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Revisiting Core Housing through Generative Design and Mass Customization

An Alternative Housing Delivery Option for Addis Ababa

Thesis Submitted in partial fulfillment of the requirements for the Master of Science in
Advanced Architectural Design

By

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Abstract

Core housing (CH) is one of the self-help incremental housing strategies in which the government provides an initial starter structure and then the resident takeover to achieve full housing incrementally. Around the 1960s, following the critical challenges faced by third-world governments to deliver full modern housing, a self-help incremental housing delivery option has been proposed and implemented in many countries, including Ethiopia. Regardless of some limitations, various studies and cases worldwide indicate that CH strategies have advantages in alleviating housing shortages by combining governments effort with residents' self-help housing potential. However, the conventional CH strategy lacks density, standardization, and scalability. The need for standardized speed of delivery on one hand and flexibility to accommodate owners' participation on the other poses is a unique challenge that requires an innovative design and construction delivery strategy.

Generative Design (GD) uses the principles of nature's evolutionary approach to design. It starts with design goals and then explores the design solution space to generate optimized design solutions through selection, crossover, and mutation. On the other hand, Mass Customization (MC) combines two counteracting theories of mass production and customization to minimize cost and, at the same time, meet individual needs. This study explores the potential use of GD and MC to upgrade CH strategy.

To achieve the study's objective, GD methodology, which comprises three basic steps, is employed. The first step involves analyzing secondary data and contextual reviews to identify and define critical computable parameters of CH. In the second step, parametric models are developed based on a multistory vertical expansion CH typology using Grasshopper in the Rhino 3D environment for the starter structure and unit expansion stages of CH. In the third step, an evolutionary algorithm engine 'Wallacei' is used to generate, evaluate, and select design options. Furthermore, a case project is developed to demonstrate the result of the experiment on a selected site in the inner city of Addis Ababa.

The GD experiments' result indicates the potential use of MC and GD to create a CH strategy that is flexible to accommodate owners' participation and mass-producible for speed of delivery. However, certain limitations are encountered in using an evolutionary solver in optimizing topological constraints for space layout generation during the unit expansion stage. Thus, there is room for further development of this study and potential application strategies. Nonetheless, this study's overall outcome indicated GD and MC's potential use in enhancing CH and its potential implementation as an alternative housing delivery strategy for Addis Ababa.

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List of Acronyms

CA: Cellular Automata

CH: Core Housing

FO: Fitness Objective

GA: Genetic Algorithm

GD: Generative Design

MC: Mass Customization

MOO: Multi-Objective Optimization

NSGA-2: Nondominated Sorting Genetic Algorithm-version 2

SOO: Single Objective Optimization

VPL: Visual Programing Language

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PART ONE: THESIS

Chapter One

1.0 Research Introduction

In this chapter, the research is introduced in detail in two subchapters. The first subchapter describes the main subject of this study and explains the study's background, research problems, research questions, and objectives of the study, together with its scope limitation and significance. The second subchapter defines the organization, methodology, and design of the study.

1.1 Description of the Study

1.1.1 Background of the study

Since the development of the modern programmable computer, professionals and academicians in design and architecture have been using computers in various ways. Even though the computational power and versatility have been exponentially growing, the use of computers in architecture is primarily focused on drafting, visualization, and information modeling. Following the fast development of Artificial Intelligence (AI) in recent years, the use of computation to advance the design process is gaining traction. Computer scientists, programmers, architects, and companies in the Architecture, Engineering, and Construction (AEC) industry are taping computer's immense potential to develop computational design tools and solve design problems. Generative design (GD) is considered one way of using computers beyond the 'traditional' drafting aid or visualization tool. "GD is the process of defining high-level goals and constraints and using the power of computation to automatically explore a wide range of design space and identify the best design options." (Vilaggi, 2020)

Simultaneously, the first personal computer is being developed, some scholars like John Turner (1965) and Charles Abrams (1964) were proposing a self-help housing strategy as an alternative housing delivery option for third-world countries. Following the decolonization, and the failure of the modern housing strategy adopted from the Colonies, and the subsequent proliferation of informal housing in the urban area of the third world countries have initiated the idea for self-help housing strategy (Napier, Mark, 2002). Core housing (CH) is one of the self-help housing strategies in which the government provides a starter structure, and then the owner expands the unit incrementally to consolidate full housing. In this housing strategy, the house owner is involved in the housing's financing, design, and construction process. As a result, unlike mass-produced housings, owners can have their customized housing, which suits their demand and capacity. Many case studies indicate that self-help housing has made housing accessible to the vast majority

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of low- and moderate-income families in third-world countries. Given the starter structure, owners displayed the enormous potential of housing themselves without government involvement or minimum government involvement.

Mass customization is a concept that combines two seemingly opposing theories of mass production and customization (Maria et al., 2019). It is a business strategy to manufacture a personalized design at the lower price of mass production and provide a customized solution. The emergence of GD and other computational tools has made MC palatable, especially in industrial and product manufacturing. These concepts are also experimented with and tested to alleviate the housing design delivery strategy.

Some studies and practical applications have explored the use of MC and GD to solve housing problems in the context of Addis Ababa. A computational design strategy is suggested to efficiently plan mass housing for Addis Ababa (Martin Bielik, 2013). In this study, a GD tool is proposed to effectively address the planning and designing capacity deficiency and rapid housing demand. The potential use of Building Information Modelling (BIM) integrated with mass customization is explored for 40/60 Integrated Housing Development Program (IHDP) condominiums in Addis Ababa (Shikur, 2016). Facade element prototypes are developed to demonstrate the result. Participatory and incremental housing, which uses fabricated construction elements produced by residents, is proposed and tested in some parts of Addis Ababa (Dirk Donath, 2015). This project's scalability to meet the density requirement of Addis Ababa city is not effectively investigated. There is a lack of study, which explores the potential use of computational tools to enhance self-help CH strategies in conjunction with MC in the context of Addis Ababa.

Currently, the Addis Ababa city administration does not consider CH as a part of the current housing delivery option. The difficulty of scaling this strategy is one of the critical challenges of adopting CH as an alternative housing delivery option for Addis Ababa. It is challenging for the government to control construction and design quality without infringing the flexibility and control of owners in incremental housing. A new approach and strategy are required to scale up the CH strategy and effectively coordinate the owners' self-building potential with the government's effort to make housing accessible for the mass. Furthermore, CH is a suitable strategy to address this.

“... incremental housing appears to be the only viable strategy for building affordable housing units at the scale and speed that is required to respond to the unprecedented magnitude of rapid urbanization” (SIGUS Group and TUD, 2016).

This study explores the interdisciplinary intersection between GD, MC, and CH to develop an alternative housing delivery option for the context of Addis Ababa. The underlining goal is to enhance the CH strategy by using GD and MC as a design tool and delivery method. It proposes an advanced design technology and

delivery mechanism to enable owners' self-building capacity and assist the government for efficient planning and control.

1.1.2 Problem Statement

Due to the increased pressure of urbanization and population growth, developing countries such as Ethiopia face an enormous challenge in providing housing for the growing urban population. Studies indicate that the current cities are expected to grow their urban land cover eight-fold within the first half of the 21st century (SIGUS Group and TUD, 2016). Experiences show that the current model of housing provision will not be sufficient to cope with the ever-growing housing demand. Housing strategies that are affordable to all stakeholders and efficient to be implemented at scale and speed are crucially needed (SIGUS Group and TUD, 2016).

Ethiopia, with a population size of 110 million, is the second populous country in Africa. With the current population growth rate (3.02%), the population is expected to double in the next 20 years and cross 300 million by 2050 (United Nations, 2015). As of 2017, data indicates, only 20.4% of the population lives in the urban area, and with the present rapid rate of urbanization, 4.64% annual rate (Index Mundi, 2019), the demand for modern housing is projected to increase significantly.

Ethiopia needs to deliver 73,000-151,000 formal housing units annually to meet the housing demand (UN-HABITAT, 2011). In the year 2012, the backlog of housing demand in Addis Ababa was 230,000 units, and it is estimated that annually the demand increases by 10,000 units (Gebremedhin, 2016). Addis Ababa has the highest housing demand ratio, 361 per 1000 people, than other urban areas in Ethiopia (Housing in Ethiopia an Overview, 2017).

One of the reasons for the delayed delivery of housing units is that the government has constrained financial and technical capacity to provide full housing to match the demand. For example, since the beginning of the Integrated Housing Development Program (IHDP) in 2000, 974,835 people have registered for condominiums (Mekonnen, 2017). Furthermore, until 2019, only 232,065 units have been transferred to owners. With this rate, it is estimated that IHDP needs more than 50 years to provide units for all registered people. Currently, the city administration is handing partially finished units and leave the remaining finishing work for owners to minimize the financial and delay burden. Admitted to the chronic delay, the current mayor of Addis Ababa is eyeing a strategy to provide land for registered residents to develop cooperative housing.

From the creation of Kebele houses in 1974 to IHDP (Integrated Housing Development Program) in 2000, the government attempted different housing delivery options to provide housing to the predominantly low-income urban population of Addis Ababa. The housing delivery's effectiveness and efficiency are tested

and failed to cope with the ever-increasing housing demand. A glaring indication of this failure is the proliferation of slums in the city center and squatter settlements on the city's outskirts. On the other hand, the proliferation of slum and squatter settlements indicated the residents' self-help housing potential and energy in hindsight.

Despite the government's claim to build affordable housing units for middle- and low-income residents, studies indicate that the current social housing is not affordable for the vast majority of intended target groups (Mekonnen, 2017). The down payment and monthly installments are unaffordable for most low-income residents. Besides, housing units that are provided by IHDP lack spatial flexibility to accommodate residents changing space demands. In most cases, this housing for low incomes is located on the city's outskirts, alienating the residents from their income source. In some cases, residents who won the lottery for the housing units return to live in the inner-city slums. An additional problem with IHDP is the lack of effective participation of owners in the housing process. The delivery strategy is one-sided, and it does not recognize owners' potential in making housing.

During the 'derg' regime, with the support of the World Bank, single-story site and services core housing (CH) were provided in some parts of Addis Ababa. At the time, the program was effective in addressing the housing demand of many residents. Even though the owners have successfully consolidated their housing, it was challenging to achieve density through conventional single-story and single-family self-help housing (Mota, 2019). As land becomes scarce, the site and service CH strategy has become a less viable housing delivery option. Eventually, the government has stopped this strategy and took full control of housing delivery.

Bringing density to self-help housing is crucial to make it a feasible housing delivery option in a city like Addis Abba. Upgrading CH to accommodate the need for density brings an extra level of challenge in design, coordination, and delivery mechanism. One of the challenges come from coordinating resident's ability to incrementally expand their units while at the same time producing quality building structure or urban block. This contradiction between the need for flexibility, owner's control on the one hand, and the requirement for standardized quality and speed of delivery on the other is an exciting challenge that requires an innovative design and construction delivery strategy.

A scalable and standardized multistory CH strategy requires significant coordination between various stakeholders such as the government, residents, and material suppliers. The government must produce core structures that will enable residents to occupy and expand their units, and residents should design their unit as per their financial capacity and expand it through time to meet their space demand. This incremental design and construction process should also be supported with synchronized material and construction

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delivery. Handling standardization, speed of delivery, coordination among stakeholders, and flexibility for incremental expansion poses a complex challenge that requires a novel design and delivery strategy.

1.1.3 Research Question

Main Question

- What is the potential application of generative design (GD) and mass customization (MC) to enhance CH and make it an alternative housing delivery option for Addis Ababa?

In order to answer the above main question, the following three sub-questions have to be answered.

Sub Question

- In what way GD and MC can be used to enhance the process of core housing at the core structure and unit expansion stage?
- To what extent GD and MC can be used to optimize the goals and objectives of different stakeholders and interest groups in core housing?
- What are the potential implications of GD and MC-assisted CH, as an alternative housing delivery option, in the context of Addis Ababa?

1.1.4 Research Objective

In order to address the above questions, the following objectives are laid out.

Main objective

- Explore the potential application of GD and MC to enhance CH strategy and propose an alternative housing delivery option for Addis Ababa.

Sub objectives

- Explore the potential use of GD and MC at the core structure and unit expansion stages of core housing.
- Identify the potential use of GD and MC in optimizing the objectives and goals of stakeholders and interest groups of CH.
- Propose implementation strategies of GD and MC assisted CH for Addis Ababa and enumerate the potential advantages.

1.1.5 Significance of the study

Studies show that for cities in developing countries such as Addis Ababa, meeting housing demand through the government's full housing provision is challenging. Various case studies reveal that “Incremental housing may be the only housing option at a scale that is affordable for all parties involved.” (SIGUS Group and TUD, 2016). This study brings a fresh perspective towards core housing (CH) by revisiting it through generative design (GD) and mass customization (MC). Analytically It explores the beneficiary part of the conventional CH and identifies the limitations, and proposes an alternative approach to fill the gap. Furthermore, the design challenges are approached algorithmically, leading to the possibility of leveraging computational tools and MC to solve housing problems.

The potential application of the proposed strategy can have a significant contribution in making housing accessible for the mass but, at the same time, bringing the owners to the center of the housing process. Thus, the proposed strategy democratizes the housing process, restructures the government's burden, and creates an integrated delivery system.

1.1.6 Scope of the study

Four stages of the core housing process are identified: site selection and planning, block (plot) arrangement, starter structure, and unit expansion. For this study, only the two stages, core structure and unit expansion are studied. The parametric model and generative design experiments are conducted only for the two stages. The following points are taken into consideration during the development of the parametric model and the generative design process:

- Orthogonal site shapes are considered in the development of the core structure parametric model.
- Site topography is not taken into consideration when developing the parametric model.
- Modular components and mass customization strategies are developed for core structure and unit expansion stages, but construction details are not studied in this study.

It is not the scope of this study to develop a generative design tool or software. Instead, an open-source Visual Programming Language (VPL) and multi-objective optimization (MOO) evolutionary engine called ‘Wallacei’ is used.

There is no specific data on multistory CH in Addis Ababa at the time of this study. As a result, a comparative analysis is not made between the proposed CH strategy and similar existing conditions in Addis Ababa. Instead, the research references international bodies of work on CH and revisits them from the perspectives of GD and MC to make a case for an alternative housing delivery option for Addis Ababa.

1.1.7 Definition of Terms

It is essential to understand the definition and interpretation of the following terms and how they are used and referred to in this study:

Self-help housing: This is a housing delivery strategy in which the owner is involved in designing and constructing their house with or without government support. Self-help housing can be classified as Site and service and Core housing depending on the initial provision.

Incremental Housing: Describes the process of gradual consolidation of housing starting from the initial structure. In most cases, the government provided the starter structure, and the owner takes over the incremental building process.

Core Housing (CH): is one form of self-help housing or incremental housing in which the government (housing provider) builds an initial structure that will enable the owners to start living in it and expand incrementally. Sometimes the term is interchangeably used with incremental housing, referring to the process. The term CH is selected in this study because it clearly expresses government involvement in providing the starter structure.

Core Structure: This is also called starter structure, which refers to a structure that the government builds initially to enable residents to occupy and consolidate it through time.

Starter unit: Refers similar meaning to ‘core structure,’ but it connotes the first inhabitable unit built for an individual owner in the case of multifamily core housing.

Computational Design: A general term refers to the use of an algorithm, a finite set of instructions, to define and generate design geometries and objects.

Parametric Design: is an algorithmic-based process in which design ideas are expressed using algorithmic rules and parameters to manipulate the final output of the design. It is important to note that parametric design is an advanced drafting tool and has no artificial intelligence because the human designer manipulates the parameters to come up with the preconceived outcome. In this study, parametric models are used to encode the design space, but a genetic algorithm is used to optimize and select a design solution.

Modular Coordination: is a concept of coordination of dimension and space, in which buildings and components are dimensioned and positioned in a term of basic unit or module.

1.2 Research organization, design, and method

This chapter describes the chapter organization of the study and the main topics incorporated into it. Furthermore, this research's design and methodology to collect data, analyze, and answer the research questions are described in detail.

1.2.1 Organization of the study

This study is organized into two parts. The first part contains the main thesis, and the second part showcases a conceptual project developed based on the results of the study. Part one, the main thesis, contains six chapters.

Chapter One: Introduces the research and states the problems that motivated the study. The study's research questions and objectives are discussed. Furthermore, it describes the research design and methods employed to answer the research questions.

Chapter Two: Gives introduction and theoretical framework the three main topics of this thesis. The first topic introduces the thematic subject of the study, which is Core Housing (CH). It discusses the brief background history, fundamentals of CH, and selected cases of multistory CH. The second topic of this chapter highlights computers' use in architecture and establishes a theoretical background for generative design systems. Moreover, it elaborates why the genetic algorithm (GA) is selected for this study and explains its basic principles and working mechanisms. The last topic of this chapter defines the core concepts of mass customization and its applications in housing.

Chapter Three: Reviews the housing state in Addis Ababa and highlights previous works on self-help incremental housing strategies in Addis Ababa.

Chapter Four: Describes in detail the methodology of the study. The framework analysis method used for CH typology selection, stakeholder identification, and constraint and goal identification process is described in detail. Moreover, a detailed description of how the parametric models are developed and the generative design experiments are conducted is provided.

Chapter Five: Enumerates the study's findings from the GD experiments and discusses the results' implications.

Chapter Six: Based on the result and the findings, this chapter summarizes the study and makes recommendations for future work.

Part Two: Describes the project proposal developed on a specific selected site in the inner city of Addis Ababa. Implementation strategies in the context of Addis Ababa are proposed for GD and MC-assisted CH.

Revisiting Core Housing through Generative Design and Mass Customization

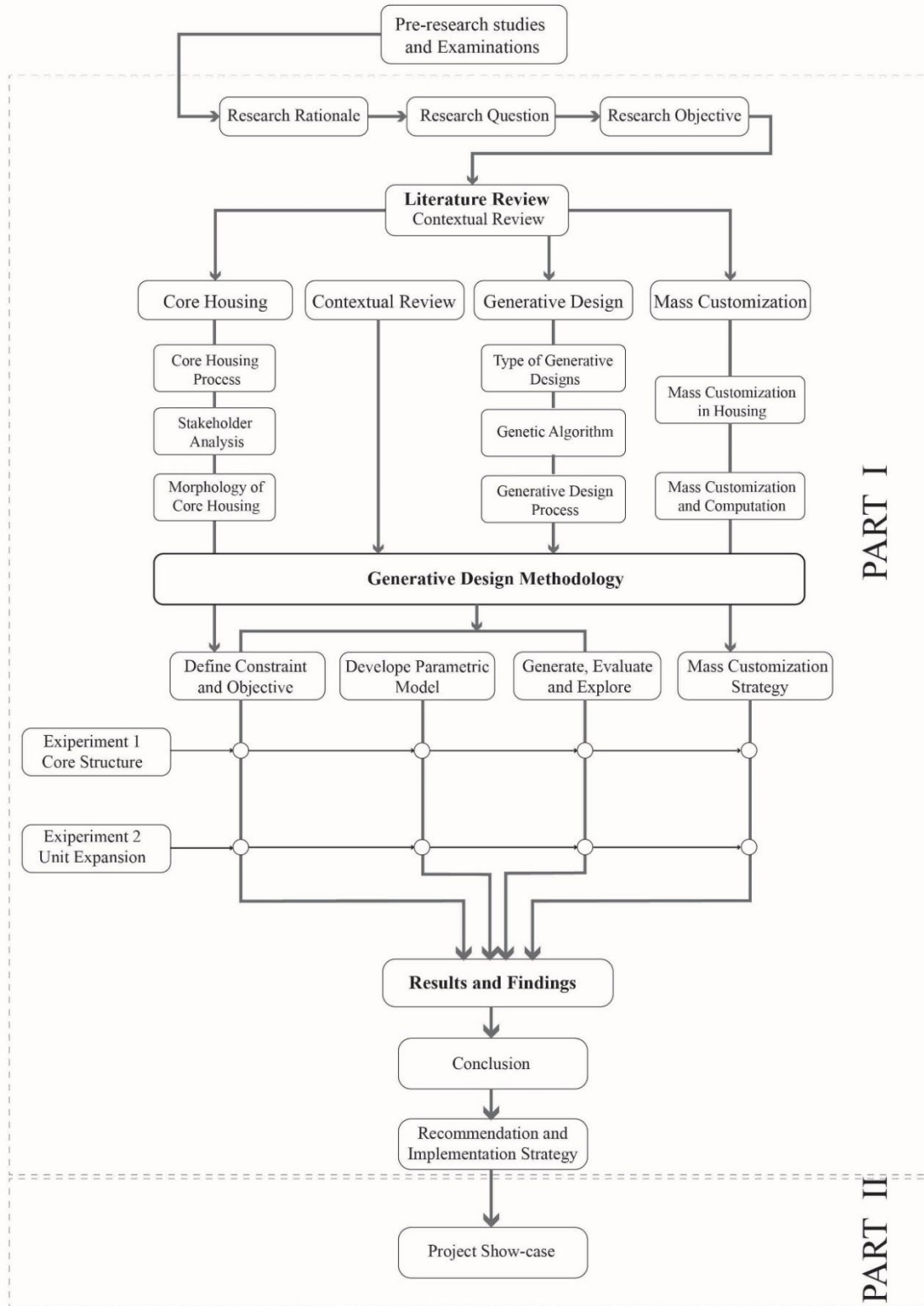


Figure 1: Research organization and design

1.2.2 Research Design and Method.

A generative design (GD) simulation method, which is predicated on a qualitative research method, effectively addresses the research question. The qualitative research method is used to study CH and produce computable frameworks converted into parameters for GD simulation. Hence, in this research, GD is the subject and the method of study.

A framework analysis strategy is used to study CH qualitatively based on secondary data collected through literature reviews. A framework analysis method incorporates six techniques: Familiarization, identifying a thematic framework, coding, charting, mapping, and interpretation (Aashish Srivastav, 2009). In this case, familiarization is the process of being acquainted with extensive secondary data set about CH and contexts of the study. After familiarization with the subject, critical thematic frameworks are developed that describe CH in terms of process, stakeholder involvement, and typology. The developed thematic framework is coded, charted, mapped, and interpreted into quantifiable and computable parameters. The result is used for developing an MC integrated GD simulation methodology.

A simulation requires replicating reality in a computer to study a particular issue without necessarily building or directly observing it in real life. It does not mean that simulation research methodology is wholly detached from reality, but it takes data and observation of real-life to recreate it and drive a project or theory out of it (Wang, 2013).

Simulation is a remarkably ubiquitous research design, which can be deployed across a broad range of topics, for purpose that span from highly targeted applications in design projects to theory building. Just as significantly, simulation frequently lends itself to many uses as a tactics within other research strategies, or as a full partner in combined strategies. (Wang, 2013)

This research design and methodology employed for this study follows four steps to answer the key research questions:

Define Constraints and Objectives: based on the secondary data analysis, four CH stages are identified. Out of the four stages, the core structure and unit expansion stage is selected. Stakeholders and their involvement levels are identified in each stage and are converted into constraints and goals. Additionally, nine types of multistory CH morphologies are identified, and one type is selected for the next step of the study based on specific criteria.

Convert to parametric model: Two parametric models are developed for the core structure and unit expansion stages of the CH process. The parametric model defines the design space and creates a link between the constraints and fitness objectives. A visual programming language (VPL) or parametric design software called ‘Grasshopper’ is used to develop a parametric model in Rhino 3D model space.

