The Shape of a Home: Using Shape Grammar to Design a Single-Family Residence

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Abstract

The goal of this research project was to study the application of shape grammar in order to investigate its potential use as a form of computer aided software as an alternative to the ever so popular Building Information Modeling software, otherwise known as BIM. Shape grammar, as well as shape computation, has been explored in a theoretical approach by various architecture and design related professionals as a means of analyzing the underlying relationships between shapes and how these relationships produce certain aesthetic outcomes. However, this research aims to help establish a method of using various readily available softwares in a way that allows shape grammar to be digitally generated in order to create floor plans for a single-family residence.

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Introduction

The philosophy behind this project has a lot to do with the terms “shape computation” and “shape grammar.” Shape grammar is used to create a language with two-dimensional and three-dimensional shapes while shape computation is a series of systems that generate geometric shapes. This notion has large ties to symbolism; however, the problem is to figure out how to calculate without units or symbols. This means the solution is to see how to calculate with shapes. This design research will therefore rely on taking an approach through abductive reasoning to explain the idea of shape grammar. Applying shape grammar to the field of design, more specifically design of the single-family residence, is a difficult task since design is largely a subjective matter. Typically, factors such as materials and the human scale play into the average person’s judgment of a well-designed home. However, many design concepts have direct ties to mathematical concepts and hard facts. In fact, many designers and artists incorporate math into their works – although they might not even be doing so consciously. The challenge becomes the analysis of the process of design. George Stiny, author of Shape: Talking about Seeing and Doing poses the question, ‘”What kind of mathematics is design?’’ Better yet, ‘‘What kind of mathematics works when I don’t know what I’m going to see and do next?’” This project will examine the underlying mathematics involved in design as well as computation of shapes and how it can all be used to describe how a designer arrives at a specific building form or arrangement. We will also analyze houses and other livable spaces in order to define a criterion to be met for necessary parts or rooms of a single-family residence. The first goal is to determine a standardized group of parts that make up a house and the characteristics they should ideally exhibit. The typology of a single-family residence is one of widely varying characteristics. So hopefully, by organizing successful aspects of a house, this research can help designers ensure they are executing a good design. This research will be directed towards architects, designers, those involved with construction-related fields, as well as anybody who is potentially interested in planning a home. It will also go in depth to explain shape grammar and the computation of shapes.

Methodology

This project has relied on typological research methods in order to walk through how single-family residences have been designed and created in the past. This helps delve into the reasons behind why certain outcomes are more successful than others. Case studies have been used to explore various spatial arrangements and configurations as well as how the parts (rooms) of a whole (the house) connect to one another. Initially, various shape computation programs were explored in order to narrow down which software would be best to help establish a process of design that relies on shape grammar. The way this was done was by using a 3D modeling program called Rhinoceros (Version 5; Robert McNeel & Associates, 2017) along with a plugin for Rhinoceros called Grasshopper (Version 1; Rutten, 2019) and most importantly a plugin that builds off of the previous plugin called SortalGI (Version 8; Stouffs, 2019). The SortalGI software was then used to establish a set of shape components that correspond to spaces within a basic single-family residence. These shape components were then altered through transformations that place them into appropriate positions in relation to each other. The shape components, after being transformed, set up the left-hand-side and right-hand-side (essentially the before and after) of the rule components used to describe the computed floor plan arrangement. These rules are then all combined together to finally form the spatial arrangement of a single-family residence.

Figure 1: From left to right; the Rhinoceros logo, the Grasshopper logo, and the SortalGI logo altered to show uniformity.

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The tasks necessary to complete this research revolves around two broad areas: defining the kit of parts for a single-family residence as well as developing a shape grammar that creates various spatial arrangements for said kit of parts. The kit of parts for a single-family residence can also be described as a set of characteristics one should consider when designing a home. All types of buildings are often regulated in many ways; mostly related to codes and zoning laws. However, when possible, single-family residences should exhibit these characteristics:

- **Entry**
  + The entryway to a residence should be located at or near the front of the house itself since it plays a big part of the initial impression a person has of a house.
  + When unexpected guests arrive, the entry takes on a similar function as a waiting room and should be inviting as well as private from the rest of the house to a certain degree.
  + When possible, a secondary entry/exit should be provided at the rear or opposite side of the house as well.
- **Living Room Space**
  + Should be a common meeting space of the house in which family members can interact as well as entertain friends and guests.
  + Should provide a conversation area with ample amount of seating.
  + Seating should be directed towards a view, a fireplace, a TV, or perhaps a combination of these options.
  + In the case that there is opportunity for a large living room, more seating should be provided than anticipated in order to avoid making the conversation area uncomfortably distant.
  + The living room is often the largest room in a house.
- **Kitchen Space**
  + Should be placed near or at the corner of the building so that there is a lot of ventilation and sunlight as well as a means of entrance/exit to the outside.
  + The kitchen should provide plenty of space for preparing and cooking food as well as sufficient storage space for pots, pans, dishes, utensils, etc.
  + When there is ample space, a pantry that connects to the kitchen is highly recommended.

- **Dining Area**
  + Should be placed near the living room as the dining area can also be used for special occasions, but more importantly, should be situated so that it has direct access to the kitchen.
  + Is often used for many other activities besides dining and should be able to accommodate.
- **Bedrooms**
  + Should be located near the sides or edges of the house so that they provide ample lighting and ventilation as well as privacy.
  + Should be placed so that natural light is provided during morning hours but avoid lights from potential traffic at night.
  + Room area should be dimensioned in order to provide comfortable clearances around a bed and necessary furniture.
  + Should provide room for a dresser or wardrobe especially if there is no closet space provided.
  + A client might require space for a desk within a bedroom, especially if there is no office room within the house.
  + There could potentially be a guest room as well in which all of these rules should apply while maintaining a slight disconnection from the rest of the house for increased privacy.
- **Bathrooms**
  + Should be placed near or attached to the bedrooms and situated in a location that is further from the common areas of the house.
  + Should only be provided individually to bedrooms if there is good enough drainage and water supply.
  + Two or more bathrooms should be located in separate locations so that they can be used at the same time in private from each other.

