, ensuring a seamless integration of the roof with the project's overall design.

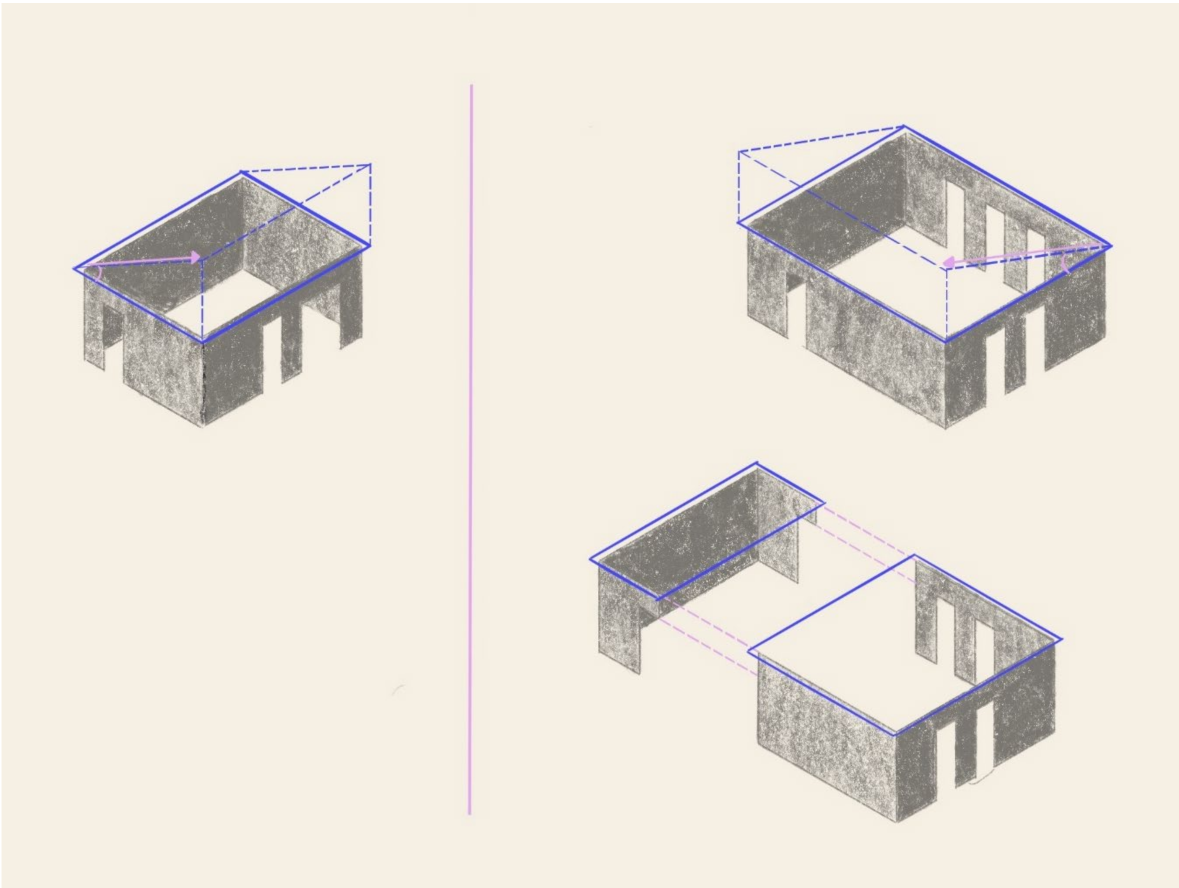


Figure 7 ROOF STUDIES

2. Connecting Spaces

Designing a space involves more than just creating an aesthetically pleasing environment. One critical consideration for designers is how space interacts with adjacent spaces, as this can impact how people move through and use the area. To achieve this, designers need to determine the spatial relationship between different areas and create rules for unit aggregation. In this example, the goal is to create a divided transition from public spaces to private spaces.

A. Creating Points

The first step in this process is to place points on each space where the designer thinks spaces should come together. In doing so, the designer must consider how circulation will flow based on the points placed. For instance, if there is a hallway, how will it connect to other hallways, and so on? I used a grid system to guide the placement of connecting points within each space, as shown in the image below.