Generative design process: A type of metaheuristic algorithm called the Genetic Algorithm (GA) is used in this study. GA is an optimization algorithm that uses a top-down approach, and it is deemed to be a

suitable type of optimization algorithm for this research. GA uses three basic principles: Generate, evaluate, and explore. A multi-objective optimization (MOO) tool called Wallacei X is used to generate design options based on the Fitness objectives set for the core structure and unit expansion stages. The generated design options are evaluated using Wallacei Analytics, and the result is presented in the form of charts and graphs.

Limitations of Simulation Research methodology

There are four general areas of concern in the use of simulation research: completeness of data input, the accuracy of the replication, programmed spontaneity, and cost/workability (Wang, 2013). In this research, the replication accuracy heavily depends on the accuracy of the parametric models to represent reality. The accuracy is limited by the ability to construct a sophisticated simulation model using only visual programming language (VPL).

In converting qualitative and quantitative data into a computable parameter, some subjective parameters will not be included in the simulation process. Creating an accurate model, if it is ever possible, is time taking and requires a deep understanding and procedure of sophisticated computer coding. In this study, the focus is made on the combined system of GD, MC, and CH. Therefore, the simulation outcome should always be evaluated compared to the result's objective and implication.

Chapter Two

2.0 Literature Review

This chapter gives a brief introduction and evaluation of previous research on core housing, generative design, and mass customization.

2.1 Core Housing

Even though self-help housing is an indigenous practice for centuries, the idea of applying this strategy for modern mass housing provision emerged around the 1950s and 1960s (Napier, Mark, 2002). From the 1920s up to the 1960s, many African countries have tried to provide full, low-cost housing in cities' outskirts. The housing provision attempt has failed as the pressure of housing demand was exacerbated because of rapid urbanization and urban to rural migration. As the government's capacity and budget got scarce, it became evident that the full provision of housing was not attainable (Napier, Mark, 2002).

In growing countries, a particular indication of government failure to provide full housing is indicated in the spontaneous proliferation of informal settlements (Napier, Mark, 2002). Furthermore, "The growing gap between supply and demand of formal housing was instead filled by increasing amount of informal housing forms" (Mannervik, 2014). Recognizing the government's failure to full housing provision has led to the emergence of a self-help housing strategy.

It is not easy to pinpoint who exactly brought the concept of self-help housing into mainstream or academia, but John Turner (1965) and Charles Abrams (1964) were vital proponents (Napier, Mark, 2002). Turner focused on the social aspect while Abrams focused on the physical aspect of self-help housing by further categorizing self-help housing into 'site and service' and 'core housing' (Napier, Mark, 2002). In 1960 Turner argued that the informal settlement potential should be recognized and promoted as an alternative housing option. In the mid-1970s, this idea got acceptance as an alternative housing delivery option from international donors such as the World Bank (Mannervik, 2014).

Once it is being implemented, the concept of self-help housing has raised some criticism. One of the proponent critics of self-help housing is theorist Rod Burgess. Burgess argued that it is difficult to relinquish the private sector's vested interest in housing, and as a result, the concept of full autonomy of owners is not achievable. "Turner is naïve if he thinks that these groups are going to forsake their economic interest in a fit of charity" (Napier, Mark, 2002). The problem of 'downward-raiding' in which higher income groups acquired the houses initially intended for the poor was faced in some cases (Mannervik, 2014). On the other hand, the opposite of down raiding, a situation where the residents of self-help housing found after several

years that they were unable to realize their homes' market value by selling them, was also observed. (Napier, Mark, 2002)

Despite the recognized problems of self-help housing, various attempts have been made to enhance and develop the concept. UN-HABITAT encourages incremental housing as a strategy of converting informal settlement gradually into a formal and decent living. Following its success at large scales, the UN considers it one of the vital housing strategies for its 'Global Shelter (Housing) strategy 2015 (SIGUS Group and TUD, 2016).

2.1.1 Aspects of Participation and control of Owners in CH

One of the critical defining characteristics of incremental self-help housing is the owner's involvement level and control in the design, finance, and housing construction. Emphasizing the importance of owners control and involvement in the process of housing Turner have said:

“When people have no control over, no responsibility for, key decisions in the housing process, then dwelling environments may become a barrier to personal fulfilment and a burden on the economy. The important thing of housing is not what it is but what it does in people’s lives. Deficiencies and imperfections in your housing are infinitely more tolerable if they are your own responsibility than if they are somebody else’s.” (Turner, 1976)

To explain the difference between conventional housing and incremental self-help housing, Habraken uses a five-level model (Mannervik, 2014). In this model, the ‘urban structure’ level represents major roads and infrastructure, and the ‘tissues’ represent the level of streets on a neighborhood scale. The ‘building’ level represents building parts, such as load-bearing walls or the foundation, that cannot be changed without affecting other building parts. Finally, the ‘infill’ level, such as partitioning walls or kitchen equipment, can be changed without necessarily forcing other building parts.

The figure below shows the comparison between owners' and professionals' control levels in conventional housing versus core housing projects.

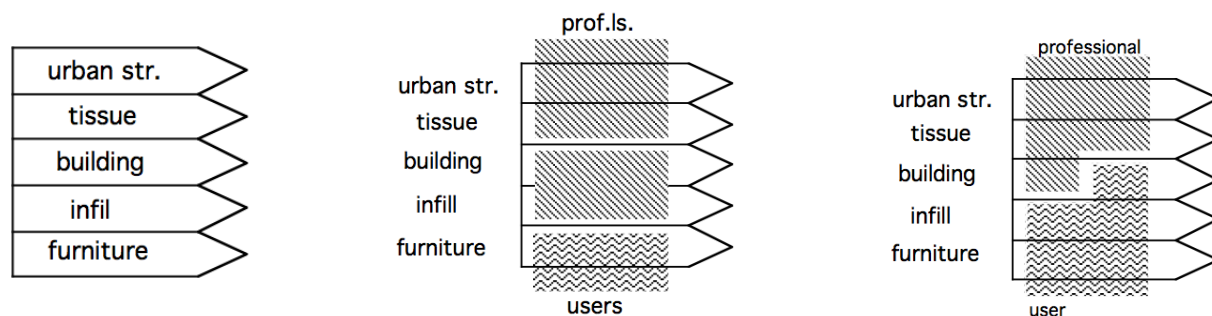


Figure 2. Left: Five level model. Middle: Control distribution in a conventional building Project. Right: Control distribution in a 'core house' scheme. (Habraken, 2002, p. 8-10) as quoted by (Mannervik, 2014)

It is crucial to balance the user/owner and professionals/government's level of control to make CH work as required. Excessive control by owners will result in a “flat hierarchy,” which resembles a squatter settlement (Mannervik, 2014). On the other hand, a professional or government's increased level of control will strip away the owner's control and flexibility and result in a monotonous mass housing project.

Additional to the government and the owners, other stakeholders have vested interests in incremental housing, such as financial institutions, cooperatives, material suppliers, construction workers, and other NGOs.

2.1.1 Core-Housing as Process

For CH, the process is more important than the end product. Unlike the formal housing sector, where the housing unit is the end product, for incremental housing, the process very crucial. John Turner calls this ‘housing as a verb,’ implying “to focus attention on the process by which urban low-income families house themselves contrary from the prevailing preoccupation with housing solely as a product.” (Riley and Wakely, 2011). Habraken has stressed this point in his keynote addressed to UNESCO in 1988.

Housing projects and neighborhoods must grow and develop over time. There is no such thing as instant environment. What is good today is insufficient tomorrow. Many housing projects that were built in Europe in the fifties and were considered examples for other countries to follow are now obsolete. [...] Being built in concrete these projects are extremely expensive to be renovated or to be demolished. (Habraken, 1988)

An incremental house expands and changes through time for different reasons. One reason can be the need for additional space because of family growth. Owners can also expand their space without necessarily increasing in their family size but the need for additional space when they have financial income. Sometimes space can be expanded for additional income by leasing the space or creating a small home-based business. Sometimes the change can be only in the material quality to upgrade the value of the house. The graph below shows how a particular case of incremental self-help housing successfully upgraded construction material and the number of rooms through time.

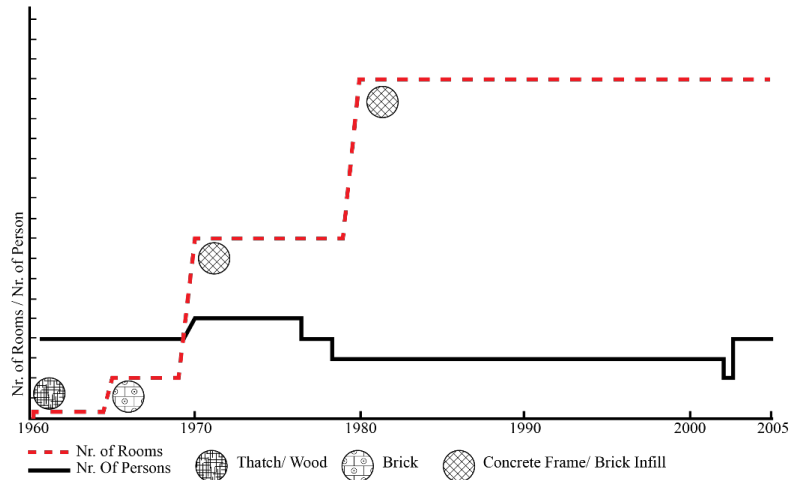


Figure 3: Example of successful incremental housing construction in Cuevas, Lima, Peru. Source: FAUA/UNI & SIGUS/MIT Workshop (material online at: <http://web.mit.edu/incrementalhousing/articlesPhotographs/pdfs/Cuevas-19-23Only.pdf>)

The starter building should be flexible enough for such kind of growth, change, and expansion. According to Dr. Reinhard Goethert, “The more complete the initial provision of the housing solution the more limited it is for future expansion.” (SIGUS Group and TUD, 2016)

2.1.2 Affordability of Core Housing

The affordability of housing is determined by two variables: capital variables and occupational variables. The capital variable is the cost associated with purchasing a house, and the occupational variable is the cost related to land lease and rates, service costs, building maintenance, loan repayments, and interest rates (UN-HABITAT, 2011).

Compared to other housing strategies, CH has distributed financing strategies, making it advantageous for both the government and the owner. For the government, CH lowers the capital expenditure compared to full house provision. On the other hand, it lowers the initial payment for owners and creates flexibility for expenditures associated with occupational variables. It can be argued that the combined result of smaller initial payment and the financial flexibility makes CH the most affordable housing option for growing countries. As a result, “Incremental housing saves time and money during start-up, which allows reaching more people in need more quickly” (SIGUS Group and TUD, 2016).

CH's affordability is affected by the settlement location because it determines the owners' economic capacity and the amount of money spent on transportation. An incremental housing located on the periphery of a city will not be affordable because it provides limited income generation potential for the owner. Nevertheless, at the same time, CH, located in the inner city, will not be affordable due to high land costs.

Revisiting Core Housing through Generative Design and Mass Customization

Therefore, proper planning and optimum location selection are vital, taking the land capital cost, transportation cost, and income potential into consideration.

Furthermore, the size and cost of a starter structure determine the affordability of CH. The bigger the starter structure, the higher the initial cost will be for the government and owners who have to pay the premium and amortized payments. Therefore, it is essential to know how much of the monthly income the owner can afford to pay for housing. In modern housing, 30% of the household income is considered affordable, but for a low-income family, this has to be reduced to 10 or 15% because most of their income is spent on basic necessities such as food, clothing, and transportation (SIGUS Group and TUD, 2016).

2.1.3 Core Housing Design and Construction

Even though self-help housing's distinct character lacks formal design and planning, studies show that proactive designing and planning are crucial for the successful consolidation of incremental housing (Riley and Wakely, 2011). A left-alone self-help housing might end up being a squatter settlement, and the quality of construction will be compromised. Moreover, studies indicate that planned core housing can quickly consolidate to achieve full housing compared to unplanned and fully self-built houses. On the other hand, a paternalistic approach or too much-controlled planning and design will leave no space for the owner's flexibility. Therefore, it is essential to strike a balance between the two extremes. At its best, proper design planning will create a starter structure that allows flexible and efficient expansion. Besides, proper and proactive design can significantly reduce costs and increase the project value for all stakeholders (Laura Sara Wainer, 2016).

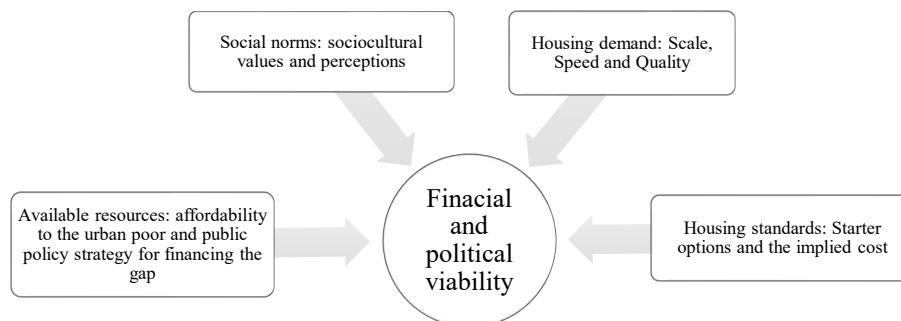


Figure 4: Normative considerations for designing low-income housing programs that address rapid urbanization at a meaningful scale. Source: (SIGUS Group and TUD, 2016)

In the case of incremental self-help housing, the process of design and construction are much intertwined. The first construction process starts with the government or the housing provider, and the owners carry out the expansion. In some cases, the starter structure is built using mass production, but the expansion process takes time to evolve; thus, it becomes difficult to impose a particular type of construction system.

accessibility of local material and building skills are essential to carry out the long process of incremental expansion. Therefore, all skills and local materials improve the self-help building process while promoting the local economy (SIGUS Group and TUD, 2016).

In the case of multistory CH, government involvement and control in the design and construction process will increase because of the coordination and safety measures required to make it work. However, the government's increased level of control may lead to uniformity, and the result might end up looking like public mass housing. Therefore, when designing multistory and multifamily core housing, the starter structure should be designed to enable the owners to be flexible and expand through time without compromising the standard and safety concerns.

Studies show that after self-help housing is adopted into the mainstream, various construction methods are used to deliver CH efficiently and in mass. In some cases, the government uses modular construction to build the starter structures fast and cheap and leaving the rest of the process for the owners, small contractors and material suppliers, and community organizations. Usually, small material providers come along to provide construction material for the incremental housing to fill in this gap.

2.1.4 Density in Core Housing

In urban areas, density is a critical criterion determining the feasibility of any form of housing strategy. However, single-story incremental housings are not affordable and could not justify the initial capital costs of the infrastructure (SIGUS Group and TUD, 2016). In a podcast by Reinhard Goethert, on 'incremental housing-the new site and services, explains that multistory starter core units can be used to induce density into core housing, but he also highlighted the effect on the flexibility (Goethert, 2019).

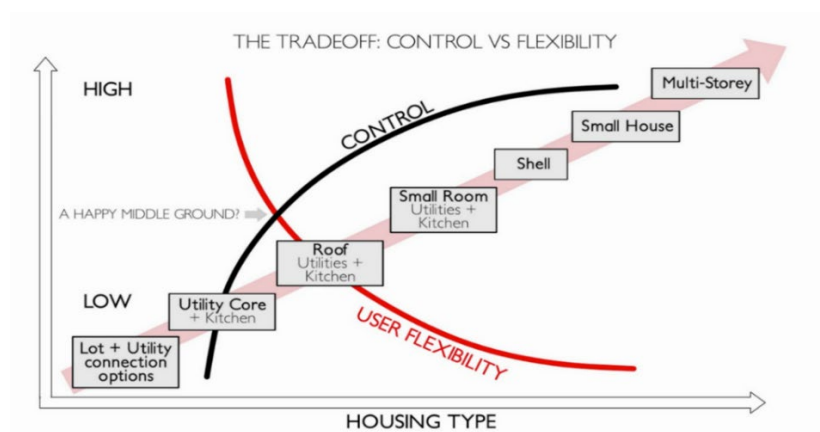


Figure 5: Control vs Flexibility. Diagram by Reinhard Goethert, Incremental Housing the new site and Service Podcast, Massachusetts Institute of Technology

Revisiting Core Housing through Generative Design and Mass Customization

The following case studies illustrate some early thinking and current practices of multistory core housings:

1. Maison Dom-Ino by LeCorbusier proposed a multistory incremental housing prototype in 1914 to bridge the gap between industrial and user-driven fill-in. It can be presumed that modern architecture, the essence of liberating walls from the load, has laid a good precedent for multistory CH's.

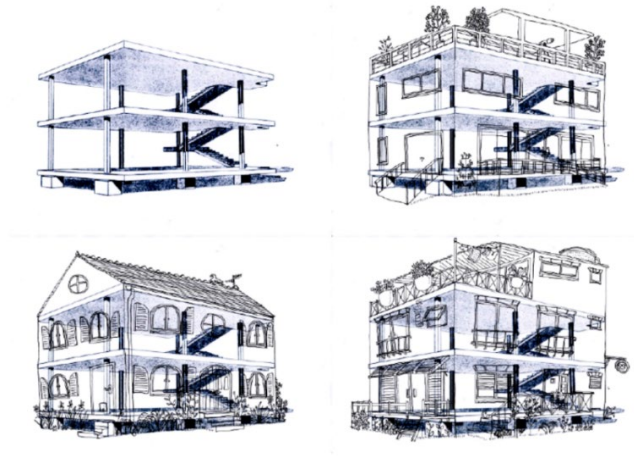


Figure 6: LeCorbusier's Dom-Ino(top left) and hypothetical user-driven in-fills Source: FLC 19209 (original) and modifications by Cotter (undated) found on <https://hotcharchipotch.wordpress.com/2013/03/31/readapt-the-habitat/>.

2. SITE conceptual-provoking proposal of elevated, layered suburban houses in which every level is a flexible platform that can be developed as a separate parcel. (SIGUS Group and TUD, 2016)

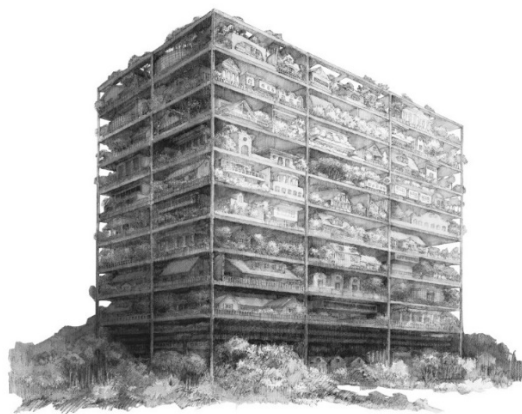


Figure 7: The firm SITE proposed elevated layered suburban houses. Source: <https://ritornoallabitare.tumblr.com/>

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- Port Said New Community Projects in Egypt: 3-story structure provided was a concrete frame for simple platforms and a standard staircase, 4 units per floor. Toilets and water supply were provided from a central core.

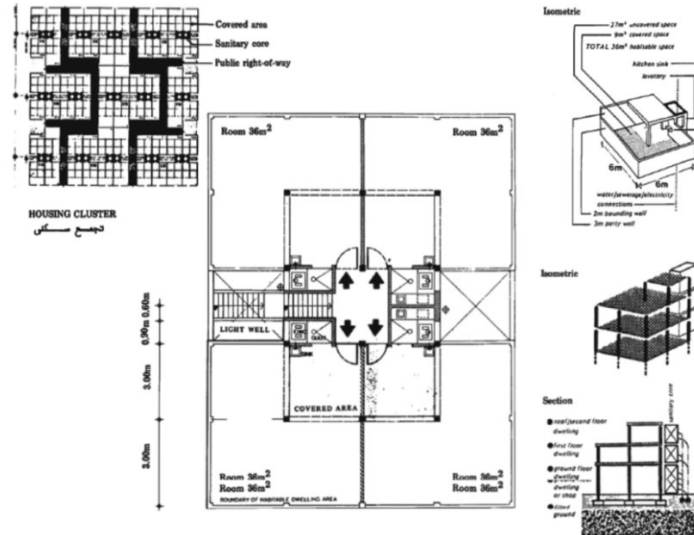


Figure 8: Port Said New Community Projects Proposal by Bullen and Partners, Shankland Cox Partnership, Binnie and Partners, Peat Marwick, Mitchell and Company, Hanna, and Partners. Source: Republic of Egypt, 1979: p. 43

- Mkalles Public Housing Project in Beirut expansion through the insertion of internal floors.

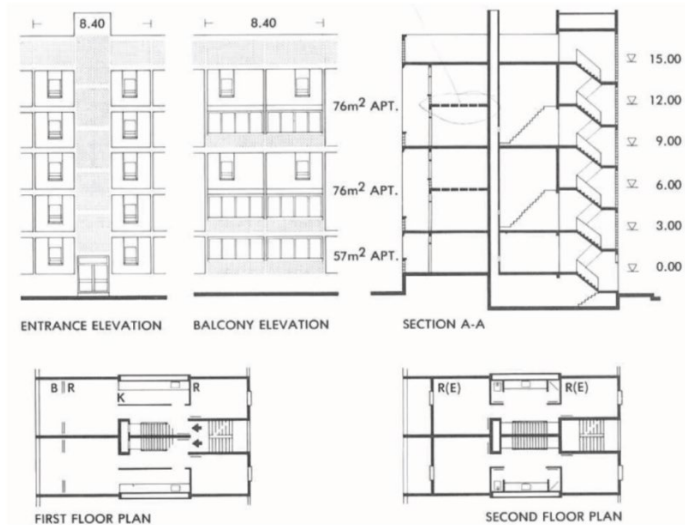


Figure 9: Mkalles Project, Beirut, Lebanon Source: Caminos et al., 1974: p. 23

- Ciudad Bachue in Bogota, Colombia: is an inspiring example of a multistory incremental housing project designed and built to be incremental and then expanded successfully. Ciudad

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Bachue is a good example that shows how the top-down provision of secure land tenure and structural safety matched the user and community-driven construction, thereby balancing public and private investment.



Figure 10: a through d: Ciudad Bachue, Bogota Colombia (Source: UNAL, undated)

Top Left: structural frame to support vertical extensions of up to 5 floors (approx. 1978) Top Right: Structural frame with wall panels (approx. 1979) Bottom Left: Early modifications, immediately after hand-over to the community (approx. 1981) Bottom Right: Cleaned and well-maintained community courtyard, after early expansion (approx. 1981) Source: (SIGUS Group and TUD, 2016)

6. Solari shows how proactive design and legal frameworks can enable incremental housing success. “For example, anticipatory design may avoid the emergence of rooms locked in the interior of the expanded building.” (SIGUS Group and TUD, 2016).