These criteria are important in creating a successful succession of spaces that relate to one another creating a home. However, another important aspect to take into consideration is the sizes of the given rooms most importantly being the actual floor areas. The size of a room should be proportionate to the other rooms and as well as they should all be based on the overall size of the house.

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Average Space Allocation for Single-family Residences						
	Small Houses (<2,000 SF)		Average Houses (2,000-3,000 SF)		Large Houses (>3,000 SF)	
Master Bedroom	231 SF	14.2%	309 SF	12.0%	411 SF	10.9%
Other Bedrooms	237 SF	14.6%	432 SF	16.8%	677 SF	17.9%
Master Bathroom	104 SF	6.4%	154 SF	6.0%	209 SF	5.5%
Other Bathrooms	86 SF	5.3%	163 SF	6.3%	285 SF	7.5%
Laundry Room	63 SF	3.8%	96 SF	3.7%	134 SF	3.5%
Entry	47 SF	2.9%	88 SF	3.4%	128 SF	3.4%
Kitchen	195 SF	11.9%	300 SF	11.6%	420 SF	11.1%
Dining Room	126 SF	7.8%	192 SF	7.4%	266 SF	7.0%
Living Room	193 SF	11.8%	223 SF	8.6%	282 SF	7.5%
Family Room	181 SF	11.1%	296 SF	11.5%	426 SF	11.3%
Other Finished Space	167 SF	10.3%	326 SF	12.7%	541 SF	14.3%
Total	**1,630 SF**	**100%**	**2,580 SF**	**100%**	**3,780 SF**	**100%**

Figure 2: A table of the average sizes of common rooms based on overall house size.

The foundation of shape grammar was developed and introduced by George Stiny and James Gips in the early 1970s and has had many implications in the arts and design world. When applied to architecture and space planning, shape grammar can be used to explain a designer's process. By using SortalGI, we can create a literal design process solely based on shape computation. A typical process of a simple shape grammar system can be generalized into a few basic steps:

- **Creating and Modifying a Shape.** The first step is to establish an initial shape along with the rules that will be applied to transform the shape.
- **Organizing the Grammar.** The computation system is set to apply rules in specific behaviors as well a set number of steps of transformation.
- **Exploring the Produced Shape Computations.** The designer can now explore the generated shapes and patterns and decide whether to continue, alter, restart, or save the resulting designs.

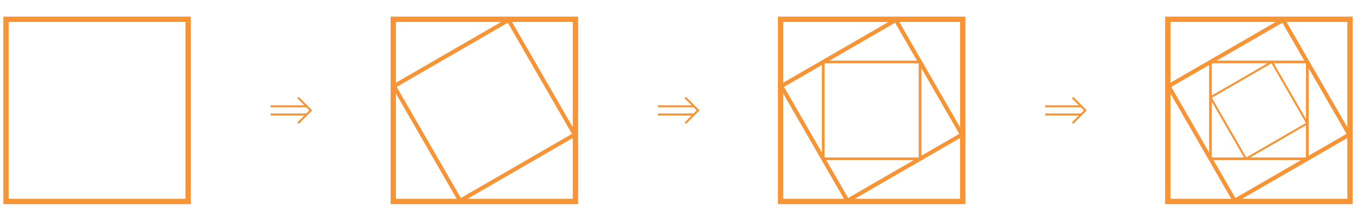

Figure 3: An example of a simple visual shape grammar inspired from *Shape: Talking about Seeing and Doing.*

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When applied to a more literal design process, a designer is likely to follow a more complex sequence of shape grammar, however. In his book, The Logic of Architecture: Design, Computation and Cognition, William J. Mitchell suggests an eight-stage process which is "more or less... a natural and intuitive design process." The following steps have been summarized from William J. Mitchell's eight stages:

- **Creating a Grid Definition.** One of the most basic interpretations of shape computation is the creation of a grid system in which to base your layout on. This is most likely what will determine whether a building is orthogonal or oblique as well as symmetrical or asymmetrical.
- **Establishing the Locations of the Exterior Walls.** This step is perhaps most simply described as grouping portions of your grid and determining which portions will become the exterior of the building.
- **Organizing the Floor Plan Arrangement.** At this stage in the process, a designer will layout where certain rooms and spaces will be located. It is likely that the arrangement will be determined based on whether or not the underlying grid provides enough space for the necessary rooms.
- **Establishing the Locations of the Interior Walls.** This step directly relies on the previous step and the of privacy or lack of privacy desired from room to room.
- **Determining Entry and Exit Locations.** The location of passages from exterior to interior within the layout of the building are likely to depend on several factors pertaining to the given site. In a symmetrical grid pattern, entrances are often located on an axis of symmetry.
- **Defining Exterior Elements.** Since the designer has now determined a spatial arrangement and the position of interior and exterior walls, now is the time to consider the exterior ornamentation.
- **Positioning of Windows and Doors.** At this point, a designer will decide where viewpoints and passages will be needed and/or desired. It is often recommended to place these elements in a way that corresponds to the others as to not create unexpected transitions through spaces.
- **Termination of the Process.** This is when the designer completes the sequence of operations and decides whether or not the plans have been correctly and successfully generated in the previous steps. If not, the designer may go back to an earlier stage or start over completely.

