AN EVOLUTIONARY APPROACH FOR TOPOLOGY FINDING IN FLEXIBLE AND MODULAR HOUSING

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Abstract. Today, the living environment is much more complex due to rapid urbanization and cities hardly can bear increasing crowds. This evolving environment together with the change in living habits, put a strain on the shoulders of architects and engineers to find faster and more effective solutions towards flexible and responsive design in future city scenarios. Modular design is one of the most suitable solutions since it is based on interchangeable components that facilitate different combinations and activities responding to emerging needs and demands without demolishing a whole edifice. There are many available algorithms defining rules for the automated generation of modular building units but mainly designed for top-down solutions. This paper proposes an evolutionary approach aiming to find topological relations among the units based on a specific architectural program concerning environmental performance. Environmental conditions define the rules for the growth of units on site. The algorithm produces an automatic layout through a set of positioning rules for units organized around a core depending on a branching system. In this sense, this paper contributes to showing how rule-based modular growth on-site is shaped with environmental and architectural concerns for future city scenarios.

Keywords. Modular Housing; Affordable Housing; Future City; Branching Structure; Evolutionary Approach.

1. Introduction

Housing is a fundamental need for every human being to live in one form or another either as a homeowner or a tenant in an enclosed space. Today, cities hardly can bear increasing crowds and have difficulties in meeting the demands of the citizens because of rapid urbanization, increase in housing prices, and the change in living habits such as co-living. Cities will require a good amount of affordable housing to cater to the large middle and lower-income demographic. Thus, the design, configuration, orientation, heating, flexibility, spaciousness, or lack thereof impacts the physical and mental health of people and can shape the life of entire societies. However, part of the existing housing stock suffers from

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heating problems due to insufficient insulation, and about 23% of houses do not get direct sunlight, and only 5.8% of homeowners in Turkey are very pleased with where they live, whereas in the EU this number is at 33.4% (Aydin, 2019). There is a gap in satisfactory housing availability, and a vast demand for good quality, affordable housing solutions in Turkey. This paper is intended to explore to tackle this problem with a flexible and modular housing approach which is exemplified on a future city project site located in Esenler, which is one of Istanbul's densest districts, with 70,000 people per km2, and a population of 454,569 inhabitants. The challenge is to re-envision high-density housing solutions in a fast and reliable way concerning environmental impacts such as daylighting.The above-stated facts reveal the significance of customized generative systems offering quick and feasible solutions considering environmental performance as well as flexibility in use from the very beginning of the design processes. Particularly, repeatable use of structures in different scenarios without demolishing existing buildings is very valuable both in engineering and architecture. Therefore, modular design is one of the most suitable solutions as it offers interchangeable components that can come together in different combinations allowing to hold different activities. In this regard, modular systems can respond to emerging needs and demands without demolishing the whole system.In innovative housing approaches such as the participatory housing solution proposed by Aravena (URL-1) and Sidewalk Labs Future City Project in Toronto (URL-2), modularity is a key term delivering flexibility, user participation, and economic gains for the occupants. Flexibility is particularly crucial to meet and adapt to changing needs and demands as fast as possible. Therefore, the design should respond to different building configurations together with allowing fast delivery of services systematically, so hierarchical distributions of functions are required. The success of Aravena's social housing project depends on user-centric participatory design. In combination with the expert knowledge, assigning users active roles in the design making process creates customization and democratization of the planning processes (Sandercock, 2005). Housing projects in future city scenarios can be expensive, so affordability maintaining the desired level of living conditions for lower-income citizens is a significant concern in social housing projects. In this regard, the concept of shared housing instead of owning (Shamsuddin & Srinivasan, 2020) and the role of given subsidy before the project starts can be the solution. However, low-income housing subsidies can also increase the occupied housing stock, so tenant-based housing programs can be more effective (Sinai & Waldfogel, 2005). Another key term playing an important role in sustaining affordability is the efficient use of resources. As Jiboye (2012) argued, sustainable and affordable housing is the optimal utilization of limited resources to provide housing for the masses as well as for future generations. Hence, future cities require systematic and holistic design approaches. For instance, the design proposal for Toyota Woven City in Japan offers a smart grid as an organizer of both infrastructure and superstructure giving priority to connectivity (URL-3). It should be stressed how mereological relations between housing units and the other city domains are synthesized to create a whole system. Unless units/parts are designed concerning inter-relations in land use scenarios, implementations cannot effectively answer design problems.