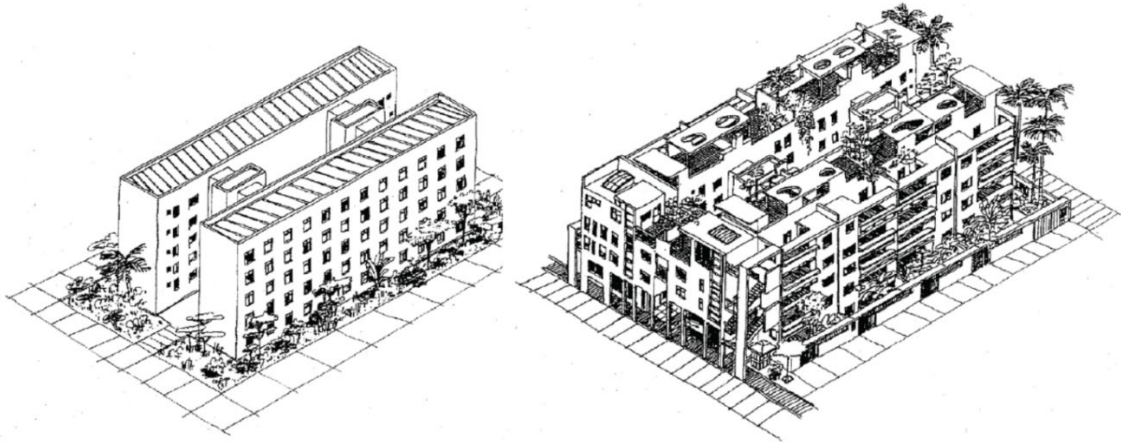


Figure 11: Potential result of inclusive regulations and technical assistance supporting extensions

Left: the original Public housing project proposal. Right: modification scenario proposal according to proposed rules and with the assistance of an architect. (Source: Solari, 1999) as it is cited on (SIGUS Group and TUD, 2016)

2.2 Generative Design

Since the emergence of programmable computers in the 1940s, architects have used computers in practice and experimental works. In the 1960s and end of the 70s, architects were interested in using computers' computational power to solve design problems through direct coding. However, this kind of experimental computer usage had lost traction as the focus diverted to drafting and visualization tools (Holland, 2011). As a result, CAD (Computer Aided Drafting) and visualization have become the dominant way of using computers in design and have shown significant development through time. In addition, the emergence of Building Information Modeling (BIM) tools has increasingly made drawings, documentation, and design coordination more efficient.

In recent years, the interest in using computers' computational capacity beyond documentation and visualizations is gaining popularity. Many architectural practices, open-source platforms, and big software companies have started experimenting with the potential use of computation, machine learning (ML), and artificial intelligence (AI) in the design process. Generative design (GD) is one of the computational tools which is getting a broad focus in the design industry, including architecture and building construction. The 2016 Autodesk website define generative design as:

Generative design is a technology that mimics nature's evolutionary approach to design. It starts with your design goals and then explores all of the possible permutations of a solution to find the best option. [...], generative design software quickly cycles through thousands – or even millions – of design choices, testing configurations and learning from each iteration what works and what doesn't. This process lets designers generate brand new options, beyond what a human alone could create, to arrive at the most effective design. (Autodesk Universtiy, 2020)

Due to the ability of GD to learn over time and produce optimized solutions, GD is included within a larger framework of artificial intelligence (AI) (Nagy, Medium.com, 2017).

2.2.1 Types of Generative Design

Based on how the system works, GD can be characterized into two broad categories: logical and biological (Loomis, 2019). The logical category of GD is based on bottom-up, rule-based, and rigorously defined language. On the other hand, the Biological takes inspiration from the natural evolutionary process, a top-down, random, and successive generational optimization. In addition to this, GD can be further categorized into five systems. These are cellular automata, genetic algorithms, L-systems, shape grammars, and swarm intelligence (Singh, 2019).

Cellular Automata (CA)

CA is a collection of specified shaped grid cells in which each cell is governed by the rule that is defined in relation to the surrounding context. Even though the system looks inspired by a nature organization system, the working mechanism is defined through rigorously defined language. Design constraints are implemented from the bottom up, governing the local behaviors of each cell. As a result, the CA outcome is often complex and difficult to predict (Singh, 2019).

Shape Grammars (SG)

A Shape Grammar is composed of an initial shape manipulated by a finite set of shape rules (grammars) to create a finite set of shapes. SGs help generates design languages or understanding existing designs by breaking them into sets of shapes and rules. However, iis critically challenging to develop grammar capable of producing designs that meet specific design goals or constraints (Loomis, 2019).

L-Systems (LS)

L-Systems produces fractal-like forms through self-repeating forms in a precisely defined rule. They are used to mimic the growth patterns of trees, and to a certain extent, they are also used to simulate the fractal growth pattern of a city. In principle, LS is a design grammar (Singh, 2019).

Swarm Intelligence (SI) and multi-agent societies

Agent-Based Models (ABM) are often used to implement social or collective behaviors (Singh, 2019). A simple property is assigned to agents that can create collective behavior by interacting with specifically defined rules.

Genetic algorithms (GA)

Genetic algorithms and genetic programming are evolutionary techniques inspired by natural evolutionary processes. It mimics the evolutionary process, and it searches the solution space to find the fittest solution that qualifies the fitness criteria.

This study focuses on the class of generative design called genetic algorithm due to two underlying reasons. First, GA is a type-generative design system that is well studied and applied in design compared to other GD systems. Hence, there are many tools made available by open-source platforms and software companies. Secondly, the type of algorithm used by GA is called metaheuristic, or search algorithm, which is more appropriate for solving architectural design problems involving geometric constraints (Nagy, Medium, 2017). This algorithm's appropriateness comes from its efficiency in navigating complex computable architectural problems, which otherwise would not be possible with the pure brute computational power of computers. In this study, the term 'generative design' is used in reference to the specific system of genetic algorithms.

2.2.2 Genetic Algorithm

Genetic algorithms (GA) are also referred to as 'search algorithms.' Its working mechanism is inspired by the Darwinian evolution theory, such as selection, breeding, crossover, and mutation. Parallels can be drawn on different levels between Darwinian evolution and the working principles of GA. For example, a genotype is an organism's composition of DNA, and the phenotype is the physical characteristics of an organism, which is determined by the gene(DNA) and an environment. The organism's gene composition creates varying phenotypes such as eye color, height, skin color, and the like. In GD, a similar classification is used to describe a particular design object or shape's characteristics. For example, a rectangle area and perimeter length can be considered a phenotype, and parameters such as width, length, or the XYZ coordinates of the rectangle corner points can be referred to as genotype. Therefore, changing the genotype (XYZ coordinate) will determine the rectangle's phenotype (area).

Furthermore, the GA's optimization mechanism is analogous to the theory of 'survival of the fittest.' For example, an organism's survival depends on the phenotype's performance (color, strength, size...), which is determined by its gene composition. Therefore, a surviving member of a species carries a better gene and

passes it to the next generation. Nature, through evolution, without knowing the system's internal working mechanism or details of the gene composition, can select the fittest organism by merely evaluating the phenotype's performance (survival). Similarly, GA uses the principle of 'survival of the fittest to solve design problems by searching and selecting the fittest solution satisfying the design goal. For example, if the fitness objective is to maximize the area (phenotype) of a rectangle, the GA will start with a random selection of XYZ coordinates of a rectangle's corner points and evaluate the resulting area. If the tested area is not the fittest one, it will create another set of XYZ coordinates (generation) and test the resulting area. It also picks the best gene combination from the older generation and crossover it with the newer generation. This process will continue generation after generation until the fittest phenotypes (Area) are identified. This top-down approach is the unique nature of GA, making it more efficient than a simple 'brute force' searching.

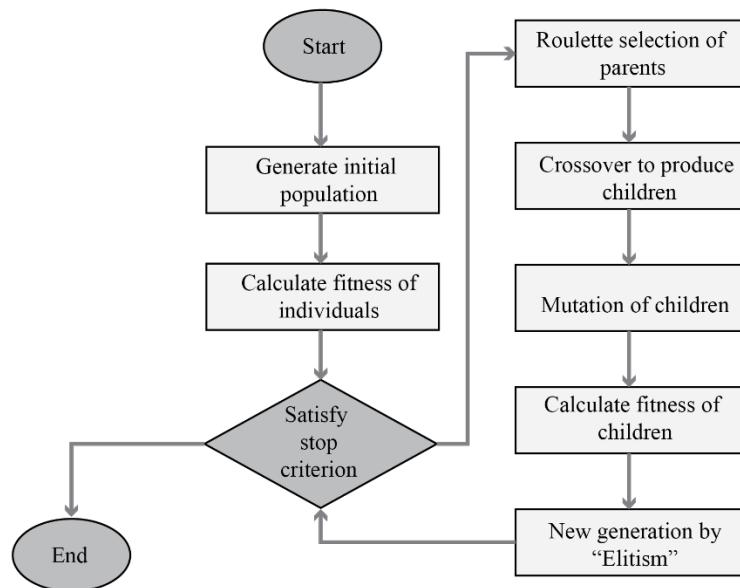


Figure 12: Basic Model for Genetic Algorithm (GA) Based on (Nagy, Medium.com, 2017)

2.2.3 Design Space

Architectural design problems are complex and usually contain computable and incomputable, measurable, and immeasurable parameters. The computable design problems often refer to objective criteria such as area, efficiency, climate responsiveness, and cost. On the other hand, incomputable design problems constitute subjective, intuitive, and artistic problems such as beauty. In GD, It is essential to understand that the design space domain is limited to the computable and measurable parameters. Therefore, defining the computable design space of a design problem is the first step in any GD process. Defining requires a

systematic breakdown of a design problem into a genotype (design space controlling parameters) and phenotype (fitness/evaluation objectives). More importantly, the optimization function should be expressed to maximize or minimize the fitness objective. Usually, a parametric model is developed, which describes the solution space and creates a computational link between genotype and phenotype.

In defining the design space for a particular design problem, it is crucial to balance between Bias and Variance. Bias and Variances are terms used in the field of AI to describe the relative flexibility of a given model – a parametric model in our case (Nagy, *Generative Design*, 2017). Bias is the condition where the parametric model is not flexible enough to explore a possible range of solutions. As a result, this model will be biased toward a predictable outcome. On the contrary, variance is a situation where the parametric model tends to become too flexible, and as a result, the solution space will be challenging to navigate and retrieve productive solutions.

The second important point to consider in defining design space and creating a parametric model is to balance between Complexity and Continuity. Complexity describes the capacity of design space to generate an unpredictable result. Continuity refers to the internal consistency and structure of the design space. The design space should allow the search algorithm to navigate between adjacent designs and make a valid prediction about the design's performance (Nagy, *Generative Design*, 2017). A well-defined parametric model is essential to benefit from GD and produce novel design solutions.

2.2.4 Design Measures/Objective and Constraints

Additional to defining a design space, a GD process needs to have design measures in the form of objectives and constraints. The genetic algorithm (GA) evaluates the design space to give us an optimized solution through these design measures. Design measures are essential for objective evaluation and exploration of design options. Excluding subjective values, GD can be used to measure simple values, such as floor area, and complex values, such as structural simulation, fluid dynamics, or occupant-level agent behavior (Nagy, *Generative Design*, 2017). GD produces a wide range of design options that are very difficult to be handled manually. Therefore, GD is an essential tool of design exploration.

2.2.5 Design Optimization

For any design space to be navigated by a Genetic Algorithm (GA), the design problem must be expressed in the form of an optimization problem. Any optimization problem can be expressed mathematically with three main components: Input vector parameters, Objective/Goal function, and Constraint function.

Input Parameters are vector inputs that define the design space, and they take three forms: discrete values, continuous values, or permutation sequences. Discrete values define a set of categories or options represented by integers. In contrast, Continuous values define and represented by continuous measures.

Furthermore, Permutation sequences define an ordering of a fixed number of elements (Nagy, Generative Design - Design Optimization , 2017).

Objective Functions: Describe the goals of the optimization problem, which only works in two directions: Maximize or minimize the fitness objective. Therefore, optimization problems need to be expressed in either of these two ways. A design problem that is defined by one fitness objective is called single-objective optimization (SOO). For example, maximize an area without considering other objectives can be referred to as an SOO, and in this case, the search algorithm will select solutions with the maximum area. A design problem that is defined by multiple fitness objectives is called multi-objective optimization (MOO). This design problem is complicated than SOO because the algorithm has to optimize more than one objective. In this scenario, no objective function can be maximized without compromising other objectives and vice-versa. As a result, there will be no single solution that satisfies all criteria, but instead, there will be multiple Pareto optimal solutions (Rohmann, 2019). It is up to the architect and designer to explore the Pareto front optimal solutions and select.

Constraint Functions: Constraint functions put bound to the domain of feasible solution space that the GA can search within. A constraint can be made to be equal to a specific value or set to be less than or higher (Nagy, Generative Design , 2017). It is essential to differentiate and determine which design measures to consider as constraints and objectives.

2.2.6 The process of Generative Design

Depending on the design problems, many studies and practitioners define the GD process in different ways. For example, the generative design process used by Autodesk University has seven steps:

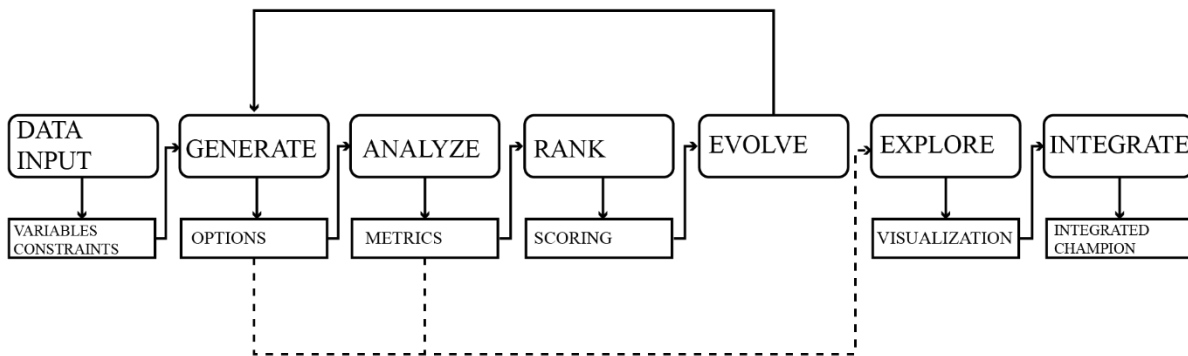


Figure 13: Generative Design Process based on (Autodesk University, 2020)

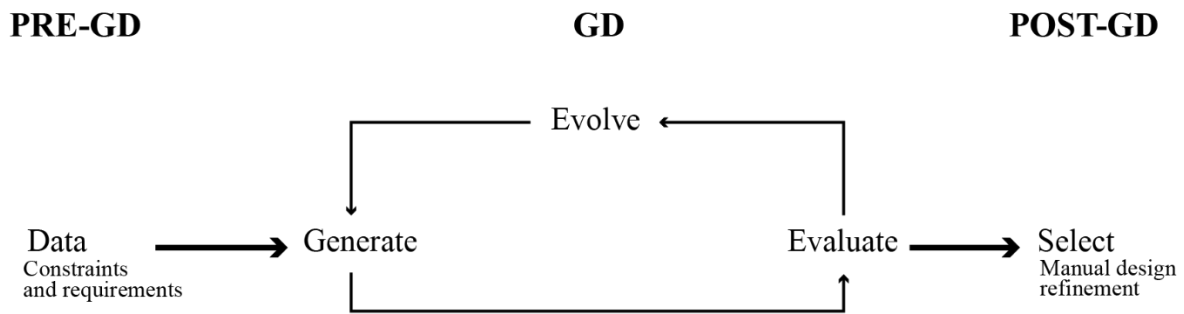


Figure 14: A Generative design process used by MARS. (Vilaggi, 2020)

In another example, the GD process used by the ‘Living’ research group for Autodesk MaRS office design in Toronto has three basic steps, which comprise supplementary activities within each step. Even though the GD process can vary depending on how the design problem is defined, any GD process can be simplified into four necessary steps.

Preparation of Input data (Defining)

Design problems are complex and usually contain computable and incomputable parameters. Therefore, it is crucial to distill out computable parameters for any problem to be tackled by GD. This step requires proper understanding and analysis of the problem, establishing a relation between parameters, defining goals of the design and constraint of the design space, and setting fitness objectives.

Parametric Model

The defined computable design problems must be expressed in terms of the relationship between parameters and geometric expressions. For example, a cube volume must be expressed parametrically, such as height, width, and depth ($w \times d \times h$) or height and area ($A \times h$). Thus, it is a process of modeling a design process in the form of phenotype and genotype to navigate the solution space using GA.

Genetic Algorithm Process

It is an iterative process of using a metaheuristic or search algorithm to generate random solutions, evaluate their fitness, select the fit solutions, crossover them with the next generation, and induce mutation until the fittest solution is found. The detailed GA process and its efficiency vary depending on the type of metaheuristic algorithm employed.

Post GA interpretation and presentation

The result of GA must be interpreted and presented as a palatable result. The designer in charge must be involved in this step to filter the best solution for the design problem. Sometimes the solution space can be overwhelmingly cumbersome, and analytic tools can be used in the selection process. Therefore, this step is not necessarily a GD process in itself.

2.2.7 Generative Design Tools

Various GD tools are developed and are being used in architectural practice and academic studies. Architects, since they are not coders by profession, use Visual Programming Language (VPL) tools. The most popular VPL is Grasshopper, which is based in the Rhino 3D software environment. Grasshopper is a parametric design tool, but it can be used in the GD process by integrating SOO or MOO search algorithms in the form of plugins. Grasshopper became popular for computational design in architecture because it is simpler to learn than coding (Nagy, Medium.com, 2017).

Another GD tool example is Project refinery, which Autodesk developed and is made available in the beta version in 2018. This GD tool operates in Dynamo environments, which use the Revit 3D platform. The ‘Project refinery’ uses a GA called NSGA-II multi-objective optimization algorithm. NSGA – Nondominated Sorting Generative Algorithm uses “Fast non dominated sorting to compute the domination rank of a solution and crowding-distance computation to achieve a diverse set of solutions.” (Rohmann, 2019) There are also other evolutionary algorithm tools that are MOO and use NSGA. The below table enumerates GA tools their characteristics.

Table 1: Comparison of VPL Generative Design tools.

Name of GA	Use	Computational tool	SOO/MOO	Type of Metaheuristic Algorithm
Galapagos	Simple and powerful SOO tool integrated into Grasshopper.	Grasshopper	SOO	
Octopus	Is works similar to Galapagos but introduces the Pareto-principle for multiple goals	Grasshopper	MOO	SPEA-2
Opossum	Uses advanced machine learning techniques to find suitable solutions.	Grasshopper	SOO/MOO	RBFOpt,CMA-ES,MACO, NSGA-II and NSPO
Biomorpher	Interactive Evolutionary Algorithms (IEAs) allow designers to engage with the process of evolutionary development itself	Grasshopper		
Wallacei	utilizes highly detailed analytic tools	Grasshopper	MOO	NSGA-II
Design Space Exploration	Support visual, performance-based design space exploration, and	Grasshopper	MOO	NSGA-II

	interactive MOO for conceptual design.			
Project Refinery	Revit integrated GD tool.	Dynamo	MOO	NSGA-II

For this study, Wallacei is used because it is a MOO tool and has a robust analytics interface called Wallacei analytic integrated into it, making the visualization and selection of design options much more manageable.

2.3 Mass Customization

Mass customization (MC) is a combination of two counteracting theories of mass production and customizations (Maria et al., 2019). The term ‘mass customization is popularized by Joseph Pine, who defined it as “Developing, producing, marketing, and delivering affordable goods and services with enough variety and customization that nearly everyone finds exactly what they want.” (Fabrizio et al., 2009). Satisfying the cost reduction through mass production and, at the same time, bringing personalized products is a challenging task. According to (Fabrizio et al., 2009), ‘Three Fundamental Capabilities’ are required to effectively handle this challenging task: solution space development, robust process design, and choice navigation.

Solution space development: Identifying the product attributes in which customers’ need diverges the most. This process aims to incorporate as many different needs as possible and delineate the solution space. Without the support of a creative and innovative approach, this can be a challenging task. Innovative tools that enable customers to register and test their preferences and tools that can interactively gather the process's data are essential. (Fabrizio et al., 2009).

Robust process design: Entertaining customers' different needs requires an efficient design framework that is flexible and robust to deliver customized solutions. It is crucial to understand that MC is focused on a process rather than a product, unlike mass production, and geared towards delivering a specific product in large quantities. Approaches such as flexible automation and process modularity are crucial methods to achieve robust process design.

Choice navigation: This is the process of supporting customers in identifying their solutions while minimizing the complexity and the burden of choice. Innovative digital tools that can match customers' requirements with a preexisting list of solutions and enable fast testing are essential in this process. Furthermore, creating products that can be configured to adapt to customer choice is one way of enabling choice navigation.

Despite the promise of MC in providing solutions that fit specific customer needs, the end product is inevitably a compromise between the range of pure standardization and pure individualization of a product. Thus, the customization ranges are pure standardization, segmented standardization, customized standardization, tailored standardization, and pure customization (Maria et al., 2019).

2.3.1 Mass production and Mass Customization in Housing

In the effort of catering housing for the mass, different technological innovations are developed. One of these innovations is an offsite construction method that takes advantage of a controlled environment to manufacture pre-assembly building parts. Offsite production of the buildings has four different levels: level 1 is simple components manufacturing and sub-assembly, level 2 is non-volumetric components, level 3 is volumetric components, and level 4 is modular building structures (Maria et al., 2019).

In response to the massive housing demand, offsite construction has been utilized since the Industrial Revolution to produce more housing units at a lesser price. Studies indicate that, compared to in-situ construction, offsite constructions and prefabrication reduce construction time, waste, and cost. In most cases, mass production is a rigid system and disregards users' specific demands and is not open to users' involvement in the design or construction process. As a result, "Housing, [...], witnessed the failure of mass production as a viable approach for producing dwellings throughout the 20th century partially due to the lack of personalized options for the users." (Basem et al., 2013).

2.3.2 The use of Computation in Mass Customization

The use of computational tools in MC can be analyzed from three stakeholders' perspectives: customers, designers, and manufacturers. First, computational tools play a vital role in facilitating customer's involvement in the design process and make choice navigation easier. Besides, interactive tools can be used to collect data about the users' preferences (Fabrizio et al., 2009). Second, for designers, computational tools assist in developing design options, simulation, optimization, and rapid prototyping. Finally, manufacturers use computational tools to help translate the design into a product with accuracy and efficiency.

The computational tool development has attracted researchers and practitioners to develop a computational design framework to integrate MC in the housing. Duarte (2001, 2005) used a shape grammar model for mass customization and demonstrated the model developed based on Alvaro Siza for the Malgueira housing project. Yi-Kai Juan (2006) Used a hybrid model that uses Case Base Reasoning (CBR) and Genetic Algorithm (GA). Duarte (2008) proposed a design system that can generate customized designs and a prefab building system that can be visualized and constructed. Neimeijer (2010) used design constraints to evaluate

and determine through Boolean operation if the user's preferred option qualifies the constraints and building code (Basem et al., 2013).

Chapter Three

3.0 Contextual Review

3.1 The State of Housing in Addis Ababa

Housing developers in Addis Ababa can be categorized into; Private real estate, public sector, co-operatives, NGO/CBOs, squatter and informal settlements by the urban poor, individuals, or private efforts for their housing and Site and services (Gebremedhin, 2016). Historically the private real estate sector has played a minor role in the housing provision. During the Socialist 'derg' regime, the private sector was not encouraged. Instead, the public or government has attempted to deliver housing through different forms and strategies. From the early rental housing schemes of 'kebel' housing in the 1980s up to the recent IHDP, the government has attempted to provide housing for various income groups. The Addis Ababa, public sector housing provision, can be divided into two periods:

Between 1974 and 1991, about 60 percent of the housing stock was transferred to government ownership following urban land and extra houses' nationalization. As a result, two types of rental housing systems were created: The Agency for the administration of Rental Houses and The Kebele Housing. (Mekonnen, 2017) The kebele houses administration accounts for 93% of the rental accommodation (UNHABITAT, 2010). Due to a lack of proper maintenance with no adjusted rent price for over two decades, these rental houses are in bad condition, and they make a more significant share of a slum in the inner city of Addis Ababa (Mekonnen, 2017). According to UN-HABITAT 2010 report, about 70% of kebele houses need total replacement, and only 30% are in fair condition because the owners pay attention to maintenance (Mekonnen, 2017).