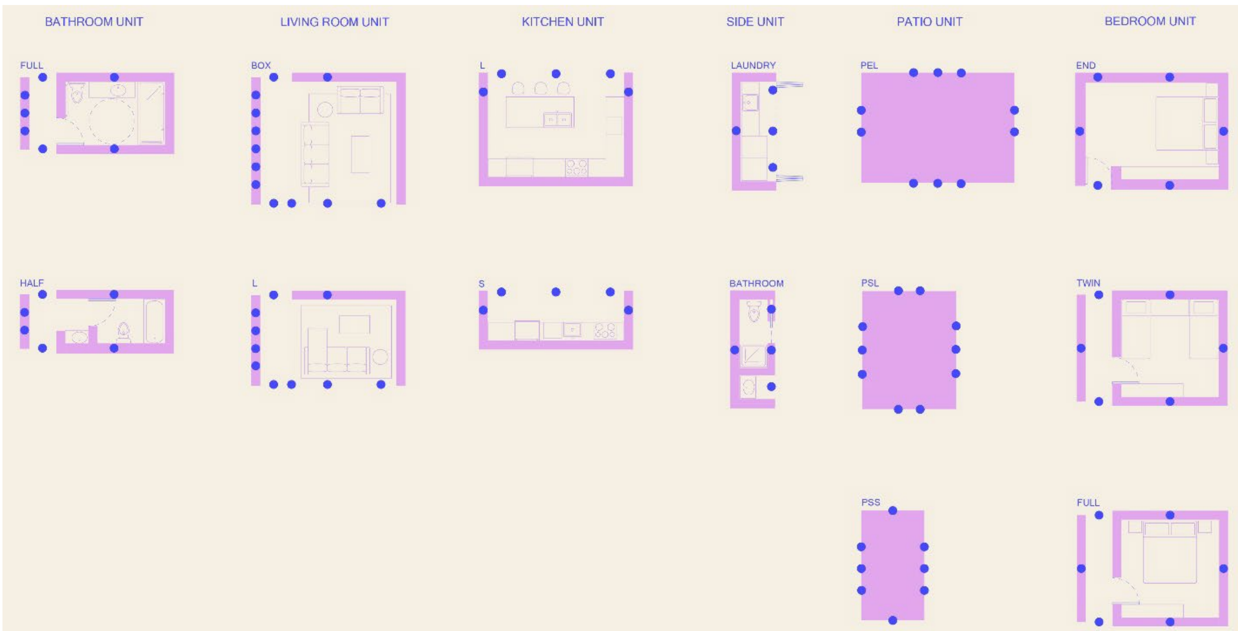
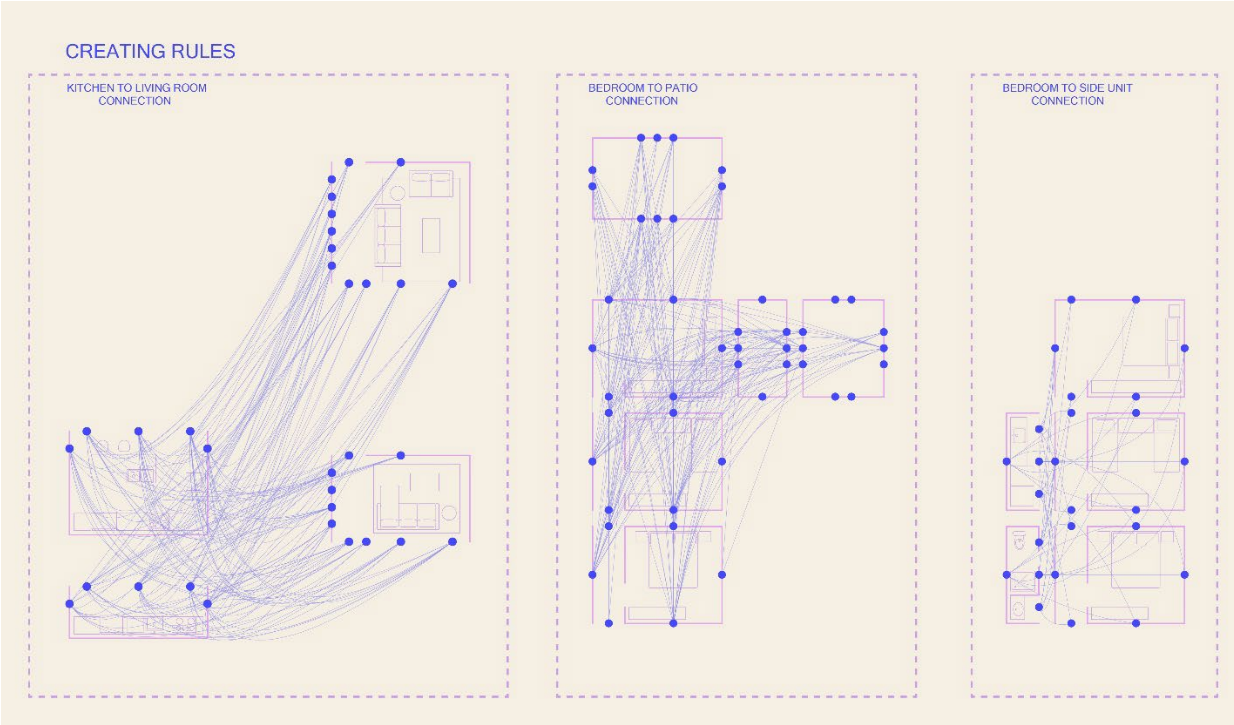


Figure 8 SPACES CONNECTING POINTS

B. Connecting Curves

Once the points are in place, the designer can determine the potential connections between them. For this step, the designer considers program transition. For example, I decided to always have the living room and kitchen together, with bathrooms between the living room and bedrooms, and bedrooms always near bathrooms and the patio area. The designer creates connecting lines according to their proposed transition to achieve this separation of programs. For instance, I created a curve from a specific point in the bedroom to another point in the bathroom to determine how these spaces could connect.



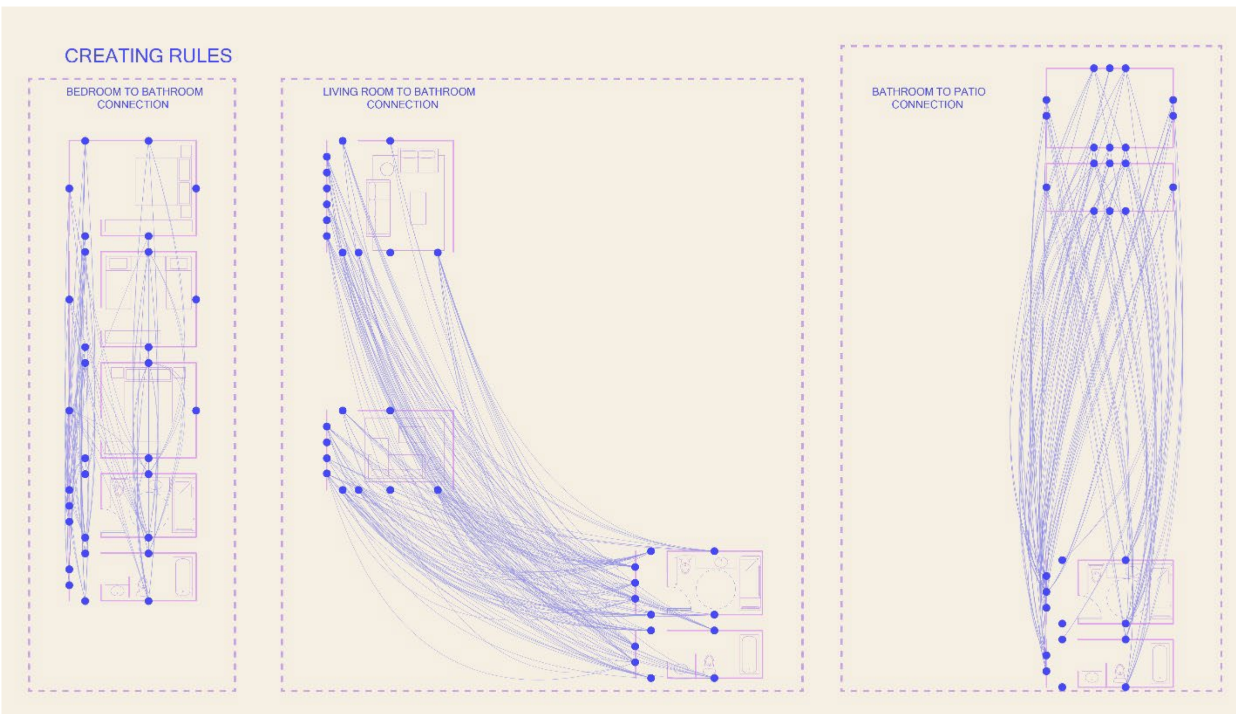


Figure 9 CREATION OF CONNECTING CURVES

C. Rule Creation

Finally, the designer inputs the points and connecting curves into the rule component. This component generates rules based on the given parameters and outputs a list that shows how the spaces are united according to these rules. In this case, I selected the bedroom and bathroom and passed the parameters to the component, which showed how the rules came together for these spaces. By following these steps, the designer can create a great space that functions well for its intended purpose.