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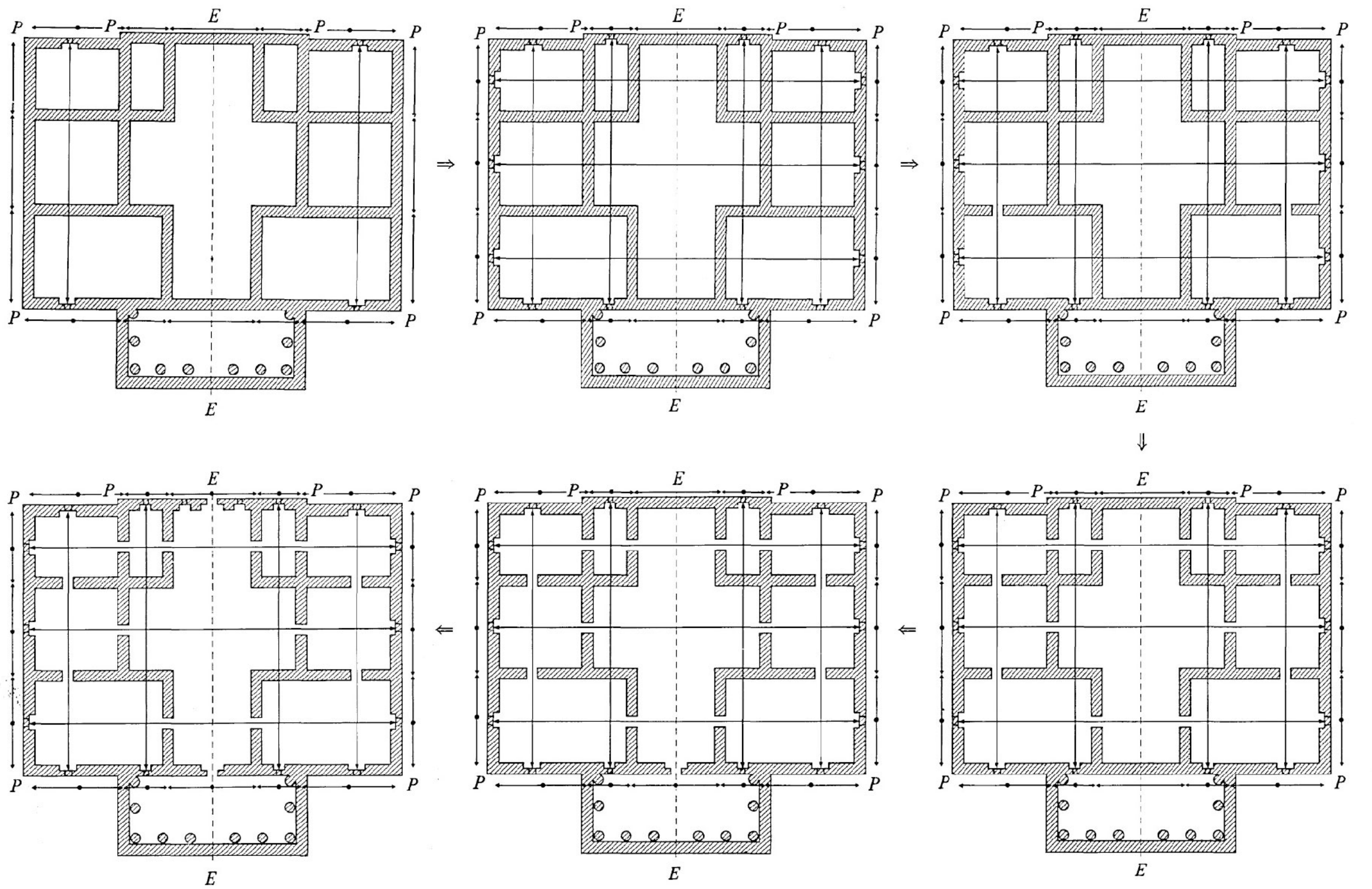

Figure 4: Generation of the windows and doors in the Villa Malcontenta using shape grammar adapted from *The Logic of Architecture: Design, Computation and Cognition.*

However, with the integration of shape grammar software, we will develop a different process that is more applicable for a computer program-aided design process. This method will rely primarily on SortalGI which is a plugin for one of the most well-known Rhinoceros plugins, Grasshopper. Grasshopper is a visual programming software that runs within the Rhinoceros 3D computer-aided design program and allows the user to produce a vast arrangement of 3D models and configurations that would otherwise be difficult to generate. For the purpose of effectively demonstrating how this software can be used to develop floor plans for a single-family residence, a fairly simple Grasshopper model using SortalGI components will be used to establish the shape computation of our own design. In a more detailed process, this procedure could be described as the following:

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- **SortalGI Setup.** The first step in order to initiate the SortalGI engine is to place the SGI Setup component somewhere in the Grasshopper canvas. It is recommended to place the SGI Update component within the canvas space as well in order to provide constant updates to the codes embedded within the software. Once these components have been placed, we can begin the creation of the Grasshopper model.
- **Creation of Shapes.** The first step of the process will likely involve one or more basic shapes to be transformed. For example, a square or rectangle could be drawn in order to create a rectilinear shape arrangement. It is recommended to create various shapes that will correspond to the desired rooms and the sizes/shapes of those rooms. This can be done in numerous different ways within Rhinoceros and Grasshopper. However, the end result of the creation of shapes will rely on the input of the given shape geometries into an SGI Shape component or SGI dShape component which allows for the input of a shape description as well.
- **Establishment of Rules and Transformations.** The following step will be to determine what types of transformations will be useful in creating a grid definition and/or spatial arrangement.