Post-1991, Condominium Housing: The new government, EPDRF, brought market-orientated reforms intended to bring the private sector to be involved in housing provision. However, the private sector could not provide housing for the ever-growing housing demand in urban areas. As a result, the old government-owned rental houses continued to be the dominant low-income houses for the next decade. This stagnation of housing provision resulted in the proliferation of informal housing. The Addis Ababa city administration has attempted various slum upgrades that were limited to improved infrastructure and services but not the housing units to curb this. This strategy was not entirely successful in meeting the overall housing deficit. The first and " prominent government program to solve the low-income housing challenge is the Integrated

Housing Development Program (IHDP), initiated by the Ministry of Works and Urban Development (MWUD) in 2005.” (Mekonnen, 2017).

Though compared to the previous government housing delivery strategy, IHDP is a better-integrated approach and is successful in many aspects, but there is a problem in delivery. Close to one million residents have registered in two terms, 2005 and 2013, and within 12 years, only 176,065 transferred to the owners (Mekonnen, 2017). Financial problems and lack of proper construction management skills were the two problems to blame for chronic underperformance. In addition to the broken promise of delivery, the housing units were not affordable for low-income owners. “ The project is focused more on ‘cost-efficiency rather than the low-income people, and most of the actual beneficiaries have been better-off families [...] Some households with large family size could not readily take the smaller units because of their small size” (Housing in Ethiopia an Overview, 2017)

Housing cooperatives are one of the primary modes of housing delivery options in Addis Ababa. It accounts for half of the formal housing provision sector. “Housing cooperatives are created by a group of people who come together as an entity to perform the function of a developer.” (Gebremedhin, 2016). It was a dominant housing delivery option between 1975 and 1991. The land was given for free, and infrastructure was also provided.

Furthermore, building materials were supplied at a subsidized rate with some technical assistance during the construction process. Loans with a minimum interest rate (4.5%) were also provided in most cases. It is regarded as a successful housing delivery option because it lessened the government's financial stress and mobilized individual efforts and organizations to achieve consolidated housing. Moreover, it encouraged the participation of the community in the housing production process. This housing delivery option was favorable for middle and high-income families, but it was out of reach for low-income people (Gebremedhin, 2016).

As it is observed in many growing countries, informal housing is one of the proliferating urban phenomena in Addis Ababa. The informal settlement produces the most significant number of housing units, one-third, exceeding the government and cooperatives. The proliferation of informal settlements indicates formal housing weakness to cope with the housing demand and self-help housing efficiency. While most informal settlements happen in the city's outskirts, there is also a type of informal settlement within the city centers in the form of extension, also known as ‘kitya’ in the local term, which affects the physical structure of the city. Adding an extension to the original building is made to create rentable space for additional income and sometimes to accommodate the growing family size. This type of inner-city extended rental house is

highly demanded due to the location and low rent price compared to other housings. “This system has absorbed a significant proportion of the housing requirement within the city.” (Gebremedhin, 2016).

3.2 Core Housing in Addis Ababa

The ‘derg’ regime collaborated with the World Bank to develop an affordable housing program called the Ethiopia Urban Development Project. The program focused on three components: a. Site development and servicing; b. construction loans for slum upgrading; and c. institutional development. The site and service projects implemented in ‘Nifas Silk’ district with 2950 serviced plots and the slum upgrading were planned for ‘Tekle haimanot’ area. The institutional development was focused on supporting the newly established Housing and Savings Bank (HBS). (Mota, 2019)

In the 1970s, site and service have gained momentum as an efficient delivery option of affordable housing for the developing world. (Mota, 2019) With the World Bank's support, the Nefas Silk site and service were developed in the same period. 130ha area allocated for this plan, and 60% of it is dedicated to private dwellings, 15% for circulation, and 25% for community amenities. Two types of plots, 160m² and 250m², were given for private dwellings to cater to different income groups and avoid creating exclusion and ghettos. (Mota, 2019)

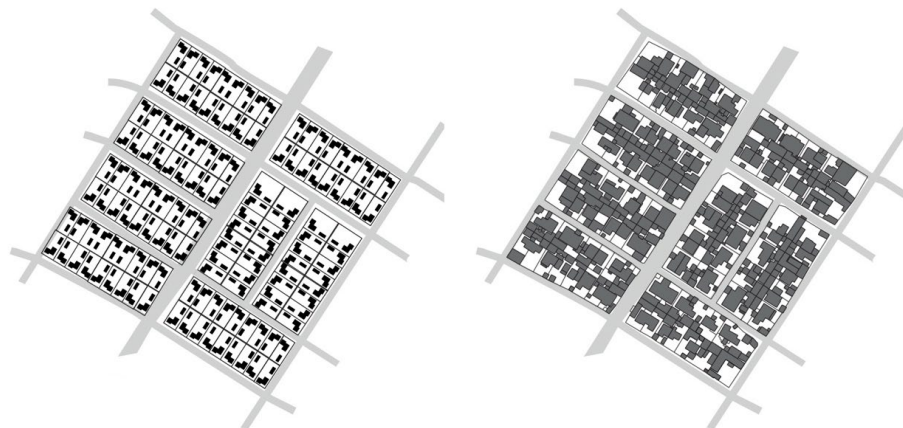


Figure 15: Plan of the Nefas Silk area. Preliminary Plan (1990, left), and current situation (2015, right)

Drawings: Juanjo Tenorio de Peroy, Lara Spagnol, Siqi Fan, Yildiz Haseki

HSB arranged the funding for the construction of the Nefas Silk site and service. The loan is prepared in three categories depending on the starter unit option. House type A contains a 11m² room built self-produced hollow block concrete and an additional separate kitchen and pit latrine. The intermediate one, House type B, has two rooms of 11m² constructed with wattle and daub (locally known as chika) and a detached kitchen and pit latrine. The third option, house type C, has a similar size type B but is built out of

Revisiting Core Housing through Generative Design and Mass Customization

concrete blocks. All house was built by the combination of skilled labor, small contractors, and self-help. The typologies are designed to accommodate growth and expansion. (Mota, 2019)

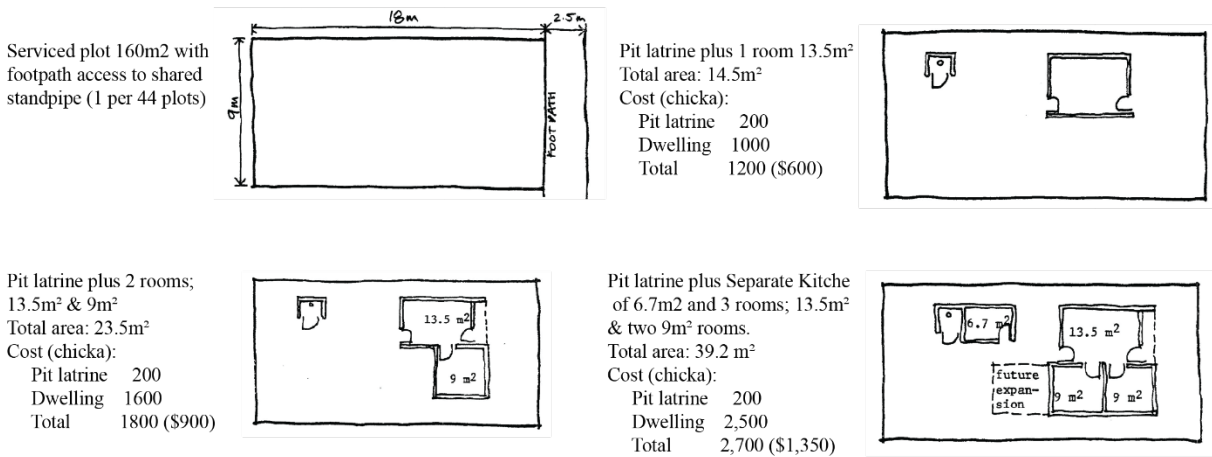


Figure 16: Left: Nefas Silk Urban Development Plan - Progressive Development of Dwelling (1982)

Source: World Bank – Staff Appraisal Report Ethiopia Urban Development Project as quoted in (Mota, 2019)

The Nefas Silk site and service was approved and started in 1983 and completed in 1991. According to the World Bank completion report, community organization effort created a cohesive community after completing the project, and the site consolidated over three decades (Mota, 2019). The incremental expansion took the form of horizontal expansion, but in some cases, it vertically expanded into multistory single-family housing. In other cases, the plot is subdivided into a rental unit generating income for the owners. Some of the 160m² plots become space for production and commercial activities with distinctive corner shops in terms of function.

“ In the Nefas Silk settlement, the physical and strategic targets of the project were successfully achieved.” (Mota, 2019) The government owned the land, and as a result, the cost of land was alleviated, and affordable housing for low-income families was achieved. With a total of 4410 units on 130 hectares, the Nefas Silk site and service development density compared to the inner city are too low.

In addition to government-planned core housings, individual residents have incrementally expanded their housings through ‘Kitya,’ a local term used to express housing units' extension. Shiferewa has surveyed and documented a self-initiated transformation of public-provided dwellings, which satisfy the definition of site and service core housing. In ‘Gerji’ area, corrugated metal sheet built emergency shelter units are consolidated through time to become dwelling units. In the ‘Kolfe’ area, a starter unit (core house) is built

Revisiting Core Housing through Generative Design and Mass Customization

through an aided self-help program and gradually expanded to respond to the family space demand. (Mota, 2019)

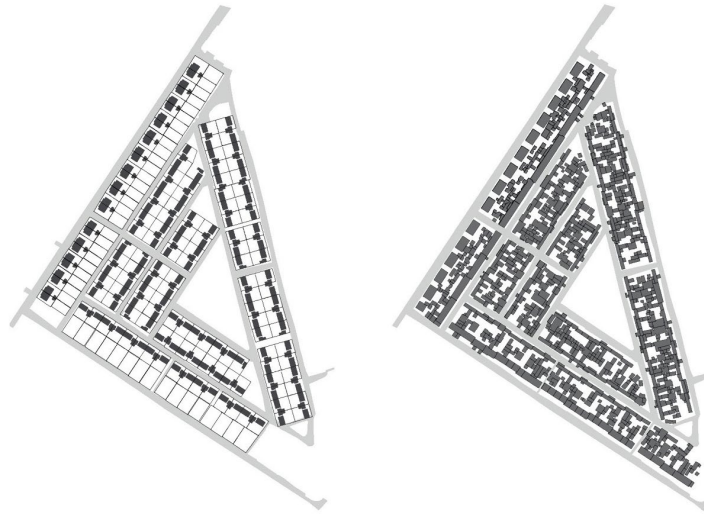
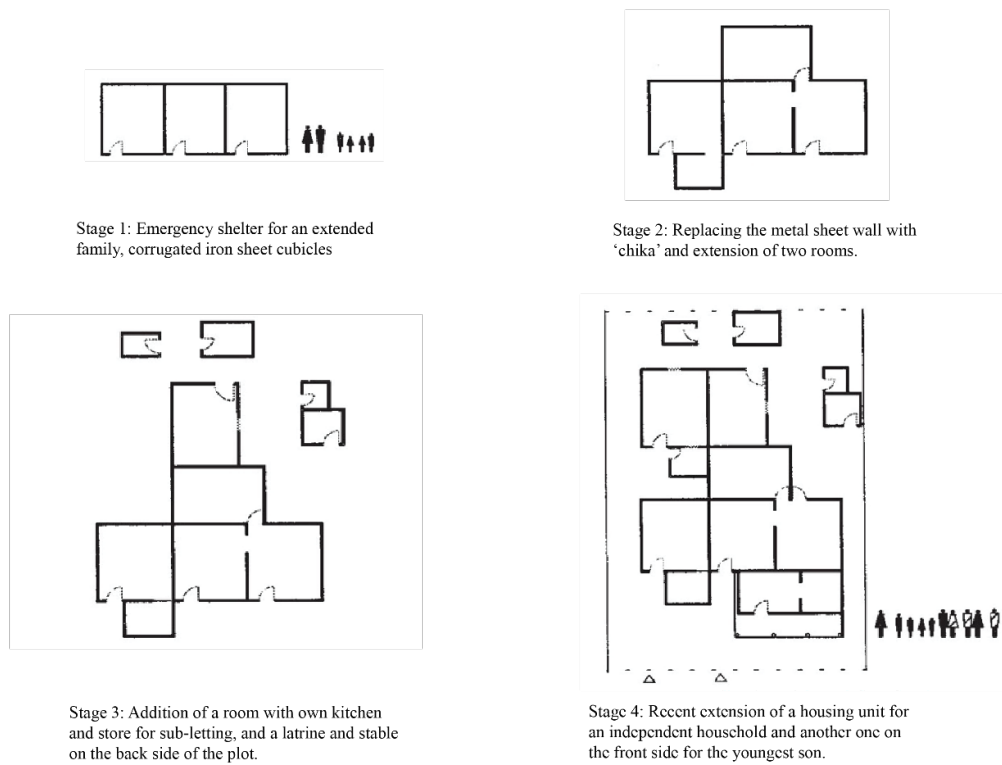


Figure 17: Plan of the "Kolfe" area. Initial morphology (1970), left, and the current situation (2015, right)

Drawings: Juanjo Tenorido de Peroy, Lara Spagnol, Siqi Fan, Yildiz Haseki



Right: Figure 18: Extension pattern in "Gerji" (1986): from a three-room provisional cubicle (46.6m²) to a compound with a total net area of 121m²

Source: Demissachew Shiferaw. ‘Self-Initiated Transformations of Public-Provided Dwellings in Addis

Chapter Four

4.0 Generative Design Methodology for Mass Customized Core Housing

4.1 Introduction

To achieve this study's objective and explore GD and MC's potential use to enhance CH, two research methods are used in combination. The first method employed a qualitative study of secondary data about CH using a framework analysis strategy. Then, the result of the qualitative study is used as groundwork to develop a GD methodology. Thus, the whole process mainly entails four stages. Furthermore, in the end, a conceptual architectural design project is developed to demonstrate the result.



Figure 19: The research process.

Defining Core Housing

Using the framework analysis method, secondary qualitative data is analyzed to identify critical parameters that define CH. The method involves; familiarizing with the subject, identifying a thematic framework, charting summary, mapping, and interpretation. The result of this framework analysis is then used as an input for the generative design simulation.

Setting fitness Objectives and Constraints

For a GD to navigate solution space and produce a desirable outcome, a design problem must be defined in terms of constraint and objective or goal. “GD is the process of defining high-level goals and constraints and using the power of computation to automatically explore a wide range of design space and identify the best design options.” (Vilaggi, 2020) While constraints define the design boundary and set specific requirements, objective/goals are fitness parameters that the genetic algorithm (GA) is required to maximize or minimize.

Parametric Model

In this study, a visual programming language (VPL) called ‘Grasshopper’ in Rhino 3D environment is used to build the parametric model. Out of the four identified CH stages, site selection, block arrangement, core structure development, and unit expansion, the last two stages are selected, and representative parametric models are developed.

Generate, Evaluate and Evolve

In this study, a MOO (Multi-Objective Optimization) evolutionary solver called ‘Wallacei 2.0’ is used to generate, evaluate, and evolve the design solutions. Wallacei is an open-source software plugin for ‘Grasshopper’ developed by Mohammed Makki, Mials, and Yutao Song (Mohammed Makki, 2019). It has two essential parts which are used in this research: Wallacei X and Wallacei Analytics. Wallacei X is a multi-objective (MOO) evolutionary solver that uses a specific class of genetic algorithm called NSGA 2. “Wallacei X uses NSG-II as the primary evolutionary algorithm and utilizes the K-means method as the clustering algorithm. Additionally, Wallacei X incorporates the JMetal, LiveCharts, and HelixToolkit libraries.” (Wallacei, 2020)

Wallacei Analytics is an analysis tool that illustrates the evolutionary algorithm's working process and facilitates the selection of solutions. The following five charts are used to analyze the GD process, tests the effectiveness, and select solutions.

1. **Diamond Chart:** This chart represents fitness values' performance on lines connecting from the center to the polygon's edge. Wallacei evolutionary solver works only by minimizing the fitness values; therefore, fitness values closer to the center are considered fitter.
2. **Standard Deviation Chart:** The standard deviation represents the distribution of a set of values from the mean value. The chart represents variation/convergence levels for each generation in the population and indicates whether the generations are getting fitter in the evolution process. The flat curve indicates increased variation, and a narrow curve indicates convergence. A shift in the curve to the left indicates better mean performance. (Wallacei, 2020)
3. **Fitness Value Chart:** “This chart indicates fitness values of each solution in the population for each fitness objective separately. Each generation is connected with a polyline, and the generations are colored from first (red) to last (blue).” (Wallacei, 2020)
4. **Standard Deviation Trend line Chart:** Presents the standard deviation value for each fitness objective independently, for each generation across the entire simulation from start to finish. The aim is to highlight specific trends in the variation and convergence of each generation across the population. (Wallacei, 2020) The lower the chart, the fitter the fitness objective.

5. Mean Fitness Trendline Chart: “Calculates the mean fitness value for each generation in the population and displays each value as a point from left (first generation) to the right (last generation).” (Wallacei, 2020)

Project Proposal and Recommendation

The output of this research is tested in a selected site in the inner city of Addis Ababa. The output entails a CH design strategy enhanced through GD and MC. In addition, the conceptual design project is developed to demonstrate the strategies and implementation mechanisms of the study’s result in the context of Addis Ababa.

4.2 Framework Analysis: Defining Core Housing

Several International literature and contextual reviews are studied, and three thematic frameworks are identified which define the key aspects of CH.

- Core housing as a process
- Stakeholders control distribution in the CH process
- Morphology of core housing

4.2.1 Core Housing as a Process

Based on the literature review and contextual study, the process of CH is simplified into four key stages: Site selection and planning, Block/Plot arrangement, the building of starter structure, and expansion of the living units. Except for the unit expansion, all have defined starting and completion times. Site planning and block arrangement are common in typical mass housing strategies, but the development of starter structure and unit expansion are the two unique characteristics of CH. Hence, this study focuses revisits the starter structure development and unit expansion stages of CH through GD and MC.

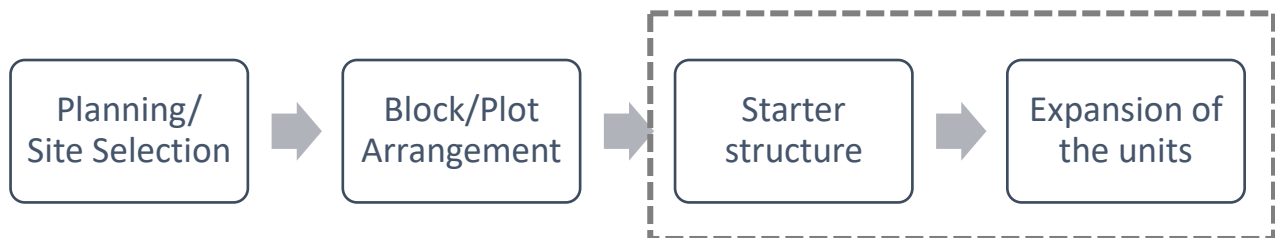


Figure 20: Stages in the process of incremental self-help Core-housing and focus of research under consideration.

4.2.2 Stakeholders Control Distribution

The level of involvement and control distribution of stakeholders in the process of CH is significantly different compared to other housing strategies. To replicate and simulate core housing in generative design,

Revisiting Core Housing through Generative Design and Mass Customization

it is vital to analyze and conceptualize the control distribution among different stakeholders. Based on secondary data and cases analyzed, multiple stakeholders and their typical role is charted.

Table 2: Relationship Matrix; Stakeholders and their involvement level in core housing

	Policy Making	Land Provision	Infra Provision	Financing	Regulation	Designing	Building	Material Provision	Organizing & Admin
Gov./City Admin	Dark Blue	Dark Blue	Blue	Blue	Blue	Blue	Light Blue	Light Blue	Blue
Banks				Blue					
NGO	Blue			Blue					
Design Professionals	Blue					Dark Blue			
Builders							Dark Blue	Blue	
Material Suppliers							Light Blue	Dark Blue	
Community Organization							Light Blue	Light Blue	Blue
Owners				Dark Blue		Dark Blue	Dark Blue	Light Blue	Blue

Involvement Level	Non	Mild	Fair	moderate	Strong
Color coding		Light Blue	Light Blue	Blue	Dark Blue

For this study, the stakeholders are simplified into three fundamental elementary groups. It is presumably assumed that the three stakeholders can representatively absorb the role of the remaining stakeholders. The minimization of the stakeholder number is adopted to economize the GD simulation. The importance of material suppliers is emphasized to link the relevance of MC in the process of CH. Studies indicate that (Dirk Donath, 2015) (Goethert, 2019) (Laura Sara Wainer, 2016) (Mota, 2019), material suppliers integral part of successful self-help incremental housing projects.

Table 3: A simplified form of control distribution in core housing

	Policy Making	Land Provision	Infra Provision	Financing	Regulation	Designing	Building	Material Provision	Organizing & Admin
Gov./City Admin	Dark Blue	Dark Blue	Blue	Blue	Blue	Blue	Light Blue	Light Blue	Blue
Owners				Dark Blue		Dark Blue	Dark Blue	Light Blue	Blue
Material Suppliers & Small Contractors							Light Blue	Dark Blue	

Revisiting Core Housing through Generative Design and Mass Customization

The role of the stakeholders and their level of involvement varies through each stage. Therefore, the following matrix is developed by overlapping the stakeholders' control distribution on different stages of the CH process.

Table 4: A simplified Stakeholders involvement and core housing stages Matrix.

	Planning & Site Selection	Block Arrangement	Starter Structure	Unit Expansion
Public				
Material Suppliers				
Owners				

The above matrix indicates that the three peculiar stakeholders' involvement is better captured in the last two stages of the CH process. Therefore, by charting and mapping, this study's focus area and scope are framed to specific stages of the process and a list of stakeholders. In light of this framework, the main objective of this study is to explore the potential use of GD and MC to enhance the control distribution of stakeholders - government, owners, and material suppliers - at starter structure development and unit expansion stages of CH.

4.2.3 Typologies of Core Housing

Studies indicate that proactively designed CH dictates the nature of the starter structure and the process of incremental expansion. For this study, based on the type of starter structure and the consecutive expansion process, nine types of CH morphologies are identified. Furthermore, each type of morphology is then evaluated based on four criteria to determine the level of appropriateness in the context of Addis Ababa. These criteria are used by SIGUS and MIT work (SIGUS Group and TUD, 2016) to evaluate and assess different self-help incremental housing typologies. The criteria are:

1. Initial affordability for the user to move-in and start living.
2. Significance for the provider in terms of reducing housing cost provision.
3. Impact on the city development by creating density, meet the zoning and building code requirements.
4. Flexibility of the structure for future expansion.

Below are nine types of CH typologies identified and together with examples and reference cases.