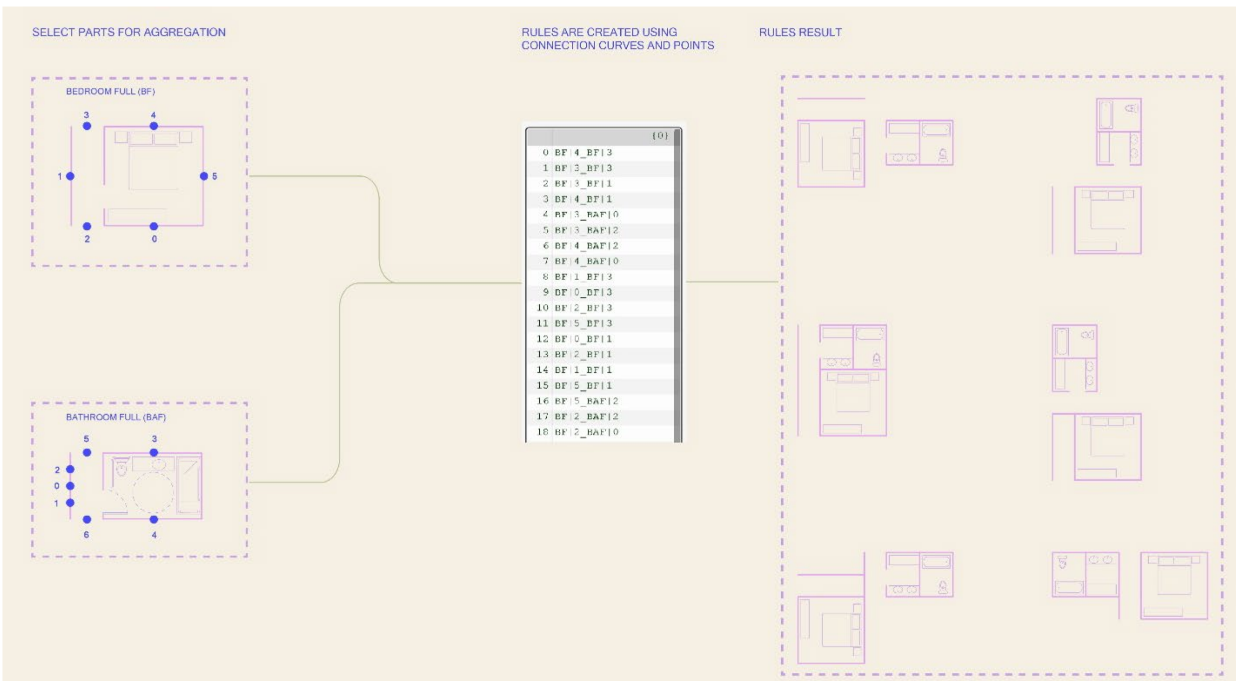


Figure 10 This image shows the inputs and the results of the rule creation process

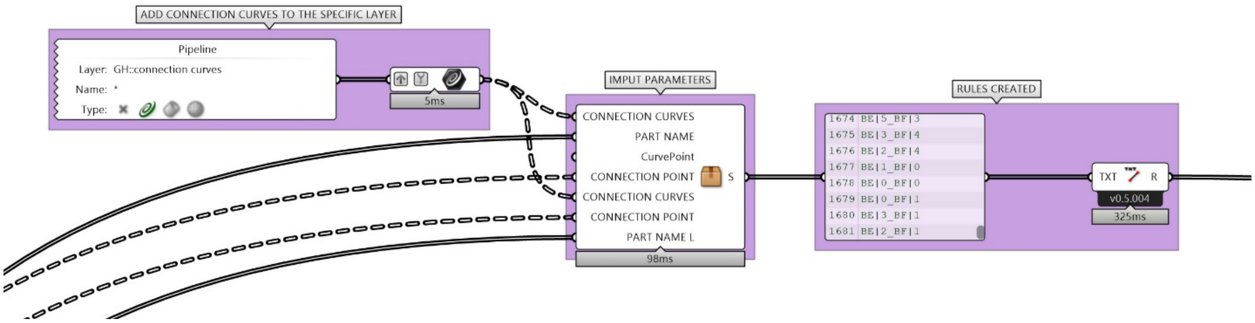


Figure 11 Grasshopper code selecting the connecting curves and parts to create the rules

3. Analyzing Site Constraints

After establishing our design rules, the next crucial step is to carefully analyze the constraints of the site. This allows the designer to tailor the aggregation system to the site's specific conditions, considering existing buildings, trees, and zoning regulations. In our case, we have chosen to prioritize the preservation of existing buildings and trees, which will guide the placement of our aggregations. Additionally, we have set rectangular boundaries to define the limits of the site, ensuring that the aggregations do not extend beyond these boundaries.