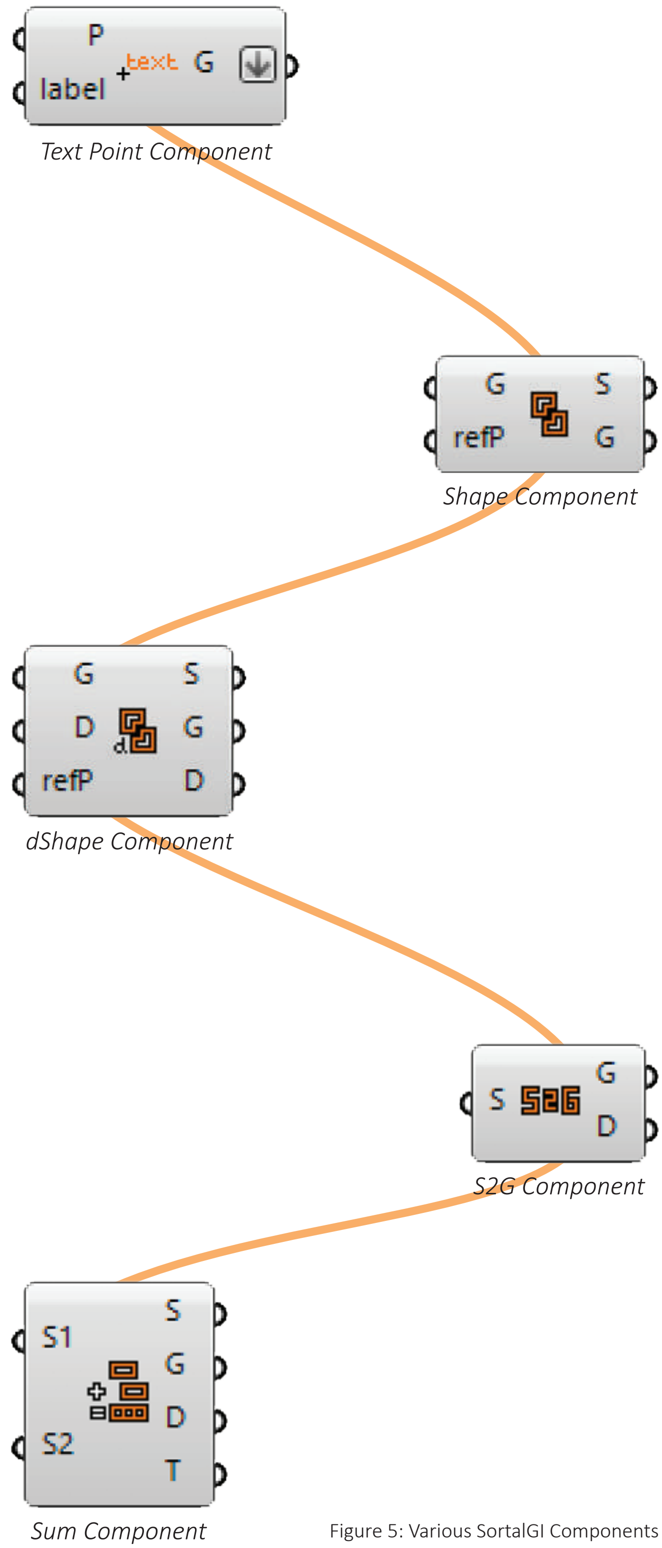

Figure 5: Various SortalGI Components

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These transformations will provide the basis for the rules by establishing the left-hand-side and the right-hand-side (or the “before and after”) of a transformed shape. The given transformations within the SortalGI application are SGI Move Shape, SGI Rotate Shape, SGI Mirror Shape, SGI Scale Shape, SGI Sum, SGI Product, SGI Difference, and SGI Sum All – all of which transform shape objects in the manner that their names suggest. If a transformation is desired for a shape object that can’t be produced through the given SortalGI components, it is possible to use standard Grasshopper transformations in order to create two variations of an SGI Shape which then become the left-hand-side and right-hand-side.

- **Application of Rules.** At this point, Grasshopper will utilize the SortalGI Rule components to actually apply the transformations established in the previous step. These rules can be applied in several different ways through the use of components such as: SGI Apply, SGI Apply All, SGI Apply All Together, SGI Derive, or SGI Matches. SGI Apply will determine all possible matches for a rule but apply only one instance determined either randomly or by a specific index value. SGI Apply All determines and applies the created rules to all possible matches. The SGI Apply All Together component