CH Typology 1


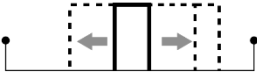
Description	Starter/Core Structure	Expansion	Reference Cases							
Single Storey Horizontal Expansion Single Family			Nefas Silk Urban Development Plan-Progressive Development of Dwelling (1982) (Source: World Bank-Staff Appraisal Report Ethiopia Urban Development Project.) See Contextual Review section of this study.							
<table border="1"> <thead> <tr> <th colspan="2">Evaluation Criterea</th> </tr> </thead> <tbody> <tr> <td>1. Affordiability</td> <td>○●○○○</td> </tr> <tr> <td>2. Significance for Gov.</td> <td>○●○○○</td> </tr> <tr> <td>3. Density</td> <td>●○○○○</td> </tr> <tr> <td>4. Flexibility</td> <td>○○○○●</td> </tr> </tbody> </table>				Evaluation Criterea		1. Affordiability	○●○○○	2. Significance for Gov.	○●○○○	3. Density
Evaluation Criterea										
1. Affordiability	○●○○○									
2. Significance for Gov.	○●○○○									
3. Density	●○○○○									
4. Flexibility	○○○○●									

Figure 21: CH Morphology Type 1

In this type of CH, government builds the starter structure on a given plot of land, and the owner expands it horizontally. It is the most common type of CH strategy, and it was also implemented in Addis Ababa during the ‘derge’ regime with the help of the World Bank. This type of core housing allows maximum flexibility for the owner, but it is land-intensive and does not promote density. Therefore, in the current Addis Ababa land value situation, particularly in the inner city part, it is the least feasible option.

CH Typology 2

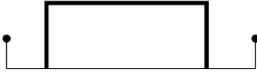
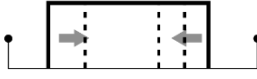

Description	Starter/Core Structure	Expansion	Reference Cases							
Single Storey Horizontal Expansion Single Family			Incremental Housing case driven by the World Bank in 1970'. ((Source: Fiji Incremental Housing Wrokshop. SIGUS P.76)) 							
<table border="1"> <thead> <tr> <th colspan="2">Evaluation Critereas</th> </tr> </thead> <tbody> <tr> <td>1. Affordiability</td> <td>○●○○○</td> </tr> <tr> <td>2. Significance for Gov.</td> <td>○●○○○</td> </tr> <tr> <td>3. Density</td> <td>●○○○○</td> </tr> <tr> <td>4. Flexibility</td> <td>○○○○●</td> </tr> </tbody> </table>				Evaluation Critereas		1. Affordiability	○●○○○	2. Significance for Gov.	○●○○○	3. Density
Evaluation Critereas										
1. Affordiability	○●○○○									
2. Significance for Gov.	○●○○○									
3. Density	●○○○○									
4. Flexibility	○○○○●									

Figure 22: CH Morphology Type 2

In this type of CH, a large roof structure is provided as a starter with some initial service units under it. Moreover, the owner takes over and incrementally subdivides the space to attain the required living spaces. In some cases, it is the owner's responsibility to build the external envelope of the housing unit. Similar to Type 1, this strategy is land-intensive and does not allow for density.

CH Typology 3

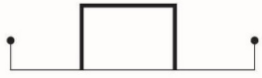
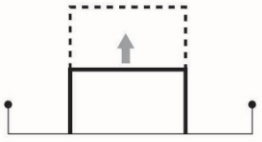

Description	Starter/Core Structure	Expansion	Reference Cases										
Multiple Storey Vertical Expansion Single Family			(Source: The Case for Incremental Housing) 										
<table border="1"> <thead> <tr> <th colspan="2">Evaluation Criterias</th> </tr> </thead> <tbody> <tr> <td>1. Affordability</td> <td>○●○○○</td> </tr> <tr> <td>2. Significance for Gov.</td> <td>○●○○○</td> </tr> <tr> <td>3. Density</td> <td>○●○○○</td> </tr> <tr> <td>4. Flexibility</td> <td>○○○●○</td> </tr> </tbody> </table>				Evaluation Criterias		1. Affordability	○●○○○	2. Significance for Gov.	○●○○○	3. Density	○●○○○	4. Flexibility	○○○●○
Evaluation Criterias													
1. Affordability	○●○○○												
2. Significance for Gov.	○●○○○												
3. Density	○●○○○												
4. Flexibility	○○○●○												

Figure 23: CH Morphology Type 3

In this typology, a ground floor structure with the capacity of adding upper floors in the future is provided initially. This strategy allows owners to add more spaces, but it tends to stay as a single-family housing unit unless rental units are provided. As a result, the possibility of achieving density is minimal.

CH Typology 4

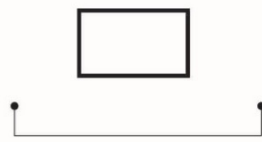
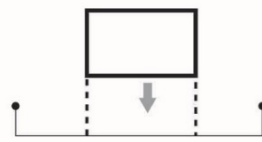

Description	Starter/Core Structure	Expansion	Reference Cases										
Double Storey Vertical downward Expansion Single Family/Multiple Family			New Dwelling for Mr. + Mrs, Namakadre, Fiji (Source: Fiji Incremental Housing Wrokshop, SIGUS P.76) 										
<table border="1"> <thead> <tr> <th colspan="2">Evaluation Criterias</th> </tr> </thead> <tbody> <tr> <td>1. Affordability</td> <td>○●○○○</td> </tr> <tr> <td>2. Significance for Gov.</td> <td>○●○○○</td> </tr> <tr> <td>3. Density</td> <td>○●○○○</td> </tr> <tr> <td>4. Flexibility</td> <td>○○○●○</td> </tr> </tbody> </table>				Evaluation Criterias		1. Affordability	○●○○○	2. Significance for Gov.	○●○○○	3. Density	○●○○○	4. Flexibility	○○○●○
Evaluation Criterias													
1. Affordability	○●○○○												
2. Significance for Gov.	○●○○○												
3. Density	○●○○○												
4. Flexibility	○○○●○												

Figure 24: CH Morphology Type 4

This CH typology provides a starter structure suspended above the ground and allows the owner to expand downward. In this scenario, the height is fixed, but the owner can reclaim the ground space to expand. This typology provides flexible space on the ground allowing owners to engage in flexible home-based enterprises (HBE).

CH Typology 5

Description	Starter/Core Structure	Expansion	Reference Cases
Double Storey Horizontal Expansion Single Family/Multi in row house			Incremental House designed by Elemental in Quinta Monroy, Chile. Source: Fiji Incremental Housing Wrokshop. SIGUS P.58)
Evaluation Critereas			
1. Affordiability	○ ○ ● ○ ○		
2. Significance for Gov.	○ ○ ● ○ ○		
3. Density	○ ○ ● ○ ○		
4. Flexibility	○ ○ ● ○ ○		

Figure 25: CH Morphology Type 5

In this case, a multiple floor starter structure with stairs is provided, leaving the adjacent space open for the owner to expand horizontally, but vertical expansion remains limited. The positive aspect of this typology is that the initial starter structures frame the expansion, and a controlled urban façade can be created.

CH Typology 6

Description	Starter/Core Structure	Expansion	Reference Cases
Multi Storey Horizontal Expansion Multi Family			Multi-Story Public Housing in Egypt. (Source: Multi Story Incremental Housing at the World Urban Forum, Naples, 2012. P.8)
Evaluation Critereas			
1. Affordiability	○ ○ ● ○ ○		
2. Significance for Gov.	○ ○ ● ○ ○		
3. Density	○ ○ ○ ● ○		
4. Flexibility	○ ● ○ ○ ○		

Figure 26: CH Morphology Type 6

This morphology type is a multi-story and multifamily housing in which the owners collectively and synchronously expand the original structure across all floors. This morphology type creates density, but there will be safety and structural integrity issues of the additional structural elements and require all owners' coordination during the expansion process.

CH Typology 7

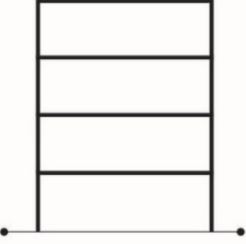
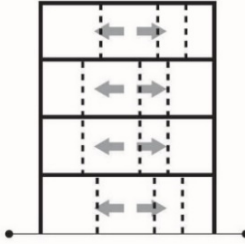
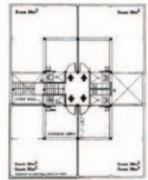
Description	Starter/Core Structure	Expansion	Reference Cases					
Multi Storey Horizontal Expansion Multi Family Evaluation			Port Said New Community Projects Proposal. (Source: Multi Story Incremental Housing at the World Urban Forum, Naples, 2012. P.30) 					
<table border="1"> <tr> <td>1. Affordability</td> <td>○ ○ ● ○ ○</td> </tr> <tr> <td>2. Significance for Gov.</td> <td>○ ○ ● ○ ○</td> </tr> <tr> <td>3. Density</td> <td>○ ○ ○ ● ○</td> </tr> <tr> <td>4. Flexibility</td> <td>○ ● ○ ○ ○</td> </tr> </table>				1. Affordability	○ ○ ● ○ ○	2. Significance for Gov.	○ ○ ● ○ ○	3. Density
1. Affordability	○ ○ ● ○ ○							
2. Significance for Gov.	○ ○ ● ○ ○							
3. Density	○ ○ ○ ● ○							
4. Flexibility	○ ● ○ ○ ○							

Figure 27: CH Morphology Type 7

This morphology type is a multi-story multifamily core housing strategy where owners can expand horizontally across the given floor. It allows for density creation, but managing the unused space, can be challenging.

CH Typology 8

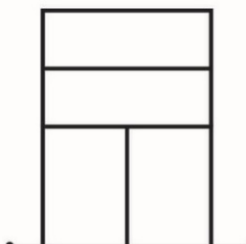
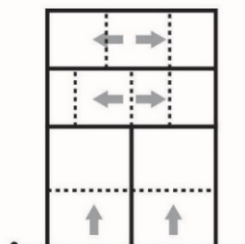
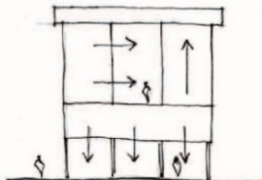
Description	Starter/Core Structure	Expansion	Reference Cases					
Multi Storey Horizontal & Vertical Expansion Multi Family Affordability			Different expansion approaches combined. (Source: Evolvable Multi-Storey Housing. P.11) 					
<table border="1"> <tr> <td>1. Affordability</td> <td>○ ○ ● ○ ○</td> </tr> <tr> <td>2. Significance for Gov.</td> <td>○ ○ ● ○ ○</td> </tr> <tr> <td>3. Density</td> <td>○ ○ ○ ● ○</td> </tr> <tr> <td>4. Flexibility</td> <td>○ ● ○ ○ ○</td> </tr> </table>				1. Affordability	○ ○ ● ○ ○	2. Significance for Gov.	○ ○ ● ○ ○	3. Density
1. Affordability	○ ○ ● ○ ○							
2. Significance for Gov.	○ ○ ● ○ ○							
3. Density	○ ○ ○ ● ○							
4. Flexibility	○ ● ○ ○ ○							

Figure 28: CH Morphology Type 8

This approach combines vertical and horizontal expansion within a multistory and multifamily structure. Density with variety can be achieved with this approach but coordinate the combined incremental expansion of different owners can be challenging.

CH Typology 9

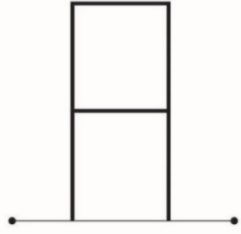
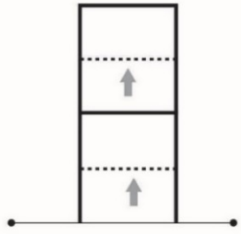
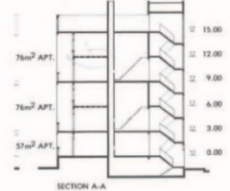
Description	Starter/Core Structure	Expansion	Reference Cases
Multi Storey Vertical Expansion Multi Family			Mkales Project, Beirut, Lebanon (Source: Multi Story Incremental Housing at the World Urban Forum, Naples, 2012. P.30)
Evaluation			
1. Affordability	○ ○ ● ○ ○		
2. Significance for Gov.	○ ○ ○ ● ○		
3. Density	○ ○ ○ ○ ●		
4. Flexibility	○ ○ ● ○ ○		

Figure 29: CH Morphology Type 9

This typology constitutes a multistory and multifamily housing structure in which floor to floor height is big enough to accommodate additional floor insertion. Thus, the total housing unit area can be double within a defined unit boundary by inserting an additional floor. In this study, this typology is selected for the development of GD simulation for the following reasons:

- The expansion is made vertically within the unit, and the cumulative result incrementally creates density without changing the original structural framework.
- Compared to other multi-story and multifamily core housing approaches, this gives better flexibility for expansion. The double floor height is manageable for owners to successfully occupy the lower and upper floors by inserting the floor whenever required. The main structural grid should be constructed by the government considering the additional future floors that need to be constructed out of lightweight materials.
- Architecturally, the double-story core structure has the potential to become an organizing datum to frame and guide the incremental expansion of respective starter units. Thus, it is a critical factor for the creation of a proper and acceptable urban façade.
- This option saves government expenditure by minimizing cost because it reduces the number of floor slabs required to be built to achieve a specific density. For instance, a G+6 density can be achieved by only building three-floor slabs and allowing the owners to insert floors in-between.
- Moreover, this typology is convenient to convert the upper floor for rental, which will add income for the owners and absorb housing demands like the traditional ‘Kitiya’ houses.

Based on the above-selected CH typology analysis, two experiments are conducted to explore the potential use of GD and MC at the development of starter/core structure and unit expansion stages of CH.

4.3 Experiment 1: The use of Generative design to develop Mass Customized Core/Starter Structure

The starter/core structure is usually built by the government, city administration, or donors so that the residents can start to occupy it and incrementally expand it. For this study, as described in the previous section, multistory and multifamily CH typology is selected, where owners insert floor within the double floor height to conduct the GD experiment. The amount of amenity and level of completeness of the starter structure provided by the government can vary depending on the budget. For this study, the core structure is assumed to have floor slabs every other story, structural columns, vertical circulation, building service, and the partition wall between units. The structure is assumed to be constructed out of mass-produced precast concrete structural elements configured in a different arrangement to fit the site context and fitness objectives. The experiment starts with defining constraints and objectives, taking into consideration the three stakeholders defined above.

4.3.1 Defining Constraints and Objectives for Development of Core Structure

The following list of constraints and objectives are identified for this study.

Constraints

- Site boundary: the simulation for this site is developed to work on sites with orthogonal edges.
- Building Setback and allowable building height are dependent on the adjacent road width.
- Construction technology: A Modular construction system with reconfigurable structural elements is selected.
- Allowable structural grid: only a 6m by 6m structural grid is considered for this study.
- Floor to floor height: 5.4 m height which allows the owners to insert floor at 2.7m.
- Building service distribution: plumbing and drainages are located at every six-meter adjacent to the corridor of the floors. Details of the Mechanical, Electrical, and Plumbing service are not taken into consideration for this study.
- Vertical circulation type for core structure: U-shaped stair with total width of 3m and 6m length including the landings. Elevators are not included considering that it will be walkable housing.
- Residents income category: this experiment is conducted considering the conceptual level of design; therefore, the residents' income is not considered.
- The cost of construction: the real-time cost of the structure is not calculated for this experiment, but the cost efficiency in relation to the building shape is considered below.

- Starter Unit typology mix ratio: different types of unit typologies are produced based on the possible combination of the structural grid, but specific input is not assigned in the model.

Objectives/Goals

1. **Maximize density:** A given site density is governed by total gross floor area(GFA) divided by total site area (TSA).

Indicator: The commonly used indicator for density is Floor Area Ratio (FAR)

$$FAR = \frac{GFA}{TSA}$$

Goal: Government prefers to maximize the number of residents that settle in a specific area to justify the land, infrastructure, and starter structure cost.

2. **Minimize Cost:** This is the summation of all elemental costs, which requires detailed enumeration of the bill of quantity(BOQ) estimation at the detail design level. For this study, cost efficiency at the conceptual level is calculated based on the building shape. Different types of indexes determine the relationship between building shape and cost (Stainislaw Belniak, 2013).

- W/F index – the wall/floor index.
- LBI index – the length/breadth index.
- PSI index - the plan/shape index.
- Cook’s JC (Shape-effectiveness) index.
- POP (Plan compactness ratio) index.
- Building planning “m” index.
- VOLM (volume/block compactness) index
- Optimum envelope area.

Indicator: Compared to others, the W/F index is found to be the most sensitive index for building shape (Stainislaw Belniak, 2013). Since the floor to floor height is fixed for this experiment, the shape sensitive index is preferred against volume sensitive indexes. The W/F index specifies the ratio between the wall surface area and floor surface area in which a smaller index’s value indicates cost-efficient building shape. The following formula expresses the W/F index:

$$\frac{W}{F} = \frac{L - L_s}{L_s} * 100\%$$

L: Building perimeter calculated from the contour of the outer walls, L_s: Perimeter of the square of the same surface as the building being compared (Stainislaw Belniak, 2013). Square is the most cost-efficient shape.

Goal: Creating a cost-effective starter/core structure is the preferred goal of government. It also affects the affordability of the housing provision hence affects owners indirectly.

- 3. Maximize the efficiency of vertical circulation location:** vertical circulation elements, stairs, are a significant part of the starter structure. The number of vertical circulation elements is related to the occupancy type and total floor area. Their location and distribution are determined by fire code and distribution efficiency. For this study, a predetermined number of stairs are selected, and their positioning is optimized. This is a hypothetical assumption used to test the GD system.

Indicator: The length of the line connecting one stair from the other and the area inscribed is assumed to be an indicator for the efficient distribution of vertical circulation. For a given number of stairs and GFA, a large area inscribed by the line connecting each stair indicates a fair distribution of stair locations.

Goal: Locating the vertical circulations to optimize their distribution.

- 4. Maximize courtyard space:** For block size greater than the allowable space depth (12m from exterior surface assumed) from both sides, a courtyard will be generated. This courtyard space is considered a favorable condition considering that it will create social space and aid natural light and air circulation.

Indicator: Total area in m² of the generated courtyard space.

Goal: maximize courtyard space to allow natural light and ventilation into the starter units that face the courtyard space and maximize green space for communal use.

- 5. Minimize solar radiation received by the structure at certain hours of a day:** Studies indicate that the shape and orientation influence the amount of solar radiation a building receives at a specific duration. A plugin called Ladybug is used to calculate the total amount of radiation that a building surface receives during daytime from 12:00 pm up to 5:00 pm.

Indicator: Kilo-wat per hour (Kw/hr.) received by the external surface of the structure external envelop.

Goal: Create self-shading to minimize the amount of solar radiation that falls on the total massing by diversifying the structure height.

- 6. Flexibility for unit expansion:** Flexibility of the starter structure is very important for the residents during the expansion of the unit.

Indicator: The simple indicator for space flexibility is avoiding columns that will be created inside the starter unit space.

Goal: maximize the spatial flexibility by creating column-free space, which will be helpful for the owners during space configuration.

7. Mass customization of construction elements: This is the ability to create as minimum variants of structural elements as possible and at the same time be able to produce as many variety design options as possible using those elements.

Indicator: Total number of variants of construction components or prefabricated modular elements and potential for configuration.

Goal: minimized elements of construction components to increase the efficiency of the mass production process for material and construction providers. It determines how fast the housing can be delivered. In addition, material and construction suppliers benefit from the increased customizability of the modular elements, reducing the number of elements that need to be produced.

The table below distributes constraints and objectives in relation to the three stakeholders. In addition, it indicates how the goals of each stakeholder can be addressed at the starter/core structure stage of core housing.

Table 5: List of constraints and objectives in relation to the stakeholder at Core Structure Stage.

	Gov't/City Admin.	Owners	Material Suppliers
Objective /Goal	<ul style="list-style-type: none"> • Maximize density • Minimize cost • Efficient vertical circulation distribution 	<ul style="list-style-type: none"> • Increased flexibility for unit expansion • Minimize solar radiation at certain hours of the day. • Maximize the courtyard space. 	<ul style="list-style-type: none"> • Efficient mass production of modular components • Increased customizability of modular components

4.3.2 Parametric Model for Mass Customized Core Structure

Based on the defined constraints, a parametric model is developed to generate a hypothetical core structure. For this experiment, the parametric model is developed to function on a rectangular site with an average size of an urban block. The following steps are undertaken to develop the parametric model.

Input: Site Boundary polyline.

Step 1: Construct the setback. Based on the regulatory requirement, the site boundary is offset inward from each direction.

Revisiting Core Housing through Generative Design and Mass Customization

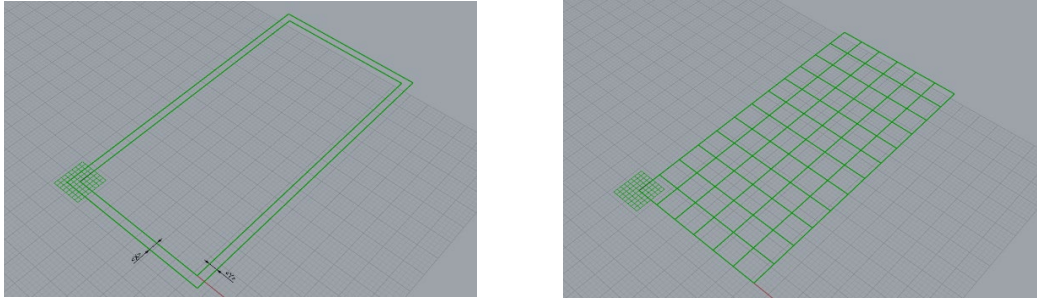


Figure 30: Left: Step 1 and Right: Step 2

Step 2: Divide the site into modular rectangular sizes. A 6m-by-6m square size is used to divide the site in x and y-direction.

Step 3: Assign a height value that is controlled by a discrete value parameter. Based on the selected double floor morphology, the height value is a multiple of 5.4m. The height of each module multiplied by 0, 1, 2, and 3 values giving the result of 0m, 5.4m, 10.8m, and 16.2m heights. For this parametric model, a maximum height of 16.2m is considered to avoid lift requirements.

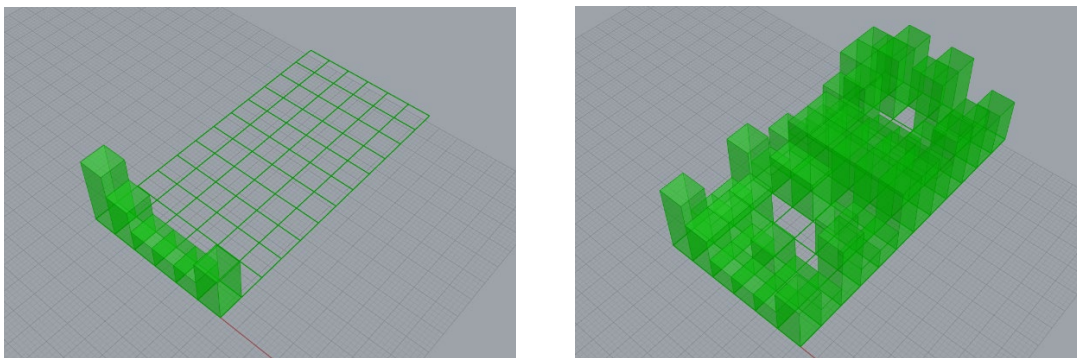


Figure 31: Step 3: assign the height value and create the volume of the core structure.

Step 4: Generate a courtyard. Modules located two blocks away from the exterior boundary are considered to be part of the courtyard.