Therefore, it needs a certain level of adaptability and flexibility to implement the required living conditions, and to cope with deconstruction and reconstruction of existing implementations over and over. These relations among the units should be well-defined in regards to architectural and environmental criteria, in this sense.Many rule-based solutions automatically generate adaptable and flexible housing proposals through modular design. For example, cellular automata are created by the local communication between cells over time by simple rules of the neighborhood (Wolfram, 1984). This approach can provide interesting experimental results in land use scenarios controlling density, however, it does not address specific requirements of architectural design. It usually involves a response to a design summary and constraints, and existing environments (Herr & Kvan, 2007). Another rule-based design solution is shape grammars, which can produce designs through known and finite rules that generate new shape compositions by their repeated application of basic building blocks (Stiny & Gips, 1971). Also, branching systems are widely used for hierarchical organization. The branch structure is a basic topological growth mechanism that maximizes the surface area of a tree limb, human lung, or coral algae, and sends out resources, and responds to structural forces (Park & Lee, 2019). Hierarchical branching can be used as an organizational tool for ordering information, space, resource flow, or even software logic (Jabi, 2013). All these rule-based solutions should be encouraged by environmental and architectural criteria to function efficiently in real-life scenarios. Thus, it needs optimization for efficient use of sources sustaining fitness criteria.There are two types of optimization problems working with single-objective or multi-objective functions. In the former, the fitness of a solution is equal to its objective function value, yet the optimization of multiple contradictory objectives is hard (Deb, 2014). The latter can particularly be useful for real-world problems offering a set of optimal solutions as it considers several conflicting objectives simultaneously (Deb, 2014). Among many other evolutionary techniques, genetic algorithms have been used in architecture as optimization methods. They operate on a population of possible solutions and searches by randomly sampling within an optimization solution space. Then, stochastic operators are used to directing a process based on objective function values (Goldberg, 1980).Taking into account the above-stated discussions on existing studies, there is still a need for customized tools for topology finding in modular design towards future city scenarios. Instead of relying on rule-based guidance in design generation, relations among modules, branching systems, and environmental conditions should be in dialogue with architectural fitness criteria. The main difference of this paper from similar past approaches responding to housing solutions, is that it proposes a semi-automated generative design approach that deals with a flexible configuration where rules are defined respecting architectural needs and environmental performances in future city scenarios. This paper presents an evolutionary approach that aims to define associative relations among the units and the site according to performance-based criteria.

2. Methodology

The offered evolutionary approach aims to define relations between parts i.e. the way components can come together, concerning optimal use of resources and energy performance of each module. Topology is defined as the way the parts are organized or connected, it is the relation among the spaces as invariant properties of the layout under any geometrical transformation (Damski & Gero, 1997). In this paper, the term topology finding encapsulates base unit generation comprising a specific architectural program and defining part relations between the generated base unit(s). The organization of the whole system is based on a branching structure which is described as multi-layered hierarchical systems containing modules within modules. The reason to use a branching system is that 'branch structure' is a basic topological growth mechanism that maximizes the surface area and thus generates flexibility for the building (Park & Lee, 2019). Therefore, it is questioned how the relations between parts can come together in the hierarchical branches from a holistic point of view.The research method is two-fold as module level and site level which are evaluated over a set of simulations. The former focuses on the generation of the base unit as a mass-based on any specific architectural program. The latter, on the other hand, evaluates the base unit(s) following a specific branch(es) on a given project site. This evaluation intends to find optimum relation which defines how units can come together according to environmental performances.The algorithm of the simulation attempts to produce a semi-automated layout by a set of positioning rules that follow requirements. The units are plugged in each other and organized around cores. These cores are indeed associated with the grids connecting to each other with a branching system. The units encapsulate residential, common, and commercial spaces whose contexts are defined by any specific architectural program. These spaces can also be categorized as private, semi-private, and semi-public. Regardless of the categorization, they are organized in the branches hierarchically.The first order of the hierarchical program distribution on the branching system is the core which serves as a distribution channel bounding main spaces. This channel is indeed associated with a smart grid in future city scenarios such as Toyota Woven City Project. The second-order focuses on the main spaces that can be regarded as housing and shared spaces. According to the needs of the residents, the units can be plugged-in or out to have bigger or smaller units. Their organization is determined by an evolutionary algorithm based on environmental analysis.The reason to use evolutionary algorithms is that the size and non-linear nature of search space in building-related problems, classical optimization techniques are not usually suitable (Kiss, 2020). Indeed, genetic algorithms tend to perform better as the size of search space increases (Tuhus-Dubrow, 2009; Wetter, 2004). The form generation workflow that tries to find topological relations among the units, consists of 4 main stages as indicated in Figure 1. The first stage creates the initial base unit as a response to a specific architectural program. Taking into consideration the standards and living habits of distinct user groups, the size of the base unit should be suitable enough to meet certain architectural criteria. Once the size of the base module(s) is determined, the second stage shows the way how these units connect with each other. Connection rules are significant since they also define assembly rules and have an impact on the environmental performance of each individual unit. The third stage focuses on the accommodation of the units on a given terrain. This accommodation is in line with the grids i.e. core with respect to the slope of the terrain. The fourth stage depicts an evolutionary approach for finding optimum connection rules between individual units and their organization on-site regarding the results obtained from the environmental analysis. In fact, these interrelated four stages may help to construct a holistic view of an integrated design process for future city scenarios. In this sense, the proposed approach shows how to find topology-based solutions that respond to the changing needs and environmental performances from the very beginning of the design processes. In light of the above-stated research flow, a case study is developed with reference to a branching system composed of a network of grids. These grids are associated with the distribution of functions which exemplifies hierarchical organization. The simulation is developed in Rhino 6, and Grasshopper using Magnetizing to create each layout based on the needs of residents, Galapagos for single-objective optimization in the generation of a base unit, Wasp to assemble discrete units, Ladybug Tools to evaluate energy and daylight performances, and Wallacei to decide assembly rules by NSGA-II genetic algorithm.