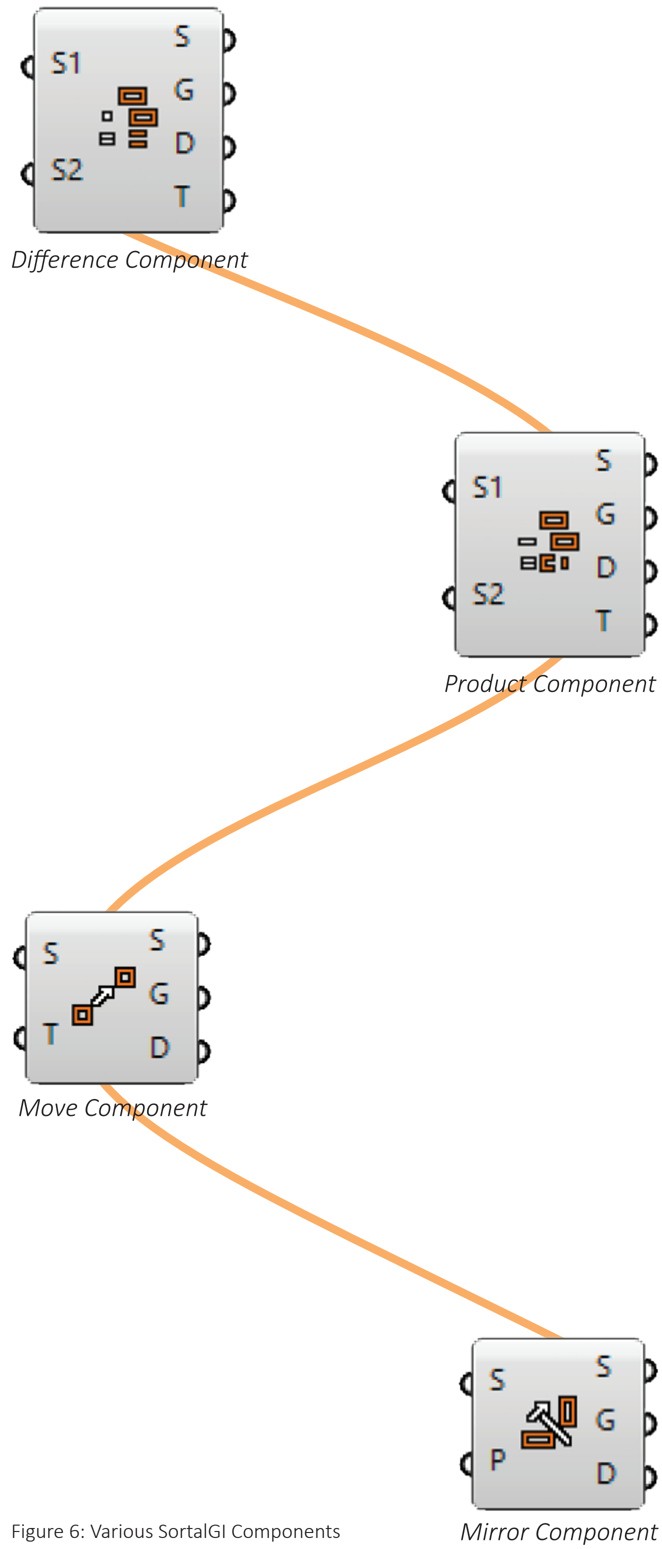

Figure 6: Various SortalGI Components

will determine all possible matches and combine them into one shape. The SGI Derive and SGI Matches components serve a different type of purpose, however. Rather than using these components to apply rules, the SGI Derive component is used to apply a given list of rules in a specified sequence while the SGI Matches component will produce a list of matches between shapes and rules without actually applying them.

- **Combination of Shapes.** This is when the Grasshopper software will render the given inputs to create the basis for the floor plans. This is perhaps most effectively done by using the SGI Sum All component in order to combine any number of SGI shapes together. When finished, the process of shape computation within the utilized programs will be terminated. In order to use the resulting geometry within Rhinoceros or other programs without the use of Grasshopper and SortalGI, the SGI Sum All component should be baked.

From this point on, a designer could potentially develop this further in a couple of different approaches. On one hand, the Grasshopper model could be further developed in order to create a more complex shape grammar in order to produce a more complete floor plan computation within the Rhinoceros model space. On the other hand, the

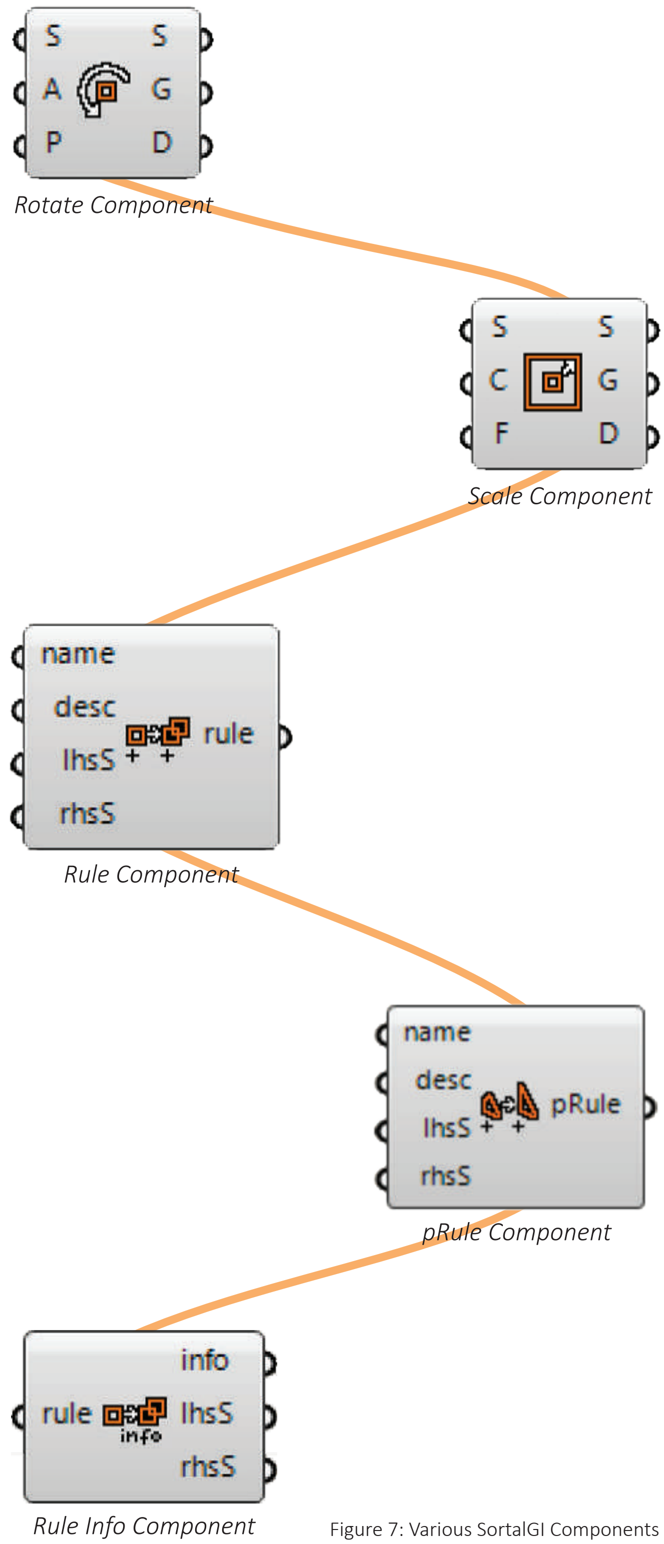

Figure 7: Various SortalGI Components

given spatial arrangement generated within the previously described method could be used as a basis to place design elements (the previously explored "kit of parts") in order to establish a more developed floor plan. For the latter method, a process similar to the following is likely to be used.

- **Placement of Modular Elements.** At this point within the process, the designer will choose at least one of the produced arrangements in order to begin the creation of floor plans. This is when the aspect of architecture comes into play. This step will essentially involve placing rooms within the computed grid arrangement.
- **Refinement of Floor Plans.** Next, there will likely need to be some type of revision applied to the design of the spatial layout. It is important to make sure the components of the floor plans provide smooth transitions between spaces in order to ensure a successful design.
- **Final Termination of Process.** At this point the designer finalizes the entire process and either accepts or rejects the given floor plan designs. Moving forward, the designer will likely begin to examine the possibilities for the elevations and other design aspects of the house given the chosen plans.