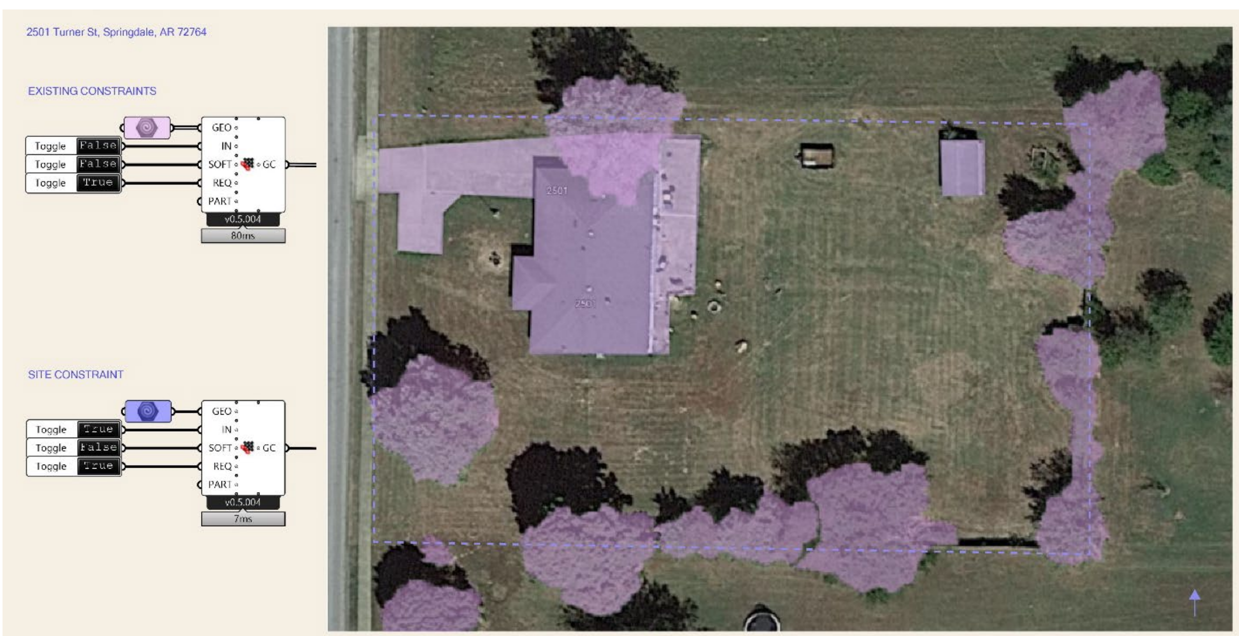


Figure 12 Pink represents the existing constraints to be avoided and Purple the site boundries

4. Aggregation Process

Once we have established our spaces, rules, and site constraints, we will pass them on to the aggregation process. This process aims to combine all the desired spaces and create a cohesive design for the house. To achieve this, we need to complete two important steps for the stochastic aggregation component to function effectively.

Firstly, we must choose a starting point for the aggregation process. For instance, we may opt to begin with the bedroom and select any location along the edge. I opted for starting at a corner as it gives me better control over the growth of the aggregation process.

Figure 13 Process of creating the starting point

Secondly, we need to determine the number of spaces required by adjusting the slider to correspond with the desired space. With these two steps completed, we can initiate the stochastic aggregation component and begin creating the composition of the house.

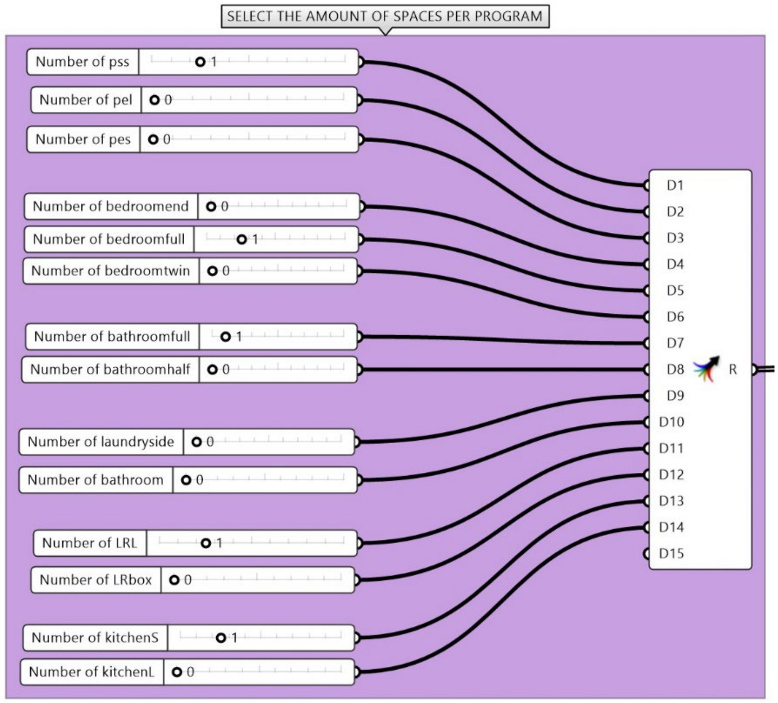


Figure 14 Grasshopper component allowing us to select the specific spaces and quantity of each

We are now set to link all elements to the stochastic aggregation component. This tool utilizes the provided parameters to generate numerous floor plans in just a matter of seconds. By using a slider, we can effortlessly switch between these options. Furthermore, we can employ optimization components at a later stage to cherry-pick specific floor plans based on our requirements. This functionality is particularly crucial as it enables designers to rapidly generate a vast number of design possibilities and evaluate the most suitable floor plans for any given scenario. As an example, below is a unit aggregation floor plan created using the given parameters – one full bedroom, a small kitchen, a small living room, a full bathroom, and a small side patio component.

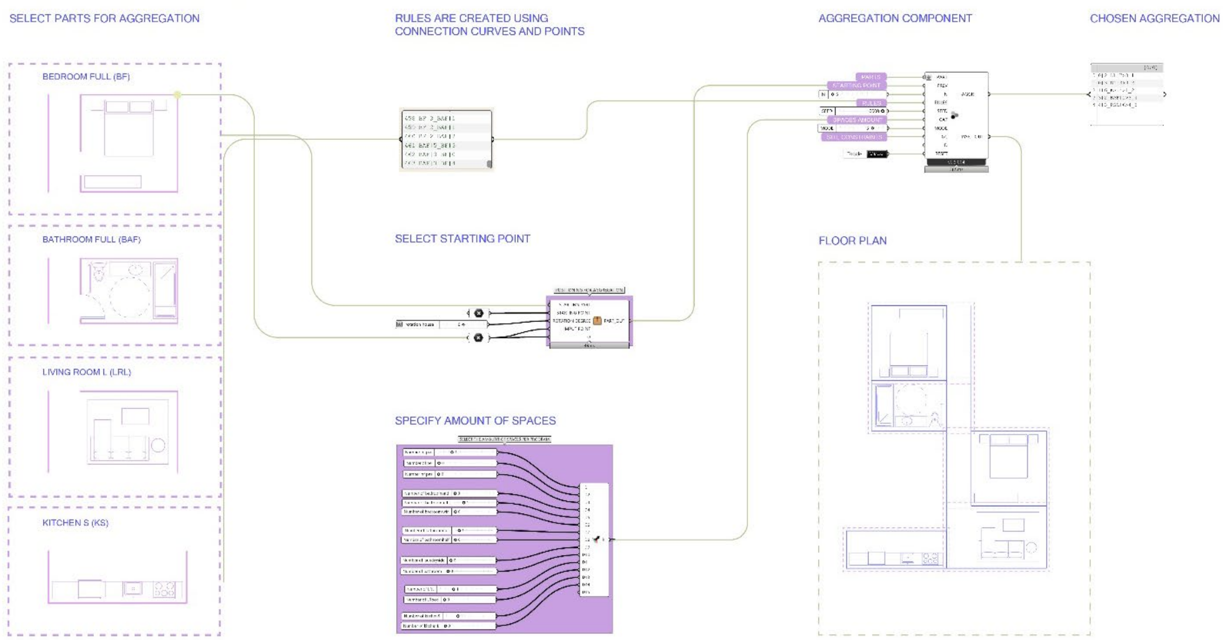


Figure 15 Stochastic aggregation process

The stochastic aggregation process outputs a set of attributes that encompass various specific curves like walls, roof rectangles, floor plan details, and window options. These attribute layers are a goldmine of information, as they contain the crucial curves required for the generation of wall panels and roofs. In addition, they serve as indispensable input measurements for running certain optimizations. Without these attribute layers, it would be difficult to extract the essential curves necessary for creating the perfect structure. The precision and accuracy provided by these attributes are unparalleled and can save a considerable amount of time and effort.