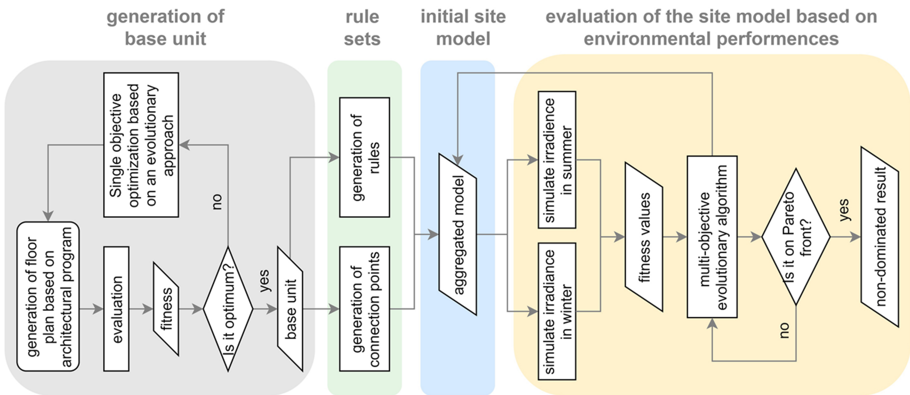

Figure 1. The flow of the Research Method.

3. Case Study

The case study exemplifies how topology findings among base units are determined by an evolutionary approach concerning environmental performances. Within this context, a simulation is developed and explained following the research flow in Figure 1. Accordingly, a layout of a base unit is firstly generated according to an architectural program. Note that the aim of this paper is not to offer an ideal architectural layout nor design an algorithm in future city scenarios. Rather, it tries to define associative relations among the units and the site according to performance-based criteria. Otherwise, predetermined rules control the whole aggregation on the site which are mainly disregarded with the social and environmental aspects. Therefore, two base units regarded as housing and common are created as an example based on an architectural program, and their connection rules are determined by an evolutionary solver. In the formation of base units, plan generation is performed based on bubble diagrams tagged with area and room name in Magnetizing. The principle behind Magnetizing depends on the fitness of the architectural program for given boundary conditions. It tries to fit all the given rooms according to the program as much as it can. In case the boundary is not adequate enough to comprise all the list, its definition needs to be reconsidered. Hence, it is further evaluated over a single objective optimization based on the evolutionary approach in Galapagos. The single objective is the placement of the entire program in the given boundary condition. Its fitness criteria are the maximization of room numbers that are placed in the boundary. Genomes are related to the number sliders defining the location of the corner points of the boundary frame. In this regard, all the program is encapsulated and then fitted in a bounding box to obtain a base unit. Once the base unit is obtained, the assignment of the connection rules should be defined. Wasp functioned with the rules based on shape grammars to aggregate discrete elements. Two inputs should be assigned to initiate the aggregation: modules to be connected and connection points and guidelines on the faces of the modules. Connection rules are strings that define how one module is connected to another recognizing the given names to the modules and id of the connection points (Figure 2). Four different rules are set for each guideline and these rules are selected by genetic algorithms to choose modules and id from a gene pool.