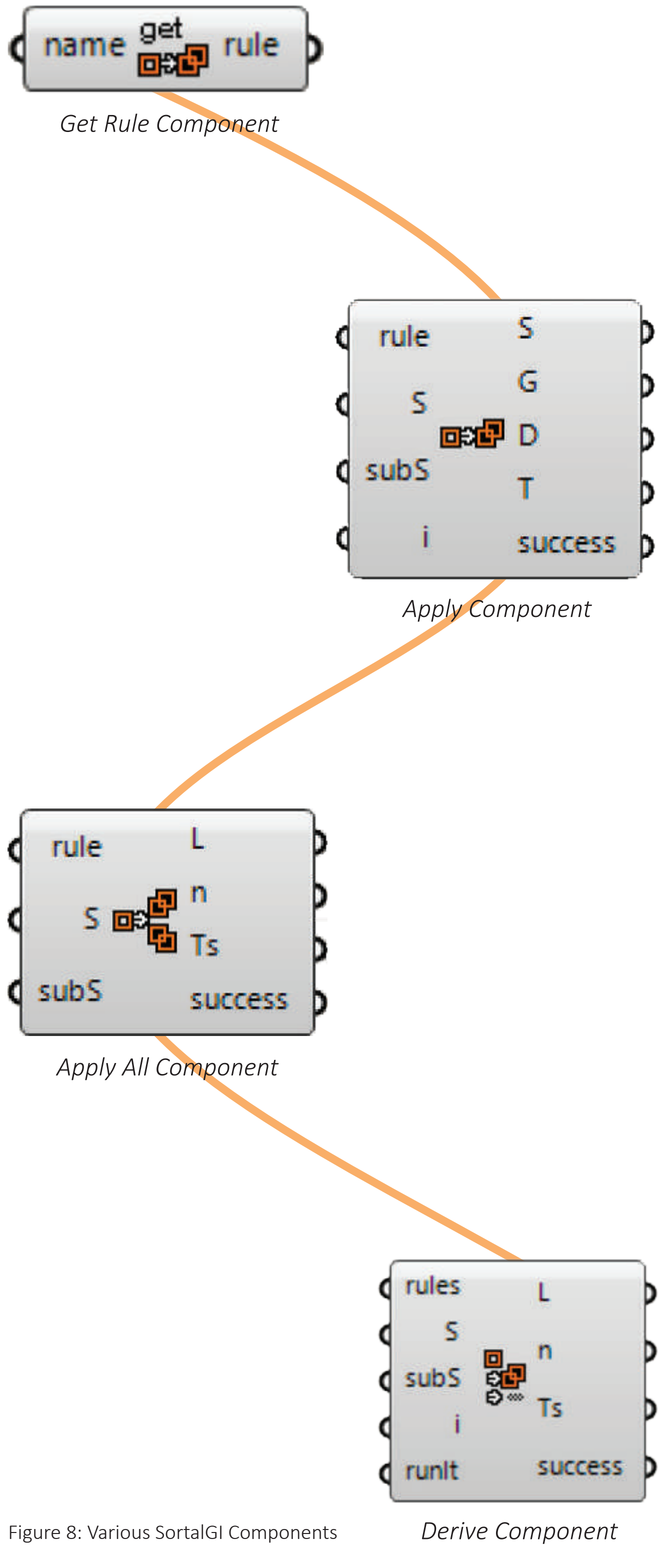

Figure 8: Various SortalGI Components

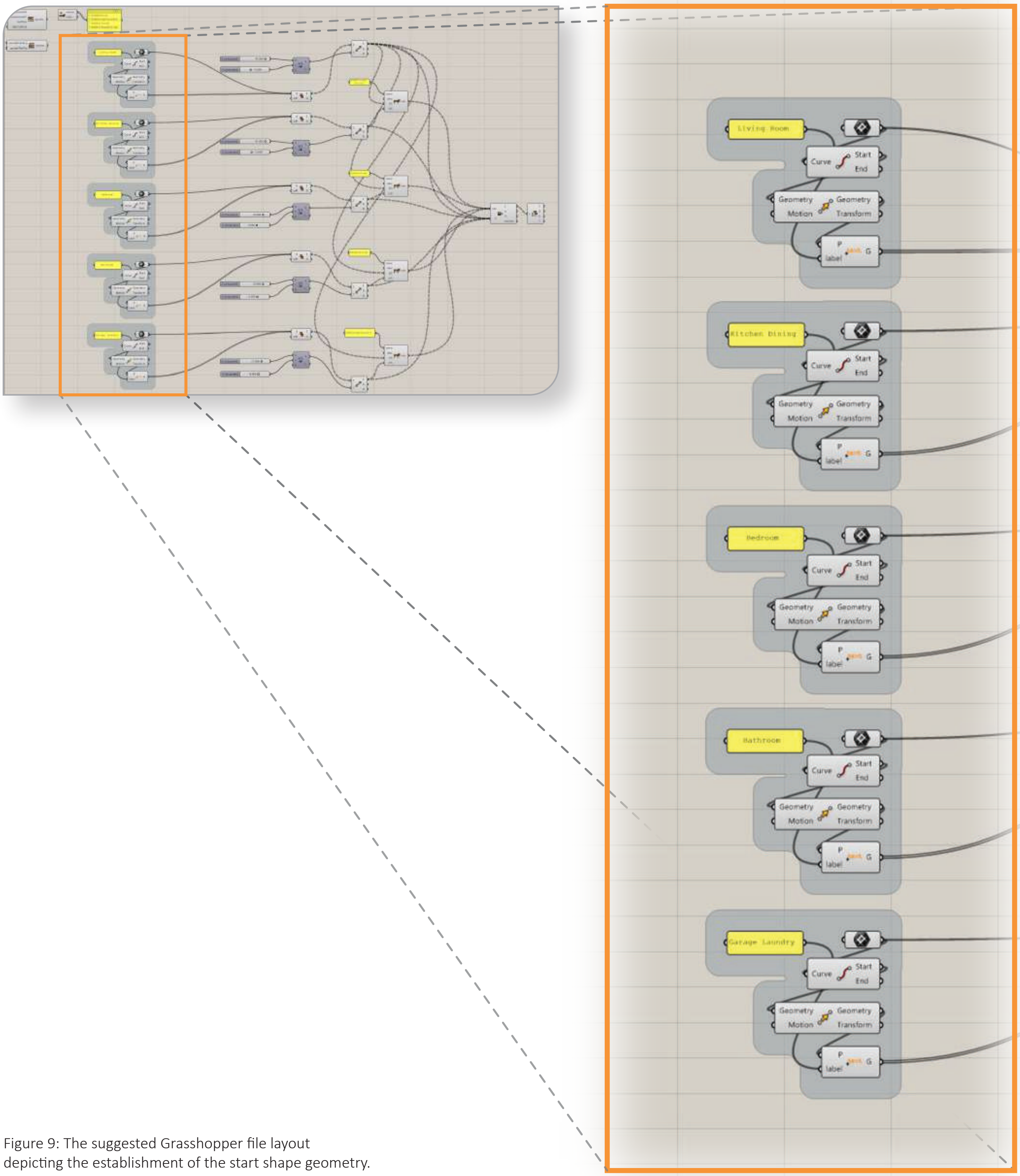

Figure 9: The suggested Grasshopper file layout depicting the establishment of the start shape geometry.