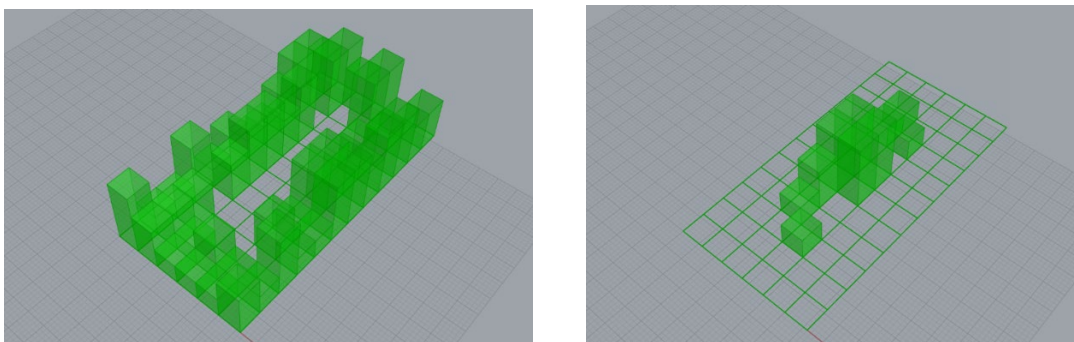


Figure 32: Step 4: Generate the courtyard

Revisiting Core Housing through Generative Design and Mass Customization

Step 5: Generate floor plate: Contour the overall volume by 5.4m interval starting from 1.5m height. It gives the floor plate layout at each level and indicates GFA(Gross Floor Area) result.

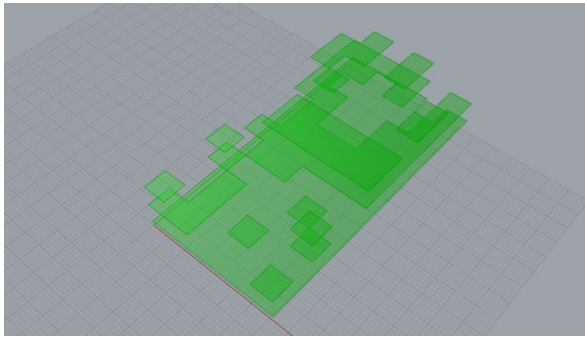


Figure 33: Step 5: Generate the Floor Plate

Step 6: Locate the horizontal circulation (corridor) at each level. It is an offset from the exterior surface of the volume considering the maximum allowable depth of the living unit, which is 10m.

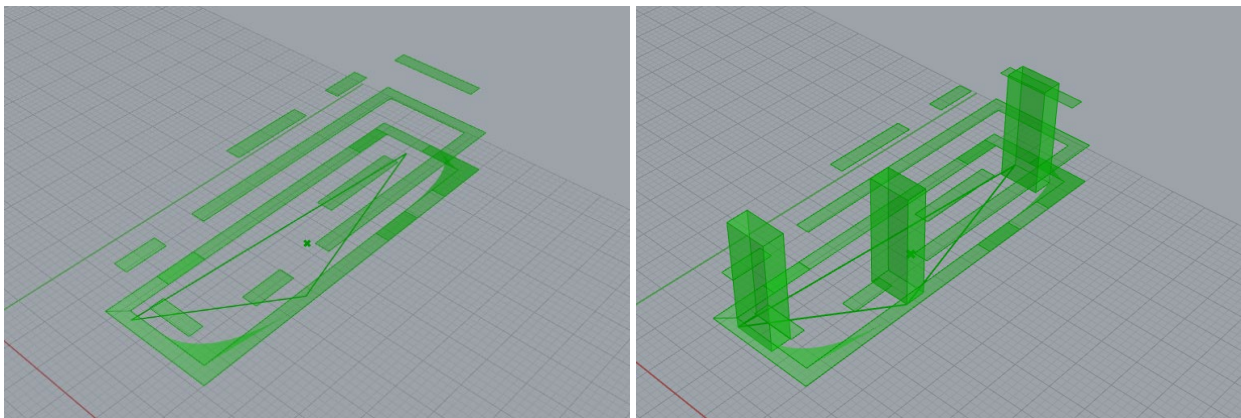


Figure 34: Left; Step 6: Generating circulation spaces.

Step 7: Locate the vertical core (stair). Divide the horizontal circulation spine(corridor) into a certain number of points that indicate the stair location. It is controlled by continuous positive rational number value, and it distributes a certain number of stairs along the corridor length.

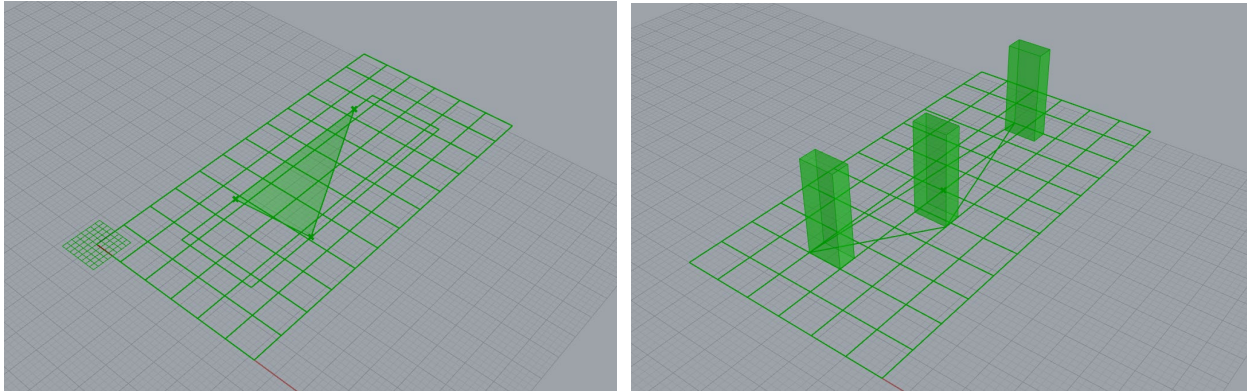


Figure 35: Generating Vertical Core Location

Step 8: Calculate the Radiation amount that falls on the surface(top and side) of the mass. Grasshopper plugin called ‘Ladybug’ is used to calculate the amount of radiation in kWh/m² that falls on the surface of the volume at a specific month, day, and hour range. 1mx1m grid cell is used to illustrate the radiation analysis.

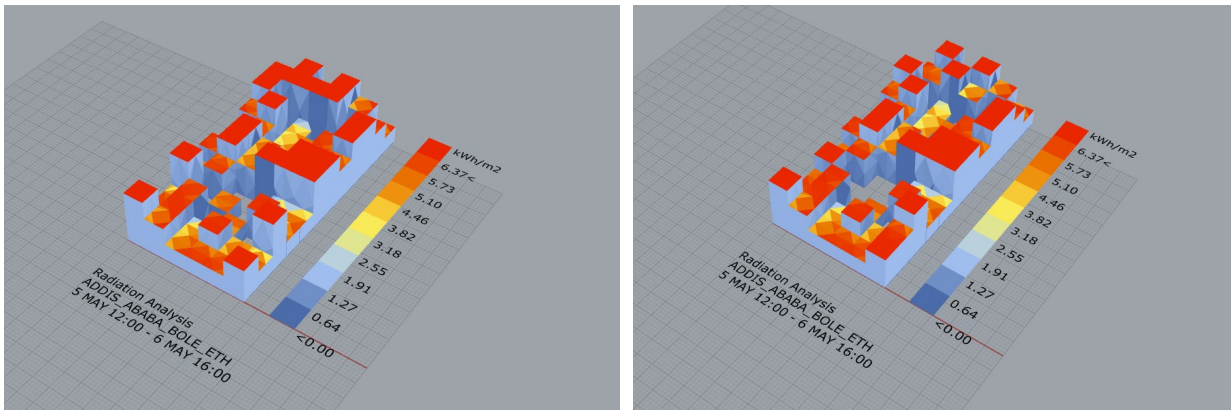


Figure 36: Right total radiation 3243.96 and left 3171.4 kWh/m². The reduction is achieved by manipulating the height of the blocks.

Step 9: Divide the floor plate generated at step 5 by a line, which delineates the corridor and unit spaces.

Step 10: Generate conceptual structural grid and beam layout and extrude according to the height of each module. The structure element sizes are not supported with structural analysis, but they are based on the acceptable level of span.

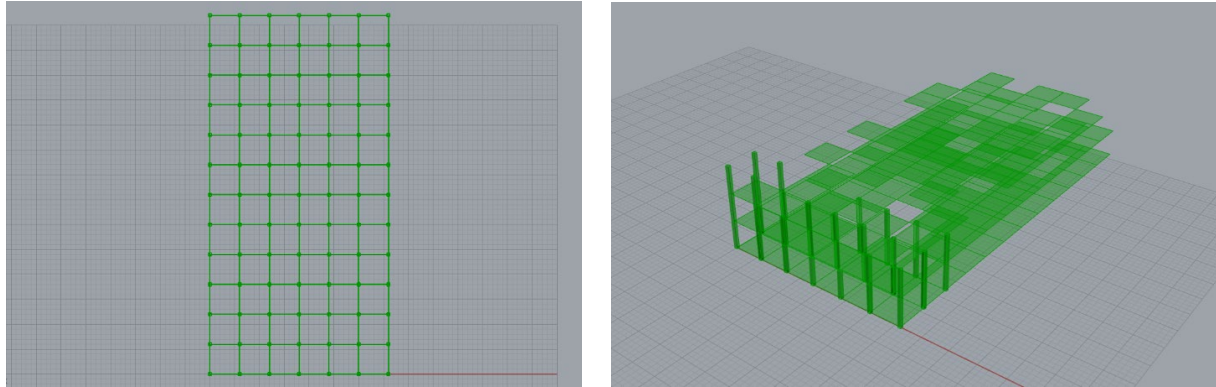


Figure 37: Generating Structural columns and beams

Once the parametric model is developed, and the fitness objectives are identified, an evolutionary algorithm is applied to optimize the multi-objective fitness criteria listed above.

4.3.3 Generate, Evaluate and Evolve

Before using an evolutionary algorithm to evaluate and optimize fitness objectives, the design space is calculated using mathematical verification. This attempt helps to understand the size of solution space and determine if using the evolutionary algorithm is worthy.

Mathematical Verification of the Solution Space

The total number of design spaces generated by the extrusion of the modular grid into four different heights can be calculated using a combination formula. The number of combinations of ‘n’ objects taken ‘r’ is determined by the following formula: combinations are used to calculate the total outcomes of an event where the order of the outcomes does not matter.

$$C(n, r) = \frac{n!}{(n - r)! r!}$$

For example, 72m by 36m site divided by a 6m*6m modular grid will have a total number of 72 modular components. Each module has 4 different states, the total number of possible combinations will be:

$$C(72, 4) = \frac{72!}{(72 - 4)! 4!}$$

It yields a total number of 1,028,790 combination options disregarding the order and feasibility of the outcome. If it is divided by 3m*3m modules, the same site will have 288 modular components. Each module has four different states; the total number of possible combinations will be 280,720,440.

The same arithmetic check can be done for all possible locations of three vertical circulation, stairs, and locations assuming the stairs are only allowed to move on a specific polyline, an offset from the exterior

surface by two modules (12m). For example, twelve by six grid will have a total number of two by eight modular grid where the stair can be located. Assuming the location of stair will snap every 3m, the total combination of the stair locations can be calculated accordingly:

$$C(20, 3) = \frac{20!}{(20 - 3)! 3!}$$

Three stairs along a 60m spine, with 3m snapping, intervals will have a total of 1,140 combinations of location. If the snapping length is reduced to 1m, the total possible combination of locations will be equivalent to 34,220.

The solution space for the courtyard space can be calculated using the same combination formula. A courtyard region with 2 by 8 modules, 16 modules taking 2 states (0 or 1, 2, 3), will yield a total possible combination of 120.

It should be noted that these calculations only determine the possible combination of the modular components. The size of solution space expands further as the number of fitness objectives are increased, which is the case in this experiment. The exact size of the solution space can be determined by using the evolutionary solver.

Generate, Evaluate and Evolve using GA

Out of the eight listed objectives, five are selected to be optimized by the evolutionary algorithm. The remaining two objectives (flexibility of space, maximizing mass producibility, and customizability) are integrated into the parametric model; therefore, they are considered an integral part of the model. A MOO (multi-objective optimization) tool, Wallacei, is used to optimize the five objectives using the continuous and discrete control input parameters. In this case, the gene parameters are only two: sliders that change the height value of the modular components and sliders that control the location of the stairs. The GA randomly manipulates the two input genomes to navigate the design space and optimize the five objectives. The MOO attempts to optimize objectives in two directions: Maximize or Minimize.

Table 6: List of fitness objectives to Maximize and Minimize

Maximize	Minimize
1. Density: GFA/TSA	2. Cost (minimize W/F ratio)
3. Distance between Stair locations	4. Solar Radiation
5. Courtyard Space	

The two gene parameters give a total of 75 genes (72 for height, 3 for location of the stairs), giving a total slider value of 591. They were computed for five fitness objectives gives a total search space size equivalent to $2.3E49$ (2.3×10^{49}). This is a massive size of search space, and to minimize the simulation time, the population size is reduced in the first to a total generation count of 100 with 50 generation size. It gives a total population size of 5000. With core i-7, 7generation, and 2.80 GHz computer, the simulation took 4hrs 18 minutes, and 53 seconds and 50 Pareto front solutions are generated.

4.4 Experiment 2: The use of Generative Design in Unit Expansion

Once the core structure is set, the residents' take over the living unit's incremental expansion according to their space demand and financial capacity. This process entails two primary activities: space expansion and construction material update. The housing unit space expansion usually happens by adding or expanding rooms or reconfiguring the space arrangement. In addition, through time, construction materials are changed to maintain or upgrade the standard of the housing unit.

Even though the owner predominantly controls this stage, the government/city administration must determine the location of basic services. The government will act as a regulatory body making sure the incremental expansion and additions are conducted within the acceptable level of safety and quality standard.

4.4.1 Defining Constraints and Objectives for Unit Expansion

Constraints of this stage are essentially related to spatial design problems and construction systems. The design and construction are intertwined because this process is fundamentally self-help incremental housing.

Constraints:

Constraints in spatial design problems can be divided into two; topological and geometrical. Topological constraints describe the relationship and adjacency between rooms. For example, a kitchen must be connected to the dining room, and the kitchen is preferred to be far from bedrooms. Geometric constraint describes the area, proportion, and orientation of the rooms. Based on this, the following topological and geometric constraints are developed for unit expansion of core housing.

Topological Constraints:

- Entrance to the building should be from the corridor.
- The location of the internal stair should be determined based on the owner's preference to rent the upper floor of their unit.

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- If the upper room is going to be rented, then the stair should be located near the corridor for direct and separate tenants' access.
- If there will be no rent, then the stair can be placed in any part of the room.
- The kitchen and bathroom should be adjacent to the corridor for easy access to utility,
- The living room and main bedroom should be adjacent to the outside, at least on one edge.
- The hallway should be adjacent to all rooms.

Geometric Constraint

The geometric constraint is described below with a minimum and maximum size of the rooms in the X and Y direction. The room areas and sizes are selected for the case of the experiment.

Table 7: Geometric Constraints for Unit Expansion

Tag	Room Name	Min-Max (X)	Min-Max (Y)	Rotation	Required Area (m ²)
HW	Hallway	[1m-1m]	[1m-10m]	0 (no rotation)	Not fixed
ST	Stair	[1m-1m]	[4m-4m]	0°, 90°, 180°, 270°	4
BT	Bathroom	[1m-2m]	[1m-4m]	0° or 90°	2
KT	Kitchen	[1m-2m]	[2m-4m]	0° or 90°	6
LV	Living Room	[3m-4m]	[2m-6m]	0° or 90°	12
MB	Master Bed Room	[2m-3m]	[2m-4m]	0° or 90°	9
B.1	Bed Room 1	[2m-3m]	[2m-4m]	0° or 90°	6
BL	Balcony/Expansion	[0m-6m]	[0m-6m]	0 (no rotation)	16-20 (not fixed)
			Total		59
			Total Space Available on first level.		60

Objectives/Goals

- The residents' goal, once their unit boundary is decided, can be categorized into two phases. The first phase is to minimize the initial cost and create livable space. Therefore, in this scenario, the cost can be considered an input parameter, and the number of rooms, material types, and space arrangement will be optimized to fit into the budget. The second phase is gradual expansion by adding room numbers, expanding room areas, rearranging rooms, and upgrading material types.
- For material suppliers, the modularization of the design elements is essential because it enhances mass production. A generative design can help residents to create a preferred design layout based on the mass-produced modular elements.

Table 8: Table 9: List of constraints and objectives concerning the stakeholder for Starter Unit Expansion.

	Gov't/City Admin.	Owners	Material Suppliers
Objective/Goal	<ul style="list-style-type: none"> - Safety and Regulatory requirements. - Cost recovery 	<ul style="list-style-type: none"> - Maximize room area. - Maximize Bedroom Number. - Upgrade Material - Increase Rent Revenue - Minimize cost 	<ul style="list-style-type: none"> - Minimize Custom elements - Maximize Profit
Constraints	<ul style="list-style-type: none"> - Site Size. - Structural grid. - Budget for starter provision. 	<ul style="list-style-type: none"> - Income - Number of family(Space need) 	

4.4.2 Parametric Model for Unit Expansion

For this experiment, three typical starter unit typologies from the result of the first experiment are selected to develop the parametric model (See Chapter Five, the result of experiment one). The units are selected to represent different units' sizes and showcase the potential use of GD and the possible solution space that can be generated.

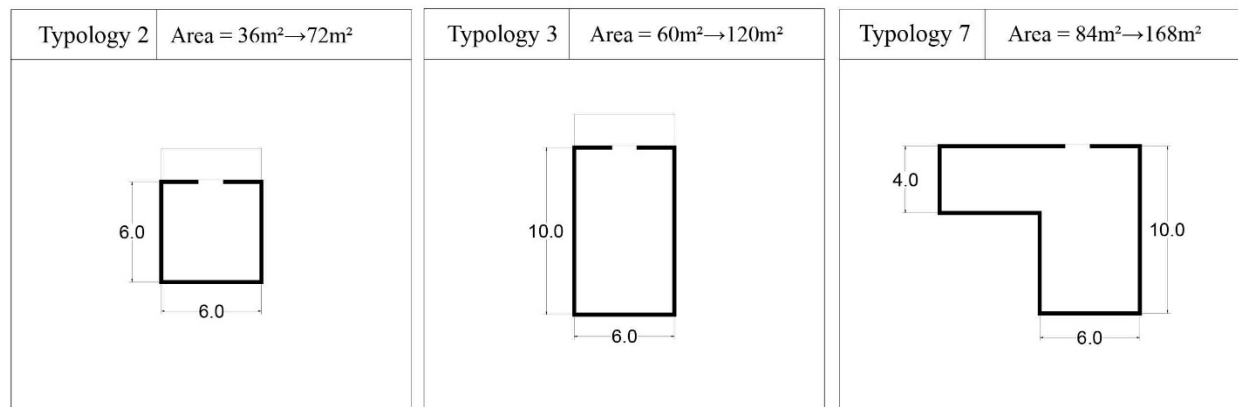


Figure 38: Selected Units for space layout generation

To illustrate the parametric process, typology 3 will be used, but the experiments are done for the three units, and the analysis and result are discussed in the next chapter.

Geometric Constraints

Step 1: Define a fixed boundary of the unit at the first and second levels. For the first level, the boundary will be the edge of the unit layout, but it will be the extent of the built area of the first level ceiling for the second level.

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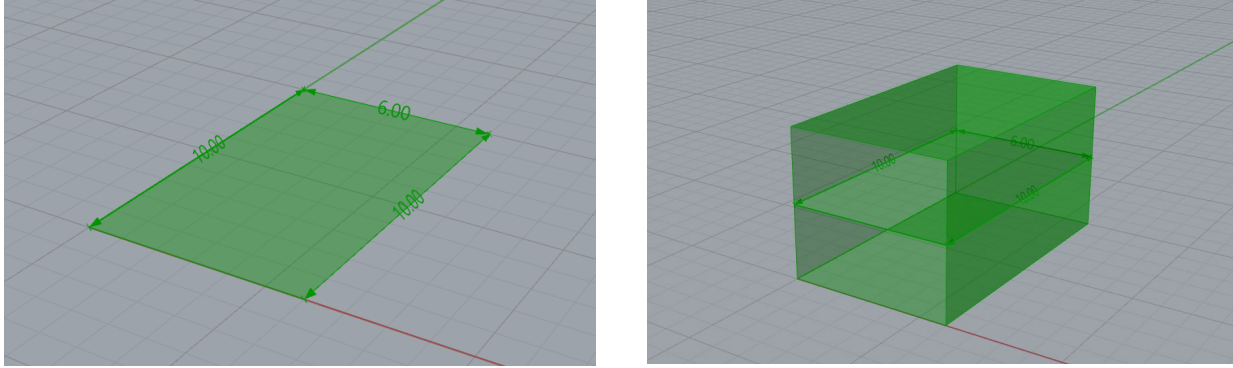


Figure 39: Defining a fixed boundary of the unit (1st and 2nd level)

Step 2: Divide the region into Wet Area (kitchen and Bathroom) and living areas (where living, dining, bedrooms, and balcony)

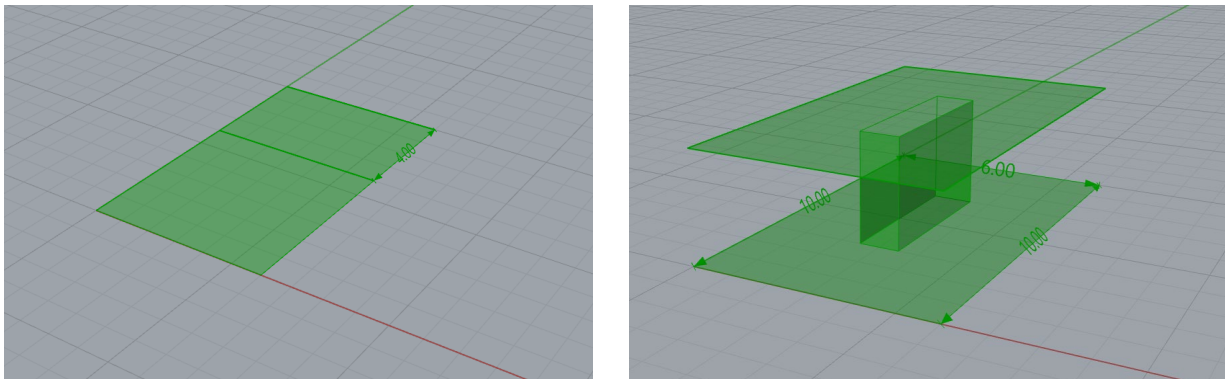


Figure 40: Dividing wet and living spaces, and creating stair connecting the two levels.

Step 3: Define the initial starter space and future expansion area. In a real case, this can be negotiated between the provider of the starter structure and the owner, taking the initial cost and the associated premium payment into consideration. In this experiment, for levels 1 and 2, the expansion area is defined as a balcony. Therefore, during the initial stage, the balcony will be more oversized, and it will get smaller as the unit expands.

Step 4: Define the access points from the corridor for the first level and second level. For the first level, the access should always be from the corridor, but for the second level, it varies depending on whether it is rented for additional revenue or fully utilized by the owner. In the first case, the - upper level rented – the stair is preferred to access the corridor directly. In the second case, the stair can be located anywhere in the room.

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Step 5: Convert the geometric constraints into a parametric model using a domain size. The domain size in X and Y determines the minimum and maximum area of the room and proportion. The location of each room is measured from its centroid. The room size is developed based on 1m*1m modular grid. All rooms except the hallway and balcony can rotate 90 degrees during the optimization process to qualify the fitness objective. Only one type of stair with a single flight is used in this experiment, considering that it is simple for construction.