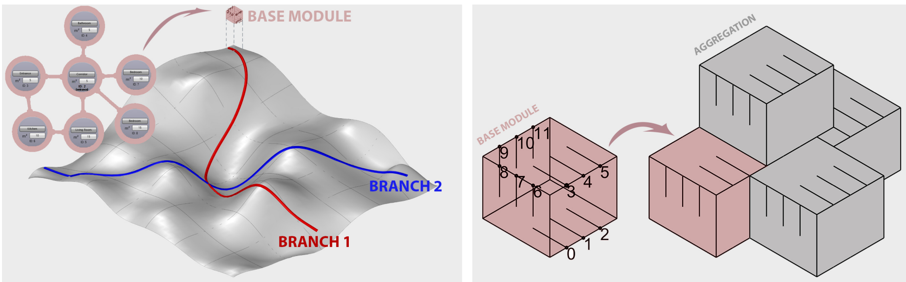

Figure 2. Left: Base Unit Generation. Right: Definition of Part Relations in Assembly Connections.

Multi-objective optimization based on environmental analysis is performed to select the way units should be connected. Performance criteria are selected as irradiance on module surfaces in winter and summer, creating a trade-off between objectives to balance the effect of the obtained sunlight. Ladybug tools are used to calculate irradiance on surfaces. The multi-objective optimization based on the Pareto method (Figure 3 on the top) is aimed to decrease the solar irradiation in summer to decrease overheating and heat gains while increasing the irradiation in winter for better daylight performance and decrease heating loads (Figure 3 on the bottom). The genetic algorithm evaluates the population size of 50 and a generation size of 50 (Figure 4).

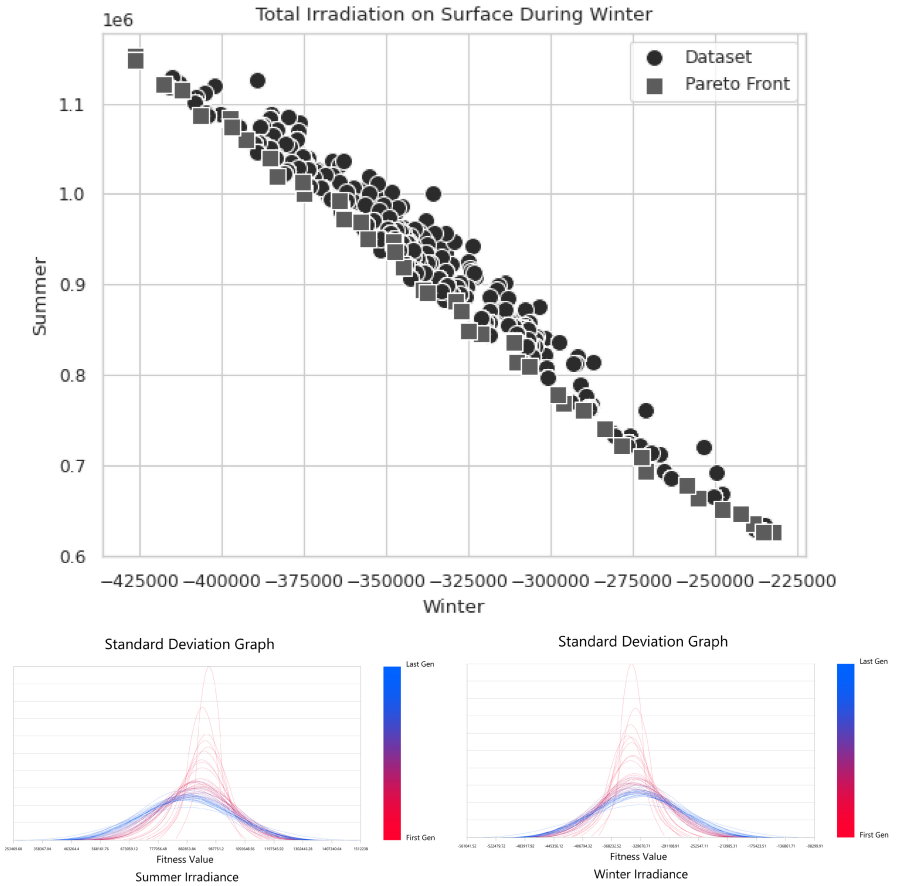

Figure 3. Top: Pareto Graph. Bottom: Standard Deviation Graphs.