4. Postprocess

After completing the stochastic aggregation process, we move on to the post-processing stage. Here, we can bring our 3D models to life by selecting the ideal window options and determining the perfect angle and direction for the roof. These crucial steps pave the way for creating a design that not only meets our functional requirements but also satisfies our aesthetic preferences.

. With careful consideration, we can craft a design that perfectly reflects our vision while adhering to practical constraints and converting abstract floor plans into tangible, realistic 3D or even BIM models.

A. Creating Panels

The first step involves selecting the walls attribute layer and inputting the curves into a component that generates extruded panels. Next, we determine the optimal window openings based on our requirements, including the height and placement. Once the windows are created, they are applied to the panels to complete the final walls.

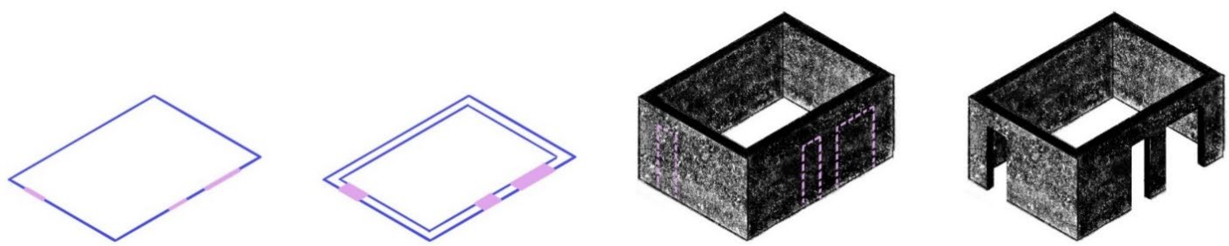


Figure 16 Process of input curves to creating the panels

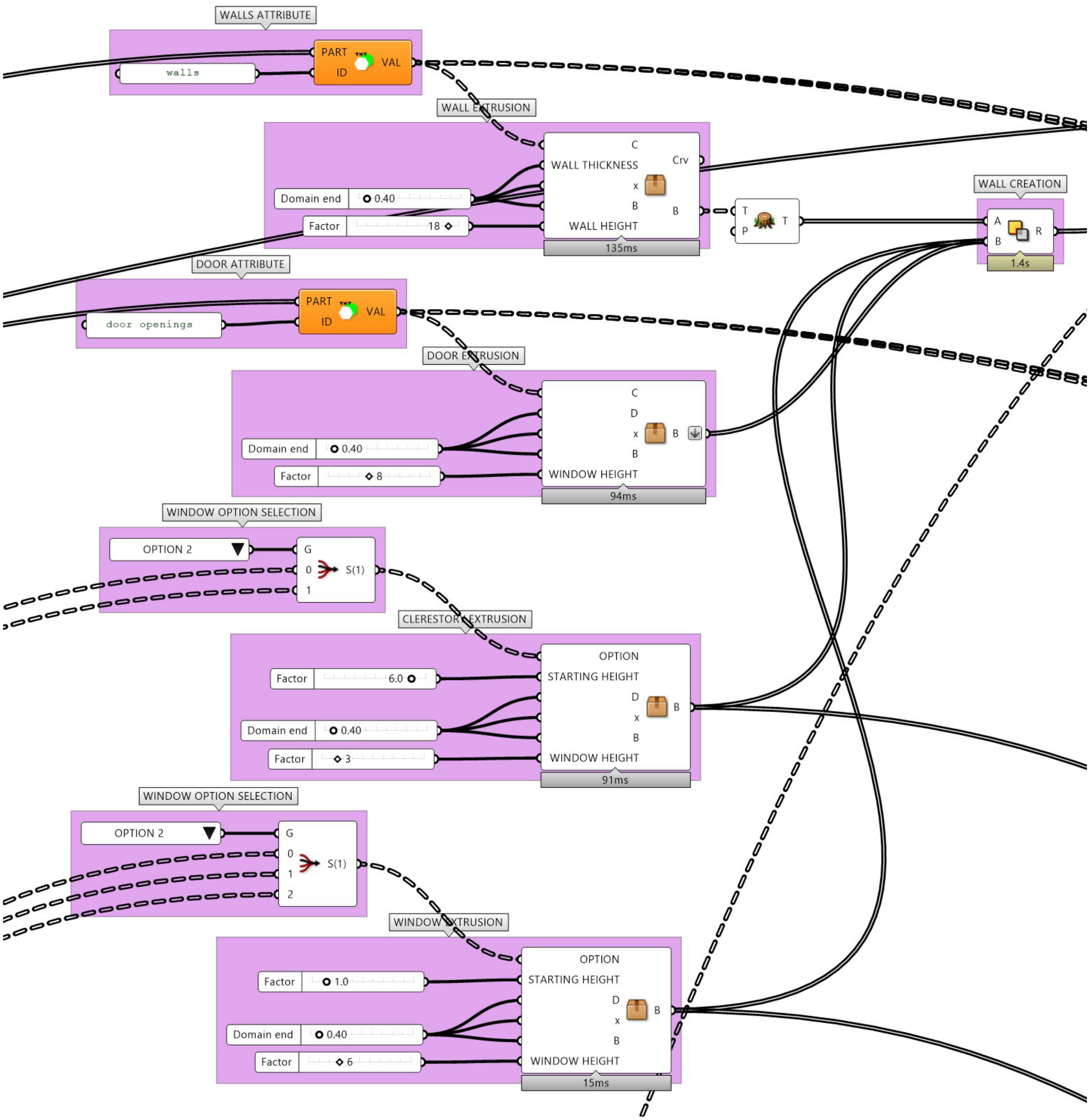


Figure 17 Grasshopper components used to create the panel system

B. Creating Roof Planes

To generate the roof planes, we utilize the roof rectangle attribute and apply it to create a plane. As previously mentioned, this component enables us to adjust the

direction and angle of each roof. This functionality is valuable for improving the interior flow of space and regulating the overall massing composition.