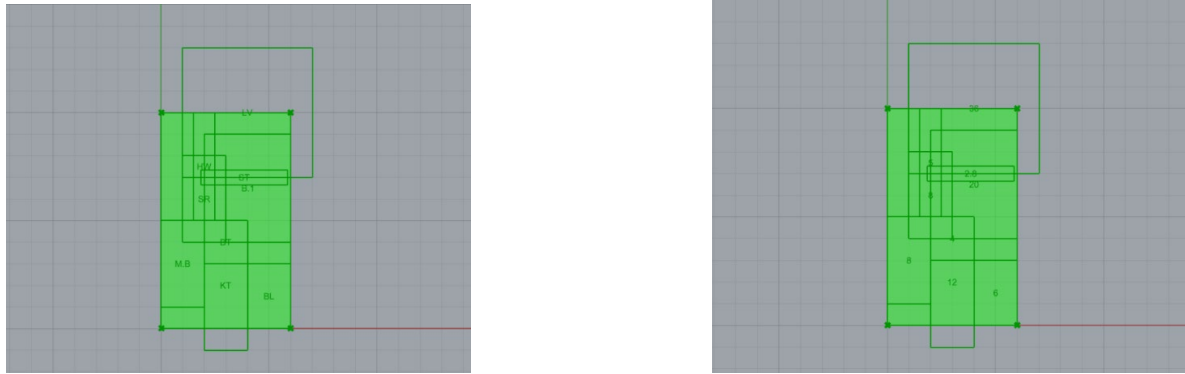


Figure 41: Left: Random placement of the rooms and Right: associated room area.

Step 6: Compare the area of the rooms that are generated using the X and Y parameters with the list of area requirements and find the absolute difference. This difference will later be used as a fitness objective. It should be checked before starting this process that the sum of the required area list should not be more than the total available amount of unit area at the first and second levels. (See table 7)

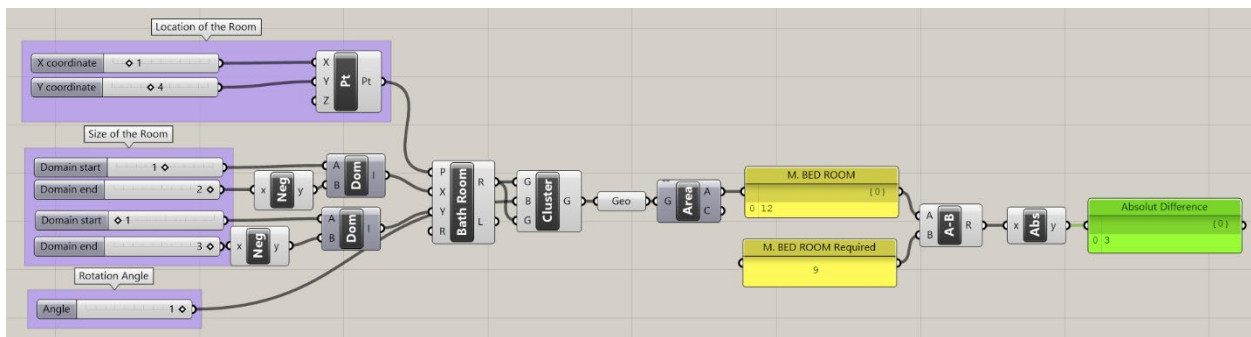


Figure 42: Grasshopper Definition for Geometric Constraint of rooms and calculating the difference from Required Area of the room and generated area.

Step 7: Generating floor plan for the second level. Because the two levels are linked by stair and wet rooms, the location of these rooms will be like the first level. Therefore, if the owner prefers to rent the second level for revenue generation, the space layout program will be like the first level. However, if the owner prefers to utilize both the levels, the kitchen does not need to be repeated on the second level; instead, more

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bedrooms will be added. In this experiment, the two modalities are tested to assess the potential use of GD in creating coordinated space arrangement in both floors and manage the incremental expansion.

Table 9: Geometric Constraint Setup Table for Unit Expansion (Second Level)

Tag	Room Name	Min-Max (X)	Min-Max (Y)	Rotation	Required Area (m ²)
HW	Hallway	[1m-1m]	[2m-2m]	0 (no rotation)	4*
ST	Stair	[1m-1m]	[4m-4m]	0°, 90°, 180°, 270°	4
BT	Bathroom	[1m-2m]	[1m-4m]	0° or 90°	2
MB	Master Bedroom	[2m-3m]	[2m-4m]	0° or 90°	12
B.1	Bedroom 1	[2m-3m]	[2m-4m]	0° or 90°	6
BL	Balcony	[1m-2m]	[2m-2m]	0 (no rotation)	4
			Total (First Phase)		30
			Total Space Available on second level.		42

Step 8: Create a façade for the units. The façade of the unit is a result of three basic components (MC solid panels, MC windows, Handrails), and the window is created on the outer surface of the units in relation to the space layout. Moreover, optimum radiation is allowed in the room, and the handrail is linked to the size of the balcony.

Topological Constraints

Step 1: Create an Adjacencies matrix indicating the link between the rooms and the external surface (access from the corridor and light and ventilation access from the exterior surface). The topological constraint can be analyzed in the first and second levels.

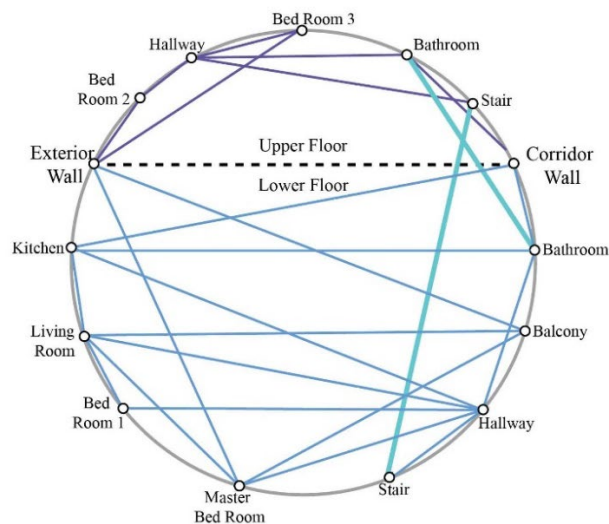


Figure 43: Topological Constraints: adjacency matrix between rooms and rooms and exterior walls across two levels.

Step 2: Calculate the intersections and unused space between the rooms. The overlap between rooms is calculated with the objective of minimizing or avoiding intersected spaces. Additionally, the absolute area difference between rooms and the unit boundary is calculated to determine gaps between rooms or room areas outside of the unit boundary. Again, the objective is to avoid gaps between rooms and areas outside the unit boundary. The assumption is that combined optimizations of the two objectives will result in a palatable space layout configuration.

4.4.3 Generate, Evolve and Evaluate

Based on the above methodology, the topological and geometric objectives are specified below:

1. **Geometric Objectives:** This objective determines the size, orientation, proportion, and location of a room.

Indicator 1: To ensure that the rooms are not intersecting, the intersection area result between the rooms must be minimized or avoided.

Indicator 2: A list of required areas for each room is prepared and is compared against the generated room areas result. The absolute area difference between the two is calculated, and the fitness objective is to minimize the difference between the two lists to match the initial list room areas.

2. **Topological Objectives:** This objective determines the adjacency between the rooms.

Indicator: minimize the distance between the rooms required to be in proximity and maximize the distance between the rooms required to be far apart.

3. **Mass Customization Strategy:** The plan layouts are constructed on a 1mx1m modular grid. The goal is to create a flexible plan layout that respects the modular layout. The modular layout is assumed to be constructed out of modular wall elements combined in a different configuration to automatically achieve the generated room layouts.

Chapter Five

5.0 Results and Discussion

This chapter reports the results and findings retrieved from the two GD experiments conducted and discusses the implication of the findings within the study framework. The potential use of GD and MC in CH at the core structure and unit expansion stage is described in detail by showcasing how the goals and objectives of the stakeholders can be optimized. The discussion section summarizes and analyzes the secondary data's findings, contextual review, and generative design experiments in relation to the research questions.

5.1 The result from GD Experiments

5.1.1 Experiment 1: Developing Core Structure

The first experimental results are presented below by making comparisons for selected fitness objectives (FOs.) and extracted Pareto front solutions. The highest rank of each FO is extracted to demonstrate the capacity of the evolutionary solver in optimizing the objectives separately. The overall result of the highest rank of each FOs demonstrates the evolutionary solver capacity in selecting the best individual solutions for a given number of generations and population sizes. On the other hand, the Pareto front solutions are not as satisfactory and palatable as is expected. The possible reasons are the immense size of the solution space, the inability of the evolutionary solver to discriminate between the FOs, and the inefficiency of the coding.

1. FO1: Minimize Solar Radiation

The highest rank is generated in the 94th generation and at the 4th individual solution. The fitness value is 312.289216, and it is ranked at 0/4999. Besides, the standard deviation has indicated variance, and the graph has shifted to the left, which indicates that fitter solutions are generated in the process. The 3D solar radiation result shows that this value is achieved by varying the block height to create self-shading and eliminating some of the blocks to minimize surface areas that receive radiation.

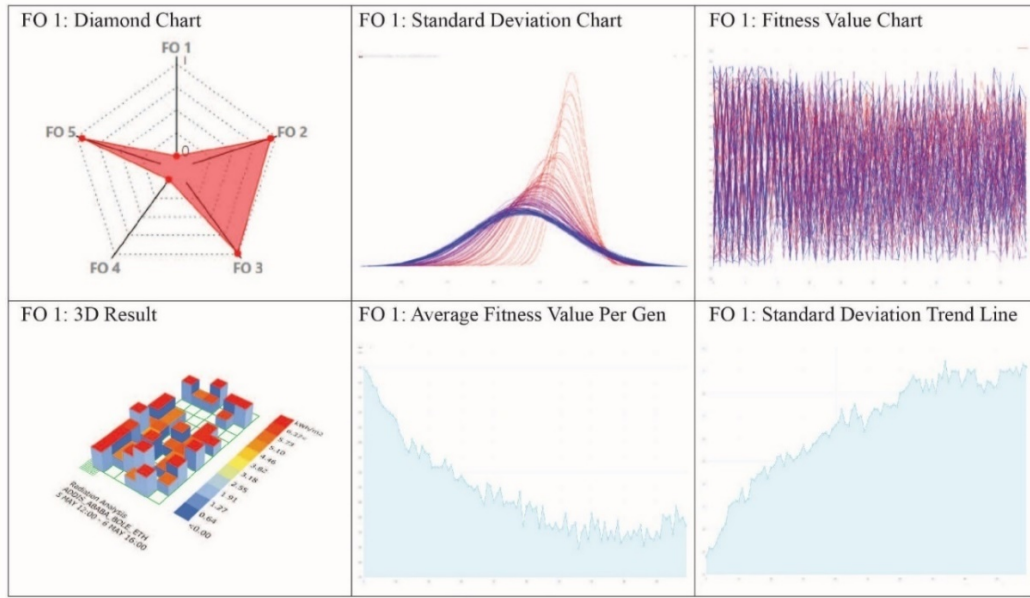


Figure 44: Result for FO1 (Radiation) optimizations

2. FO 2: Minimize the cost Index.

The highest rank is generated at 95 generations and four individual solutions. The fitness value is 0.931469, and it is ranked at 0/4999. The inverse value is 1.073. The standard deviation chart indicates variance, but the fitness values are not getting better. This is also reflected in the average fitness value per generation and the 3D.

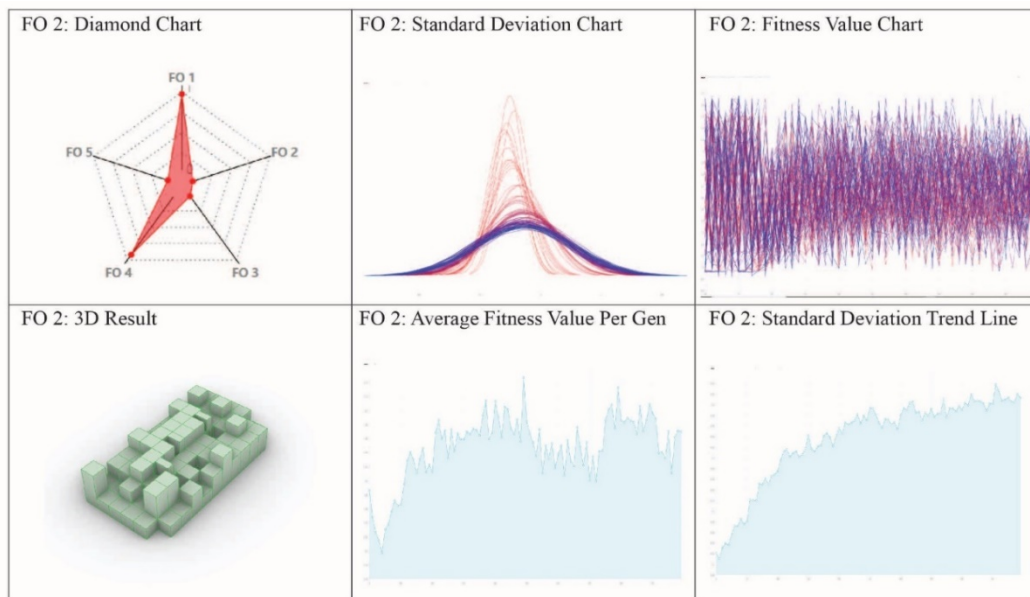


Figure 45: Results for FO2(Cost Index optimization)

3. FO 3: Maximize FAR

The highest rank is generated at the 75th generations and the 5th individual solutions. The fitness value is 0.473684, and it is ranked at 0/4999, which yields FAR: 2.11. The Standard deviation chart and average fitness values indicate that the values have variance, but they are not fittest.

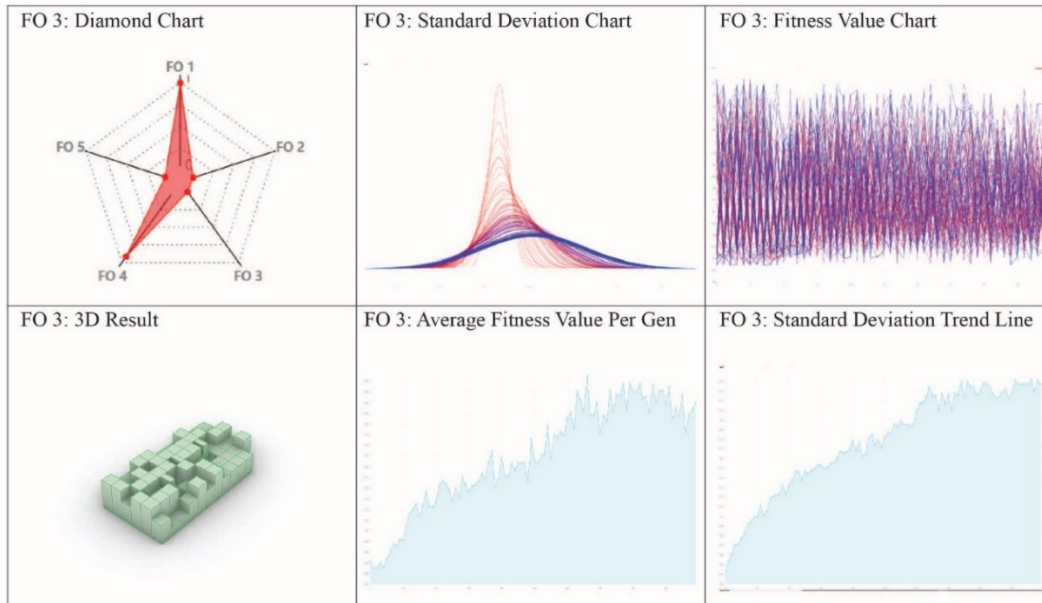


Figure 46: Results for FO 3 (Maximizing FAR)

4. FO 4: Maximize Courtyard Space

Highest rank is generated at 83 generation and the 7th individual solution. The standard deviation chart indicates that there is convergence, but the values are getting fitter. The average fitness value and the 3D confirm this.

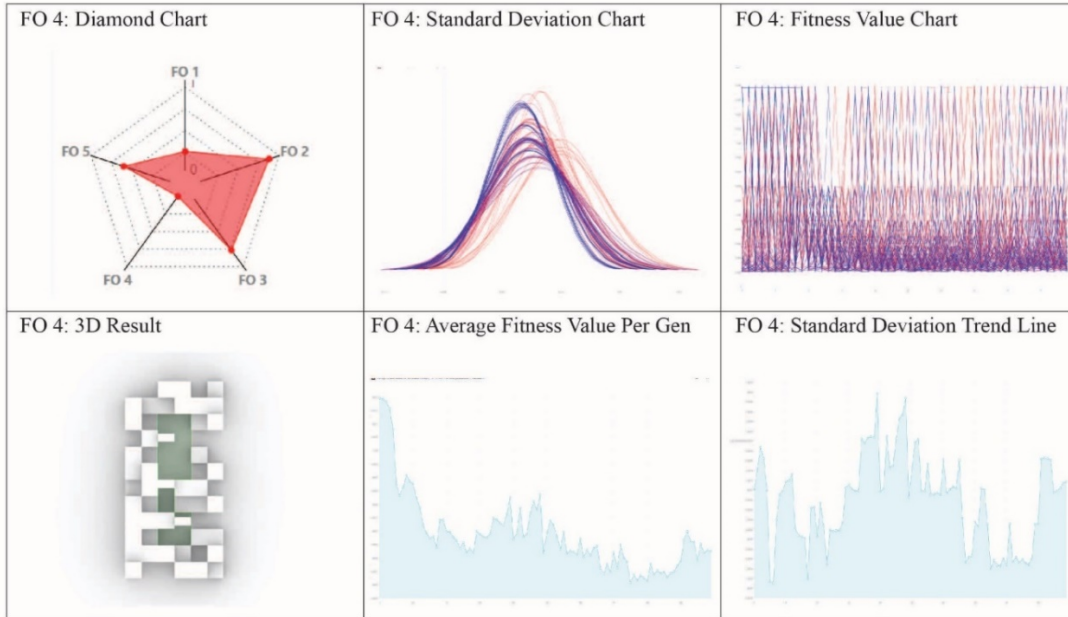


Figure 47: Results for FO 4 (Maximizing Courtyard Space)

5. FO 5: Maximize 2nd floor Circulation Connectivity.

The highest rank is generated at the 7th generation and the 3rd individual solution. The maximum fitness value is 0.007353, and it is ranked at 0/4999. It indicates that the initial random position of the model has created a fitter solution.

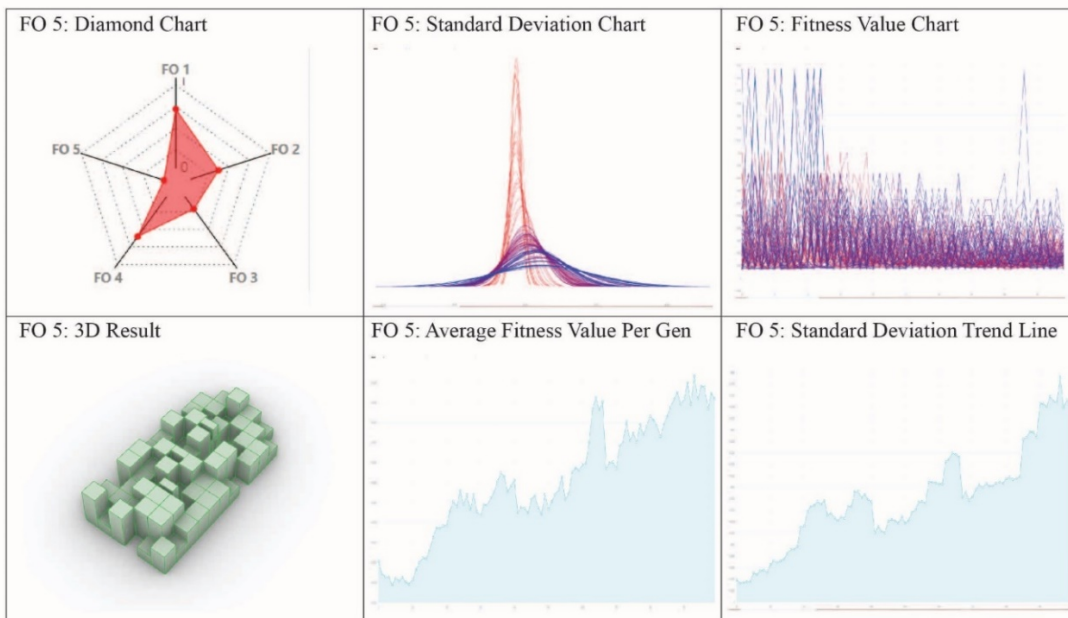


Figure 48: Results for FO 5 (Maximizing circulation connectivity at 2nd floor)

6. FO 6: Maximize the distance between the stairs.

The highest rank is generated at the 32nd generation and the 23rd individual solution. The maximum fitness value is 0.009134, which is 109.48m, which is the summation of gaps between three stairs(See 4.3.2 step 7). The diamond chart shows that the FO is optimized, but the standard deviation chart indicates that the solutions are converged too tightly. The average fitness value per generation and standard deviation trend line indicate that the solutions are not getting fitter. This is caused by the setup of the parametric model in which 72 sliders control the other objectives and three sliders separately control the stair location.

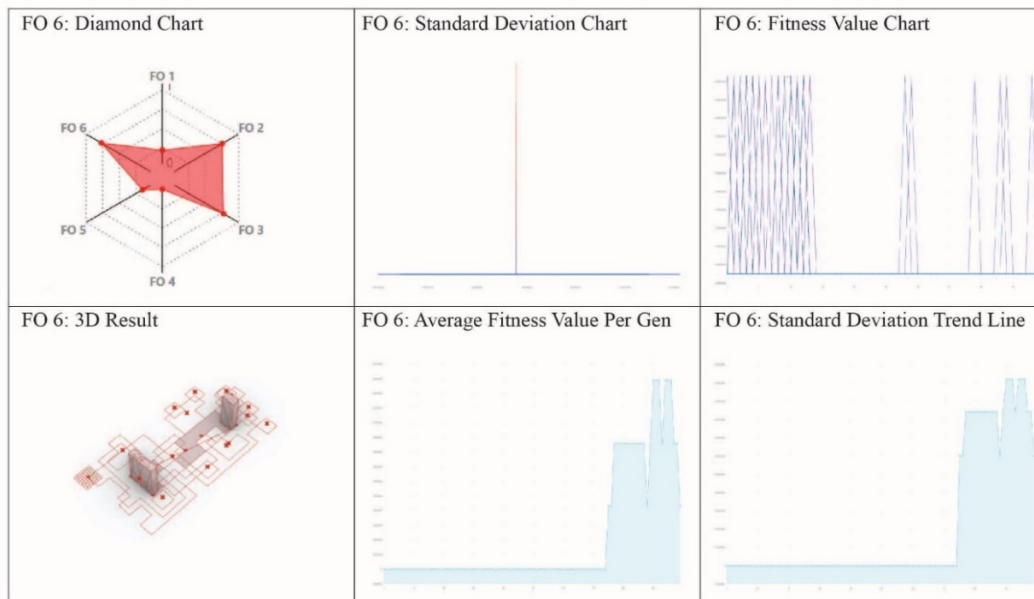


Figure 49: Results for FO 6 (Optimize the distribution of stair location)

7. Pareto Front Solutions

The Pareto Front solution indicates the compromise between the other five fitness values to achieve the best individual solutions that satisfy all the FOs. Based on the above result, FO6, stair location is removed to create a uniform gene pool (slider values). The generated 3D massing indicates variance, but most of the solutions might not be practically acceptable (See Appendix B).