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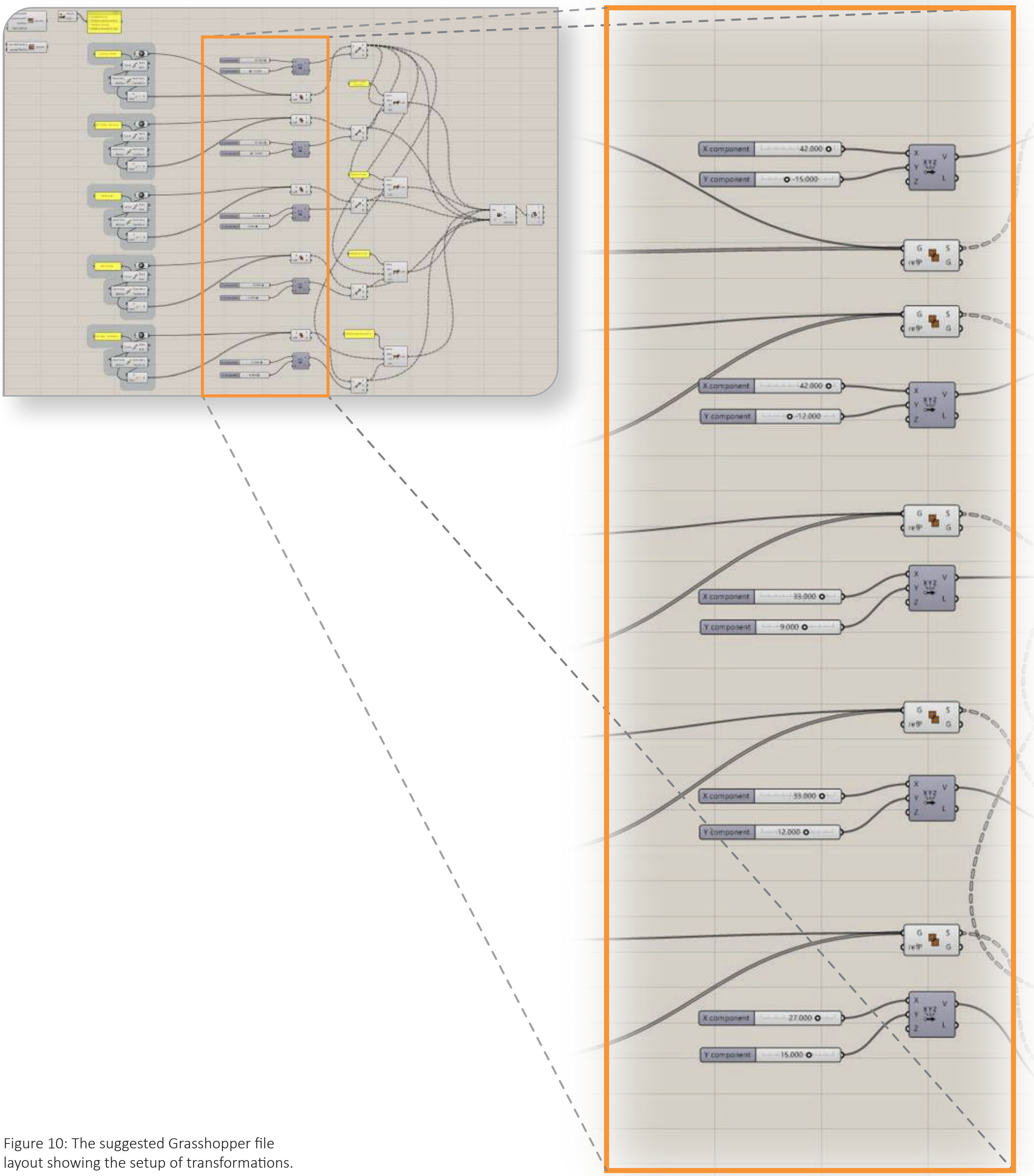

Figure 10: The suggested Grasshopper file layout showing the setup of transformations.