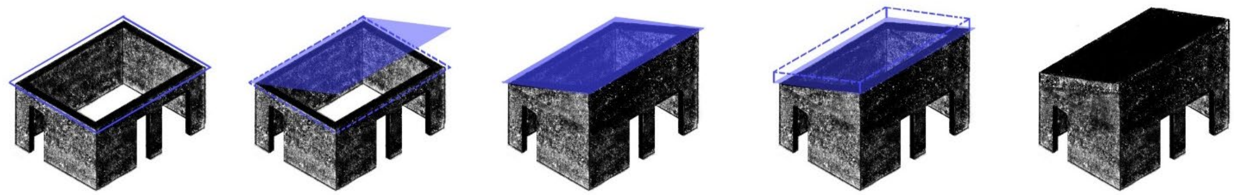


Figure 18 Process of input roof curve to create roof

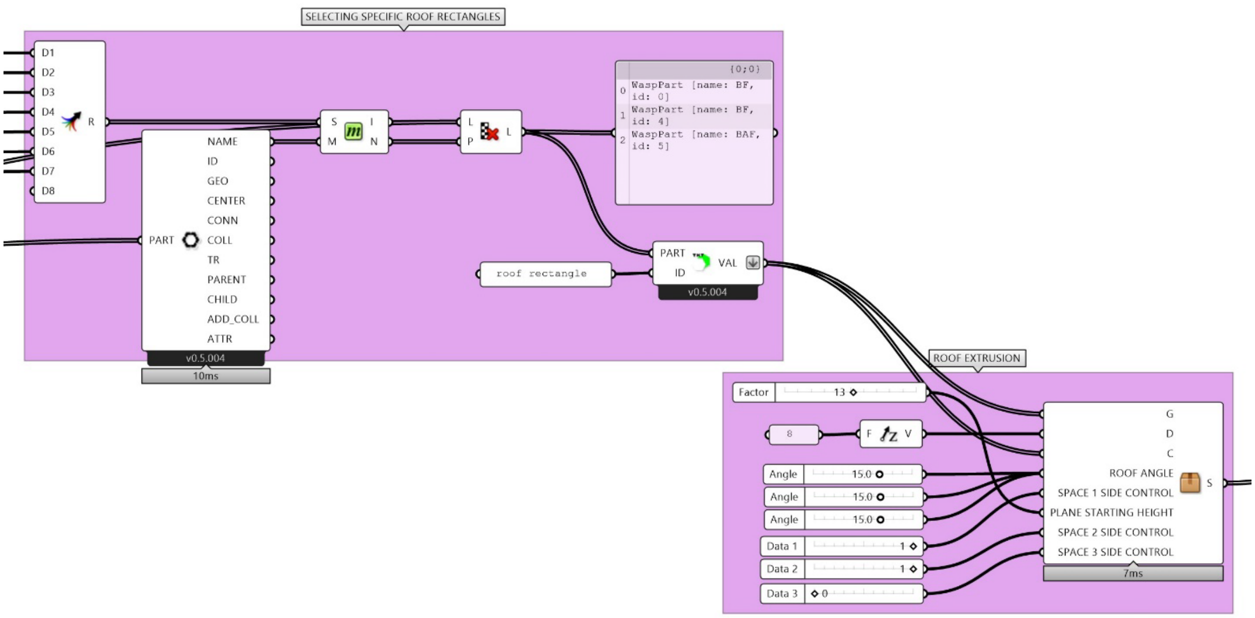


Figure 19 Grasshopper component used to create bedrooms and bathrooms roofs

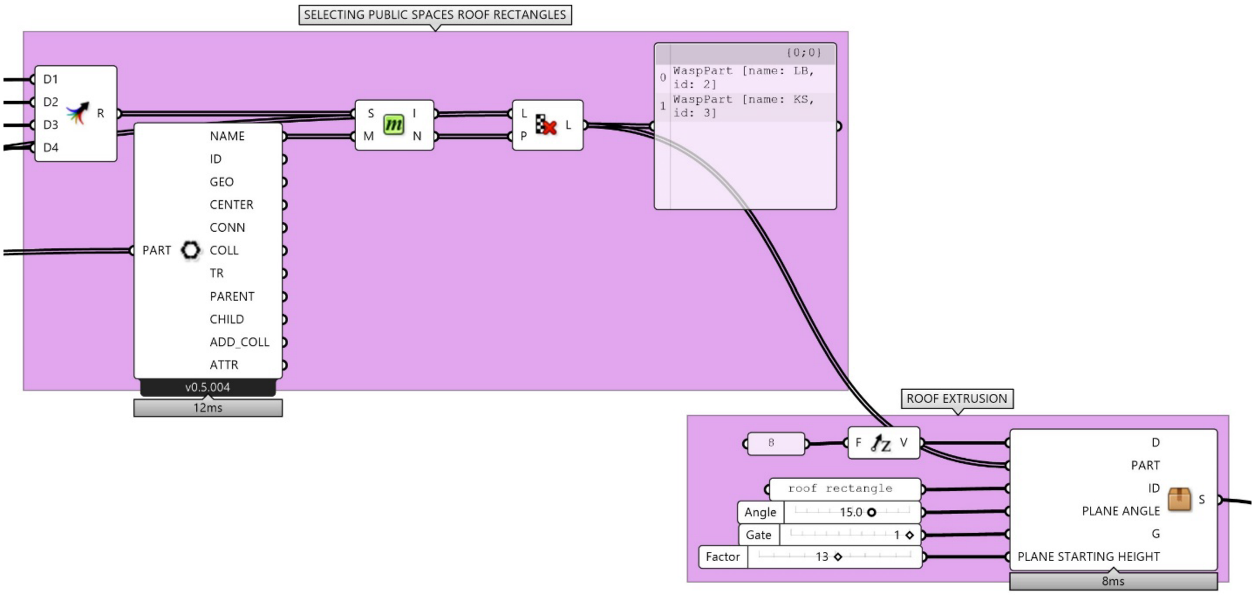


Figure 20 Grasshopper component used to create public spaces roof

5. Optimization

As we gather all the necessary inputs to develop floor plans and 3D models, we unlock a powerful tool that allows us to fine-tune our designs: optimization. This process empowers designers to select the best configurations that align with their vision.

By leveraging optimization, we can maximize or minimize certain parameters. In this case study, I explored various optimization strategies, including radiation optimization. With this approach, I could measure radiation levels throughout the year, selecting a site to either minimize or maximize its impact. Another key area of focus was external wall length optimization, which plays a crucial role in balancing design considerations against cost parameters. Finally, visibility optimization proved invaluable as it allowed me to identify optimal points both inside and outside the house, helping me to measure visibility percentages and fine-tune my designs accordingly. At the end of the day, optimization gives designers the ability to create spaces that are not only aesthetically pleasing but also cost-effective and responsive to sustainability.