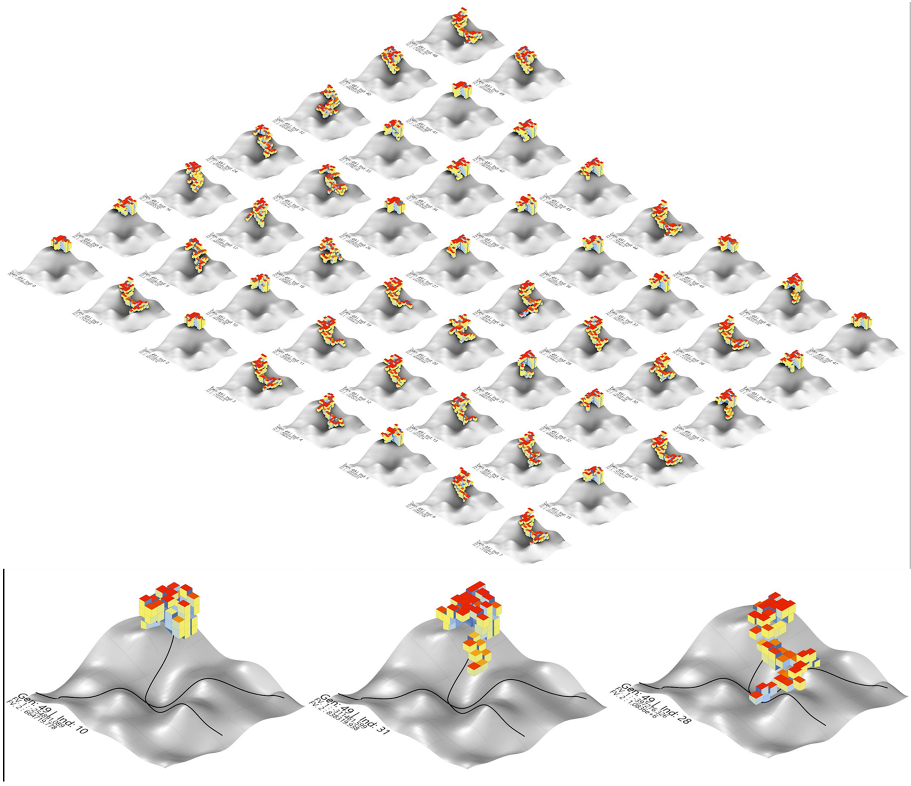

Figure 4. Optimal Aggregation of Units on Site.

By multi-objective optimization relations among units and site are defined. It is based on enhancing the daylight performance in winter and summer and the units are arranged according to the slope and the defined path lines (branches) of the site. The result of the optimization shows the optimal solution which is the best arrangement and the connection of the units on the site.

4. Results and Discussion

This study shows how rule-based design solutions can be developed through various architectural criteria and environmental performances. The genetic algorithm created rules that moved modules together to decrease solar irradiation for the summer months and separated them to increase solar irradiation for the winter months. We evaluated three optimal solutions on the project site as indicated in the Pareto Graph seen in Figure 4. This research extends to the third-order defined as an assembly level. Assembly level defines components that can be plugged-in or out within the base module. These components can be wet spaces, staircases, separation walls and slabs, and balconies. For instance, a wall can serve as a separator to create open and semi-open spaces based on telescopic movement. It can retract to create a passage between units and to extend the living spaces forward. Besides, the connection of physical elements such as walls, slabs, and staircases together with their different configurations can be embedded in the base unit design. Also, the relation between parts like core and utility services or wet spaces and base units should also be considered. In addition, further studies can be evaluated over organization criteria of structural elements or utility services. For instance, the distribution of utility services can be associated with a structural system based on branch theory. This methodology can be used in other locations in order to add further layers of exploration based on the local construction habits and architecture styles. Recently, due to covid-19, our living habits are also transforming into new typologies, where for example home offices are added to housing programs. These new mixed-use concepts trigger discussions on private and public domains in future home designs. This transformation of use case scenarios can be incorporated into new architectural programs, e.g. the level of privacy. Indeed, our approach can create intermediate social zones, where new social paradigms can melt with novel environmental and physical aspects of future home design.

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