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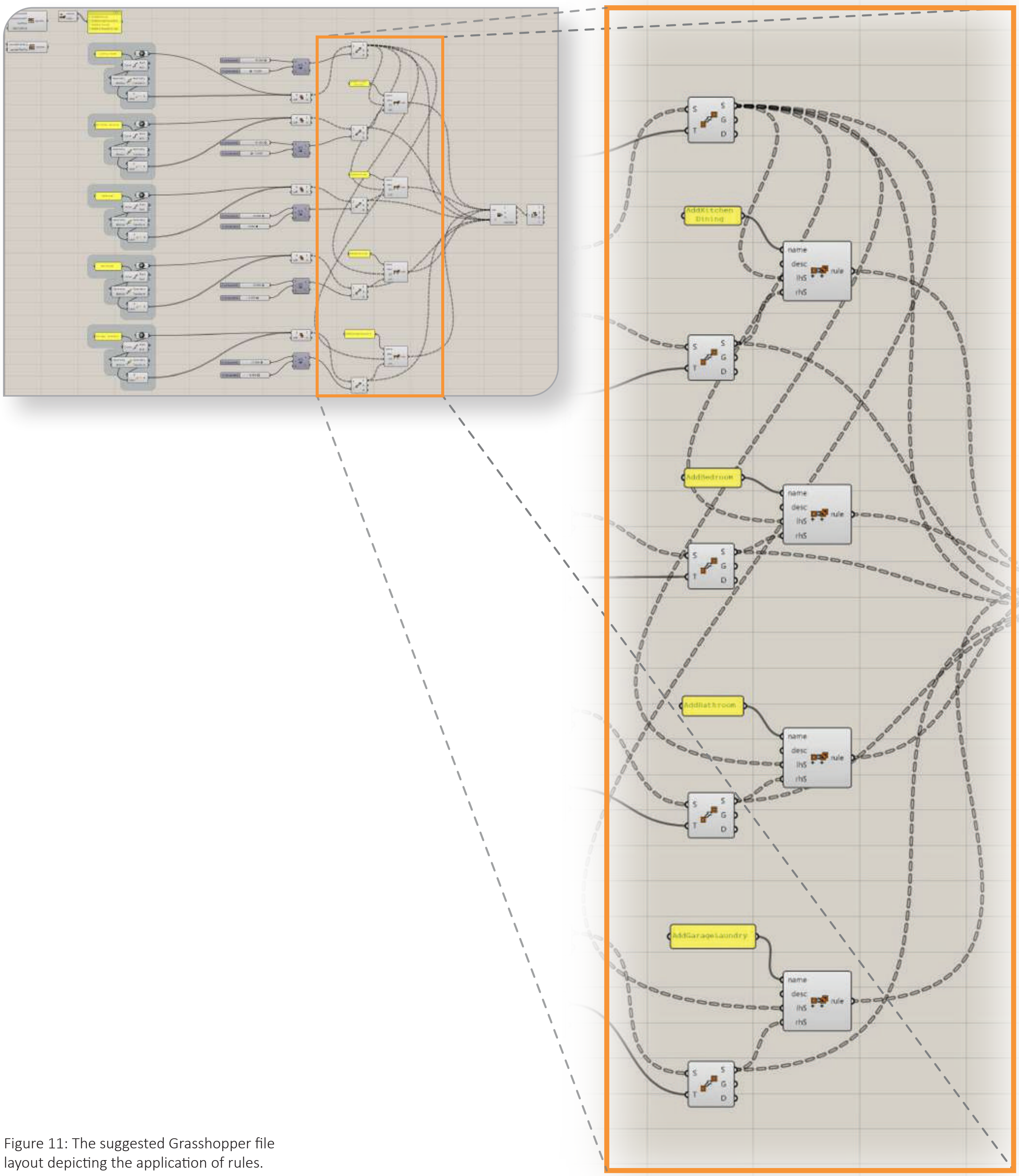

Figure 11: The suggested Grasshopper file layout depicting the application of rules.

Conclusion

The design world can often be characterized (unknowingly) by the underlying computation of shapes. These computations set up possible rules for a designer to follow, thus creating a grammar for the design of a building and its components. This concept is what led me to examine how a designer develops the design of a single-family residence using a clearly defined process. My findings thus far have included several aspects for a successful design of a house, as well as the process and application of shape grammar involved. Using these resources along with a Grasshopper plugin called SortalGI, this research helps to effectively portray the understanding of shape grammar and its importance to the field of design. Moving forward, it could be possible to develop floor plans more completely within Grasshopper through the use of the SortalGI components. Another possible area of research building off of this information could potentially lead to the development of a Grasshopper model that could do this at random, creating various floor plans at the click of a single button. However, as time permits the amount of research and development involved, it is difficult to successfully execute this approach within the defined amount of time of a curriculum. Although the development of software and programs that would be capable of this kind of automatic design could potentially be threatening to the field of architecture, it's interesting to imagine the ideas of shape grammar and shape computation playing a role in it.

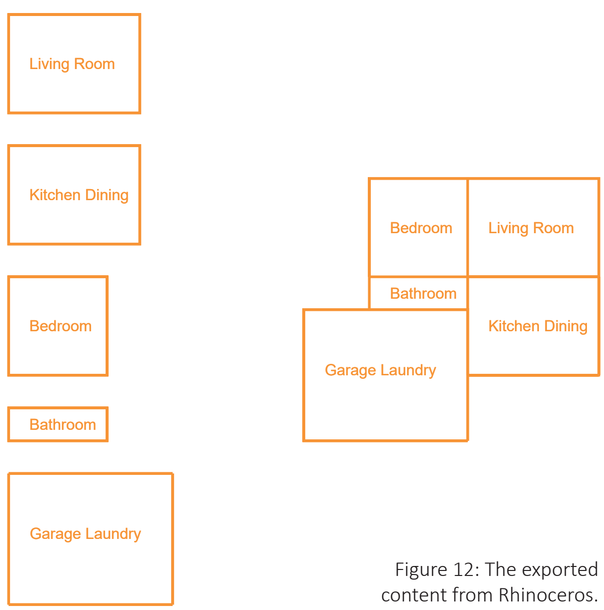

Figure 12: The exported content from Rhinoceros.

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