A. Radiation Optimization

This component serves as a valuable asset for determining the optimal approach to either minimize or maximize exposure to solar radiation by the specific design requirements. The tool in question, Galapagos, requires inputting the components to be analyzed and their corresponding parameters. To establish the ideal parameters, Ladybug is utilized to measure radiation based on the site selected, considering the time of day and days throughout the year to obtain precise measurements.

The seed slider is then used to ensure that Galapagos evaluates multiple floor plans generated by the stochastic aggregation. The Ladybug component plays a crucial role in assessing each floor plan's walls, roof, and glass, thereby determining the radiation measurement for each composition. This tool provides designers with the ability to make informed decisions based on accurate data, enabling the creation of designs that are both efficient and effective.

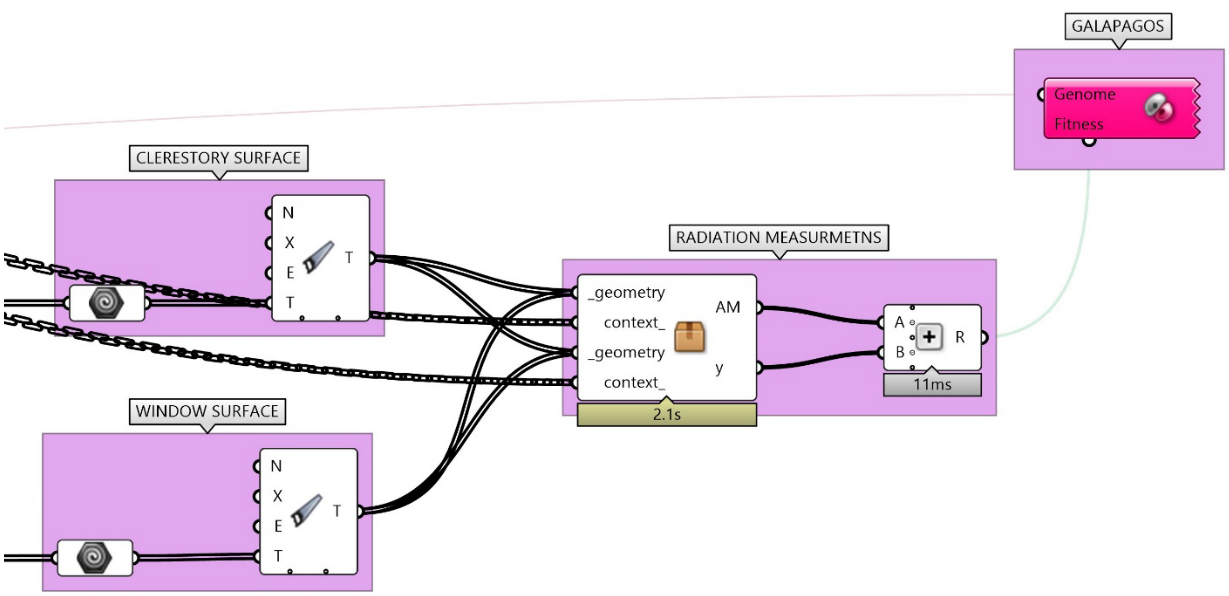


Figure 21 Galapagos component connected to ladybug component for radiation optimization

B. External Wall Length Optimization

Optimization techniques offer designers the flexibility to adjust the length of external walls based on their limitations. By leveraging Galapagos, we can maximize or minimize the length of external walls. This is achieved by creating a single perimeter

line that combines the attributes of the roof rectangle, which acts as the parameter for the Galapagos to analyze. Specifically, the component that measures the length of the perimeter curve is used as a guideline for Galapagos to evaluate the different scenarios. This process allows Galapagos to determine the length of each floor plan and generate a chart showcasing the best outcomes.

What's exciting about this optimization technique is that it highlights the most compact scenarios while also revealing floor plans with intriguing compositions that make the most of available views. In my experience, this approach has been a valuable tool for designers seeking to strike the perfect balance between aesthetics, practicality, and cost.

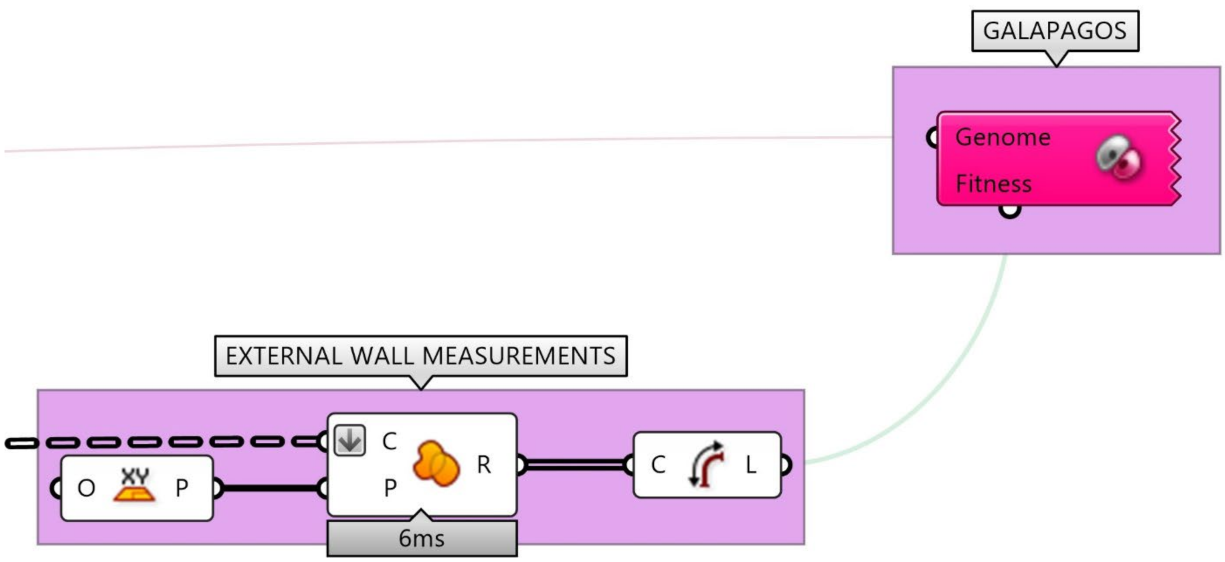


Figure 22 Galapagos component connected to component measuring external wall length for optimization

RESULTS

Once the stochastic aggregation and optimization processes were complete, I was thrilled to unveil a catalog with design alternatives. Within the following pages, I presented a diverse array of floor plans, each carefully selected based on its unique optimization focus. From radiation levels to external wall length, our tool empowered us to fine-tune different aspects of the designs to align with our goals.

In addition to the carefully curated floor plans, this catalog also highlighted the versatility of our tool in enabling mass customization. We were able to showcase the wide range of window options and various spaces that were hand-picked to create distinct housing units. This demonstration truly exemplified the power of our tool in harnessing the potential of customization by seamlessly changing and selecting different parameters.

The catalog not only showcased the creative possibilities of our tool but also underscored its practicality in real-world applications. By leveraging optimization and customization, we have unlocked new opportunities to create functional, sustainable, and cost-effective housing solutions that cater to the unique needs of our clients.

Figure 23 Catalog showcasing the attributes

Figure 24 Catalog showcasing Radiation Optimization Results

Figure 25 Catalog showcasing External wall length optimization

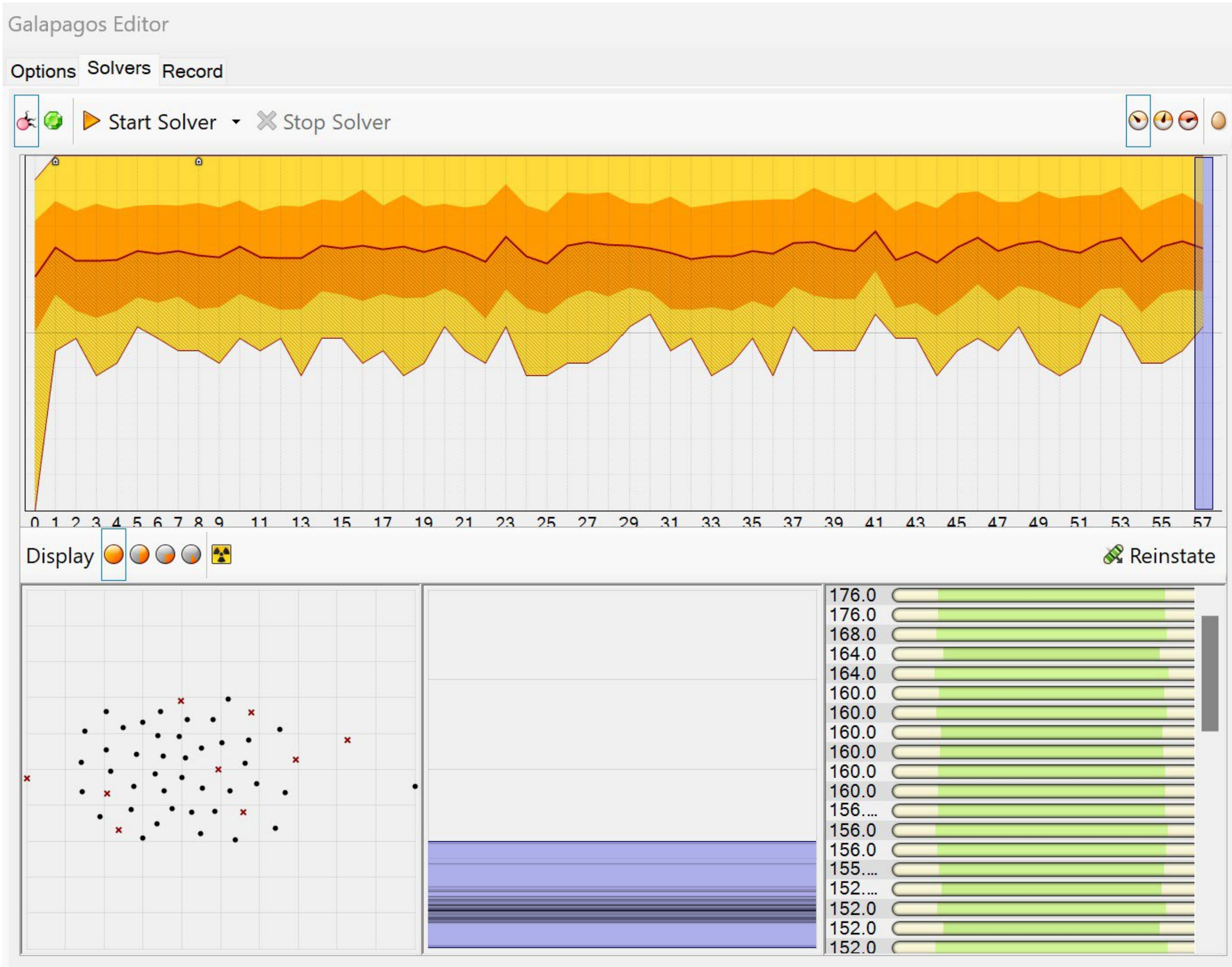


Figure 26 Galapagos External Wall Length Maximization

Figure 27 Galapagos External Wall Length Minimization

CONCLUSION

In this case study, I delve into the realm of generative design and explore how it can enhance the design process. By utilizing generative design, designers can create customized, speedy, and efficient designs that cater to specific needs. The resulting catalog is a striking testament to the immense potential of this cutting-edge technology.

Throughout the project, I gained a deep appreciation for the intricate nature of grasshopper and its vast possibilities. As I developed the tool, I found myself continually tweaking and adjusting various components to achieve the desired results. The flexibility and adaptability of generative design allowed me to explore an array of

different directions, although I had to focus on only a small portion of what I had initially envisioned.

Although AI can produce results quickly, designers' inputs are essential for delivering high-quality designs. The results generated by generative design are not perfect, and they require designers to intervene and fine-tune details to ensure their value and relevance. As designers, we can identify which of the thousands of possible floor plans generated by AI are most suitable for the project.

One key takeaway from the project is that starting with a clean set of parameters that dictate the unit's connections is crucial to achieving desirable results. By creating a grid system, I streamlined the entire process and created a cohesive system that allowed for a diverse range of floor plans, including courtyard style, L-shape style, and a combination of different typologies. This approach opens up new avenues of exploration and inspiration, and it offers a wide range of design options.

The optimization process proved to be an immensely valuable tool in identifying the most appropriate floor plans for specific needs. Designers from anywhere in the world can use this tool to create custom-tailored designs that cater to their unique requirements by inputting climate information, site context, and constraints.

In conclusion, generative design is an innovative tool that can support the design process. By adopting a thoughtful design approach and leveraging generative techniques, such as stochastic aggregation and optimization, designers can create remarkable designs with ease and efficiency. This case study highlights the vast potential of generative design and underscores its role in shaping the future of design.

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