The pre-conceived solutions for the design problems and the GD generate solutions are found to be different. For example, in the first experiment, the pre-conceived massing of the core structure is a courtyard in the middle and the floor massing in the periphery. The generative design produced design solutions that distribute the courtyards (open spaces) differently. It can be considered as the advantage of generative design in producing unpredictable results.

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The number of FOs is reduced from five to three to produce a palatable overall result. The Pareto front solutions are found to be more palatable as compared to the previous result with five FOs. It is partly because reducing the number of FOs will significantly reduce the solution space and produce fitter individual solutions in each generation and population size.

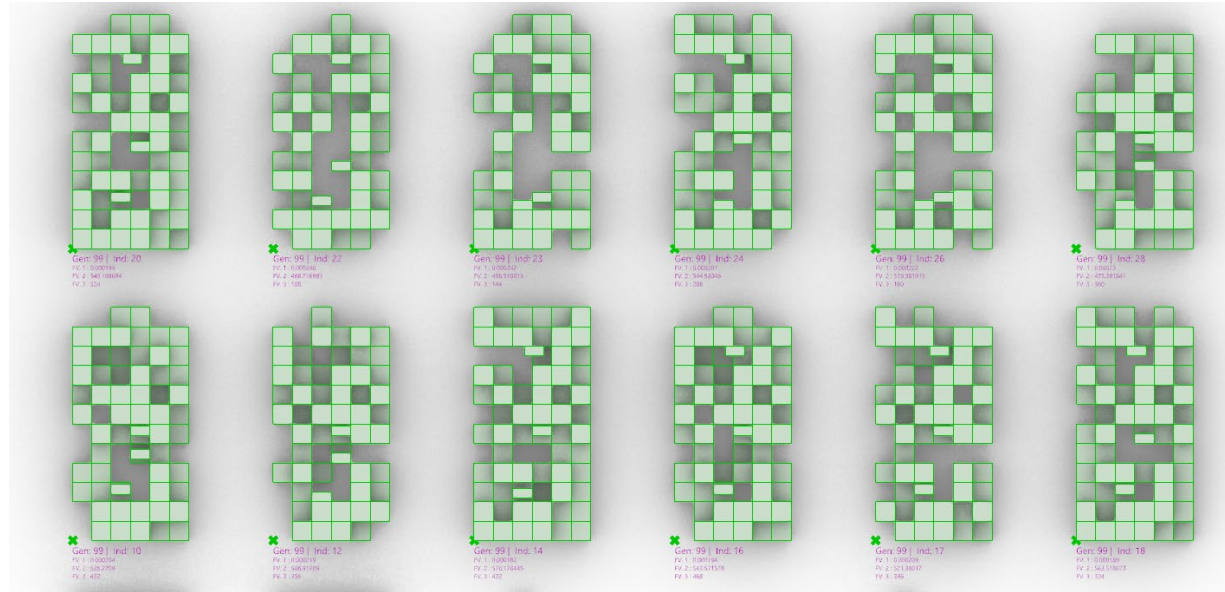


Figure 50: Top view of Pareto Front Solutions with 3 FO in consideration

8. Mass Customization for Core Structure.

The parametric model is developed based on the modular volume of 6m x 6m and height of 5.4m, making it possible to be produced out of mass-customized and mass-produced modular structural components. In addition, the parametric model can automatically generate a schematic layout of the structural elements (beams, columns, and slabs) for quick visualization. Moreover, the number of modular components can be easily accounted for, which will help optimize elemental cost at the early conceptual stage of the design.

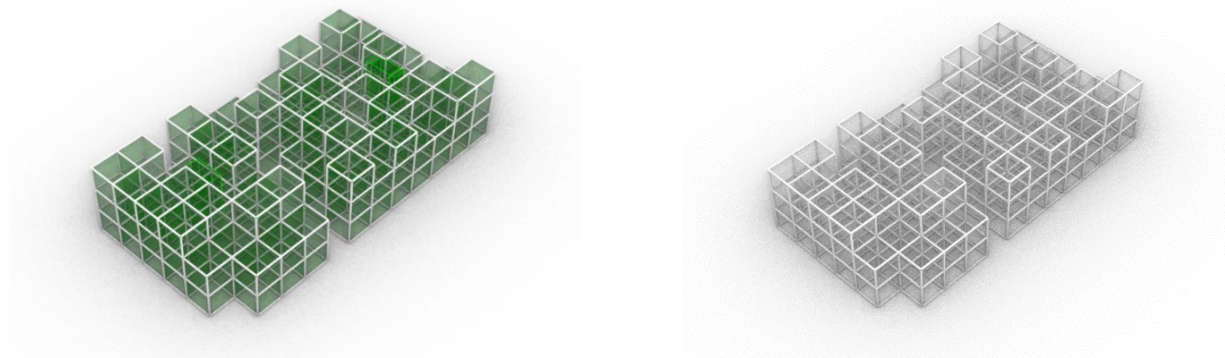


Figure 51: Modular Structural Elements of the Core Structure

9. Starter Units

In addition to the outputs mentioned above, the starter unit layouts can also be generated to generate the core structure. In most cases, starter units are provided by the government together with the core structure. Starter units can be as simple as partition walls defining one unit from the other, or in some cases, it can include amenities and services like a toilet and kitchen. The individual units (starter units) are generated based on the predefined unit area, and different types of typologies are identified. The smallest unit area is 18m² or 32m² (including the inserted floor), and the largest unit is 108m² or 116m² (including the inserted floor). The unit mix ratio can be manipulated to achieve the required number of units from each typology based on the residents’ requirements.

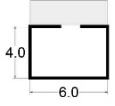
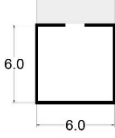
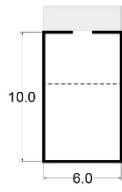
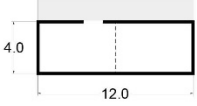
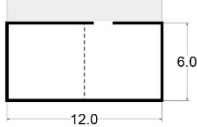
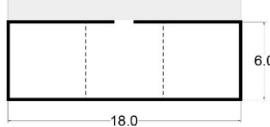
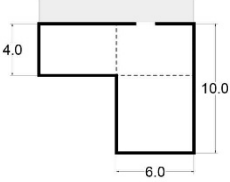
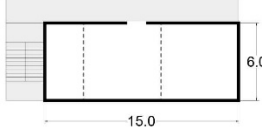
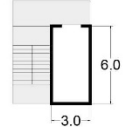
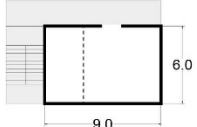
Typology 1	Area = 24m ² →48m ²	Typology 2	Area = 36m ² →72m ²	Typology 3	Area = 60m ² →120m ²	Typology 4	Area = 48m ² →96m ²	
								
Typology 5	Area = 72m ² →144m ²	Typology 6	Area = 108m ² →216m ²	Typology 7	Area = 84m ² →168m ²	Typology 8	Area = 90m ² →180m ²	
								
Typology 9	Area = 18m ² →36m ²	Typology 10	Area = 56m ² →112m ²					
								

Table 10: Starter Unit Typologies

5.1.2 Result of Experiment 2 (Unit Expansion)

Room layout optimization is conducted for the three selected unit typologies based on the topological and geometric constraints developed according to the methodology described in the previous section. The first simulation attempted to input all topological and geometric constraints considering a total of 7 rooms. The

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result was unsatisfactory even though the simulation is run for more than 200 generations using Wallacei (MOO) and Galapagos (SOO) tools.

The second experiment minimized the constraints and fitness values, and the rooms were divided into three regions. The first region (starter unit) contains wet rooms and basic amenities such as the stair (ST), entrance hallway (HW), bathroom (BT), store (SR), and a kitchen (KT). These rooms are aligned to the corridor, their size is fixed, and change of location is only allowed in the fixed region. This complements the real case scenario in which the government defines basic amenities and fixes the services before the owner takeover.

The second region contains living areas such as living room (LV) and Bedrooms (BD), which expand incrementally and controlled by the owners. Finally, the third region is assigned as a balcony, which additionally serves as an expansion area for the future. The upper and lower floor will have a similar wet room location to avoid plumbing and duct misalignment. Also, the stair will act as a common element that connects the two-floors spaces.

After applying the three regional compartmentalization strategies, the solution space was significantly reduced, and the GD outcome became more palatable and practical. However, the compartmentalization strategies made the GD model more biased towards a predictable outcome.

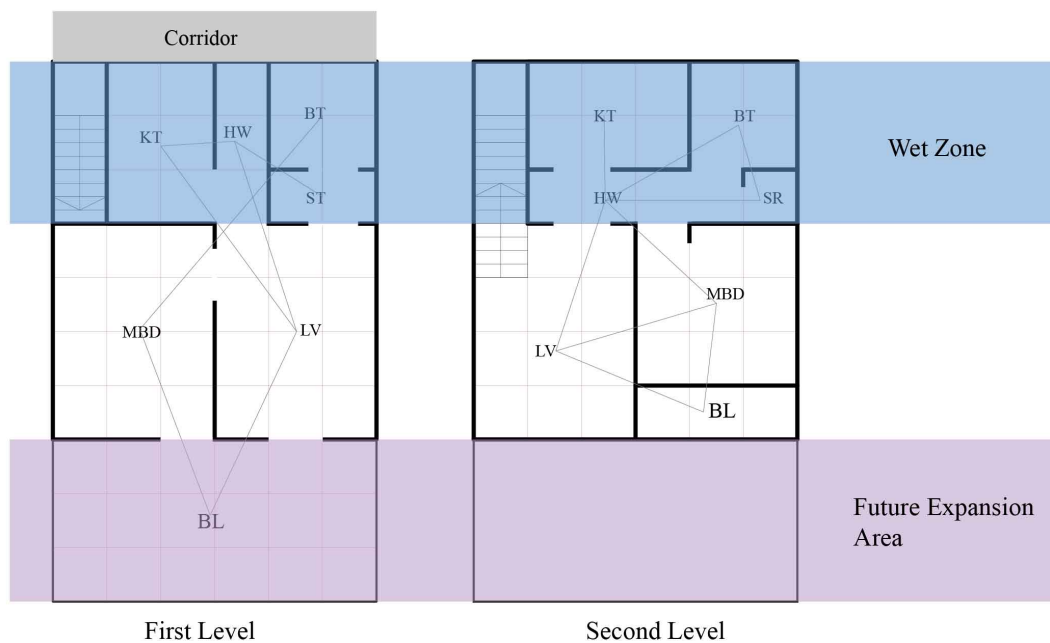






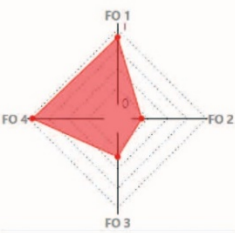
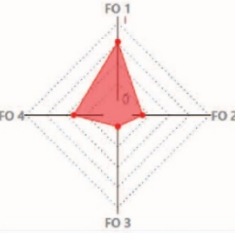
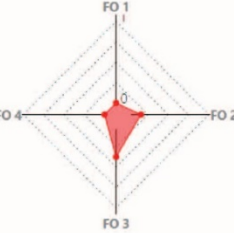
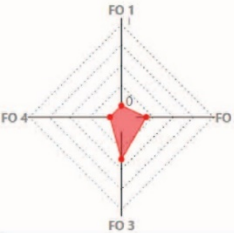
Figure 52: Zoning for unit layout

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In the second experiment, both topological (adjacency of the rooms) and geometric (size of the rooms) constraints are considered in the simulation. Since the evolutionary algorithm cannot prioritize objectives, it produced intersected rooms, and as a result, the geometric solutions are compromised. In this case, where the unit's size is defined, orientation is set, and expansion steps are taken into consideration, the topological constraints become less relevant.

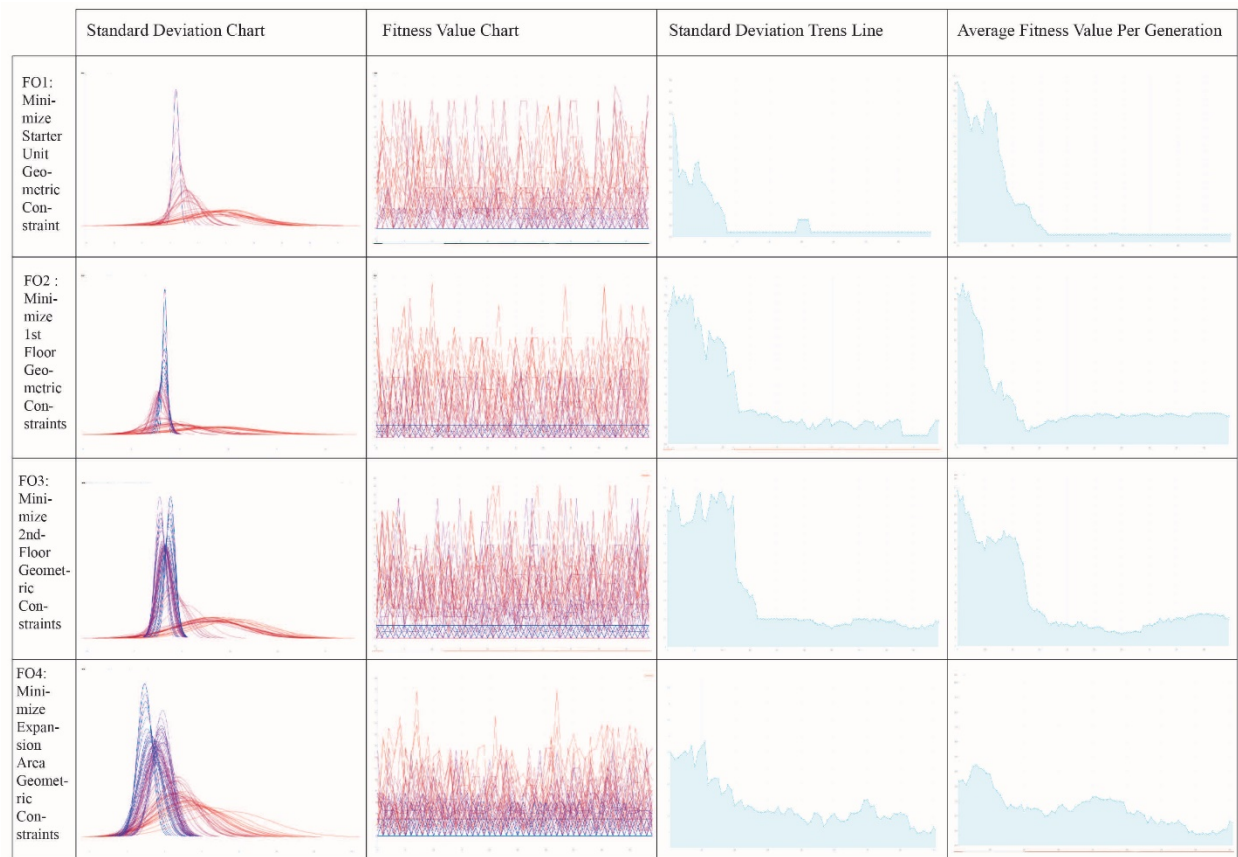
As a result, the third experiment is conducted, disregarding the topological constraint and only considering the geometric constraints. The result is satisfactory. Genetic algorithms have achieved acceptable geometric arrangement of the rooms in the two regions in just 50 generations, and after that, it became stagnant (See Appendix B.)

Table 11: Fitness Value and Phenotype Comparison between randomly selected generation and individual solutions.

Unit Typology - 3			
Solution: Gen. 12/Ind. 32	Solution: Gen. 32/Ind. 46	Solution: Gen. 80/Ind. 46	Solution: Gen. 96/Ind. 46
 <p>Floor Plan</p>	 <p>Floor Plan</p>	 <p>Floor Plan</p>	 <p>Floor Plan</p>
 <p>Diamond Chart</p>	 <p>Diamond Chart</p>	 <p>Diamond Chart</p>	 <p>Diamond Chart</p>
FO1: Minimize Starter Unit Geometric Constraint Fitness Value: 7 Fitness Rank: 4510/4999 FO2: Minimize 1st Floor Geometric Constraints Fitness Value: 3 Fitness Rank: 828/4999 FO3: Minimize 2ndFloor Geometric Constraints Fitness Value: 1.5 Fitness Rank: 1731/4999 FO4: Minimize Expansion Area Geometric Constraints Fitness Value: 10.5 Fitness Rank: 4785/4999	FO1: Minimize Starter Unit Geometric Constraint Fitness Value: 2 Fitness Rank: 3835/4999 FO2: Minimize 1st Floor Geometric Constraints Fitness Value: 3 Fitness Rank: 828/4999 FO3: Minimize 2ndFloor Geometric Constraints Fitness Value: 0 Fitness Rank: 0/4999 FO4: Minimize Expansion Area Geometric Constraints Fitness Value: 3 Fitness Rank: 2035/4999	FO1: Minimize Starter Unit Geometric Constraint Fitness Value: 0 Fitness Rank: 0/4999 FO2: Minimize 1st Floor Geometric Constraints Fitness Value: 3 Fitness Rank: 828/4999 FO3: Minimize 2ndFloor Geometric Constraints Fitness Value: 3 Fitness Rank: 1886/4999 FO4: Minimize Expansion Area Geometric Constraints Fitness Value: 0 Fitness Rank: 0/4999	FO1: Minimize Starter Unit Geometric Constraint Fitness Value: 0 Fitness Rank: 0/4999 FO2: Minimize 1st Floor Geometric Constraints Fitness Value: 3 Fitness Rank: 828/4999 FO3: Minimize 2ndFloor Geometric Constraints Fitness Value: 3 Fitness Rank: 1886/4999 FO4: Minimize Expansion Area Geometric Constraints Fitness Value: 0 Fitness Rank: 4785/4999

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Table 12: Fitness objectives and the associated analytic chart for space layout.



The standard deviation chart indicates convergence at the younger generation, but the shift to the left indicated that the solutions are getting fitter. Besides the standard deviation trend line and average fitness value graph line, the solutions get closer to the X-axis. In the case of FO1 (Minimizing the starter unit geometric constraint or the intersection between the rooms), the solutions get stagnant at the early stage. The experiments have revealed that the limitation of a genetic algorithm in tackling space layout design problems is to a certain extent. It should be noted that only visual programming language is used in these experiments, and certain limitations come with it.

The starter unit typology three is considered to have a rental unit on the second level in the example below. Hence the stair and the hallway are separated, and each resident will have a separate entrance to their unit. The upper and lower floor wet areas are aligned to create a suitable condition for the plumbing. The owner's decision to rent the upper floors determines the space layout for both the upper and lower floors. If rental units are considered, the stair access to the upper floors needs to be separated from the lower floor entrance for the upper units. If the owner uses the whole unit, then the stair placement will have multiple options, and the intermediate floor does not need to be inserted from the onset.

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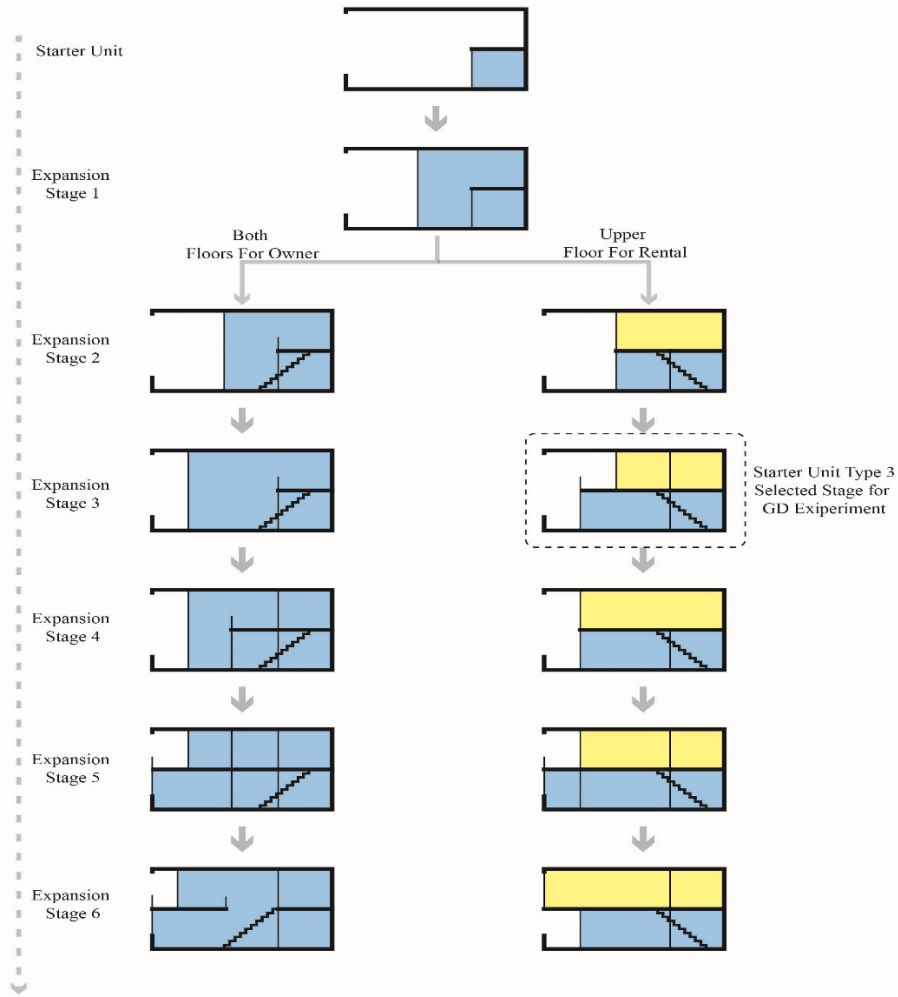


Figure 53: Expansion stages for unit typology 3 considering with and without upper floor rental options.

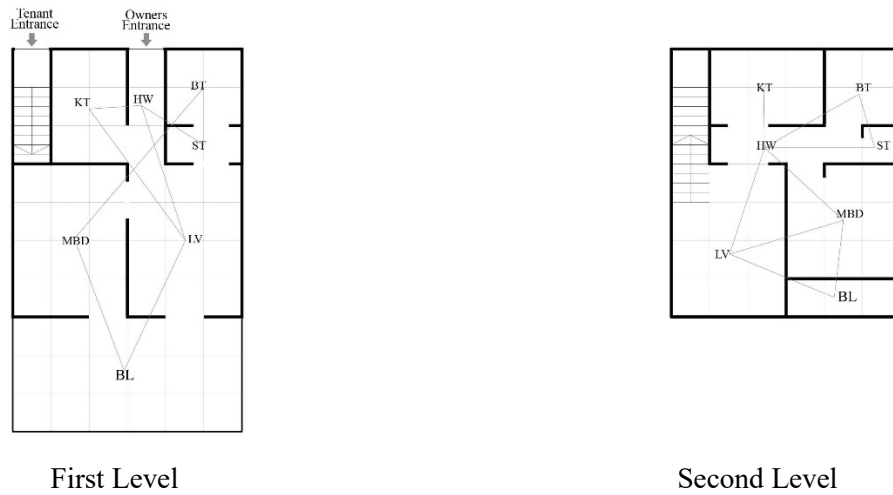
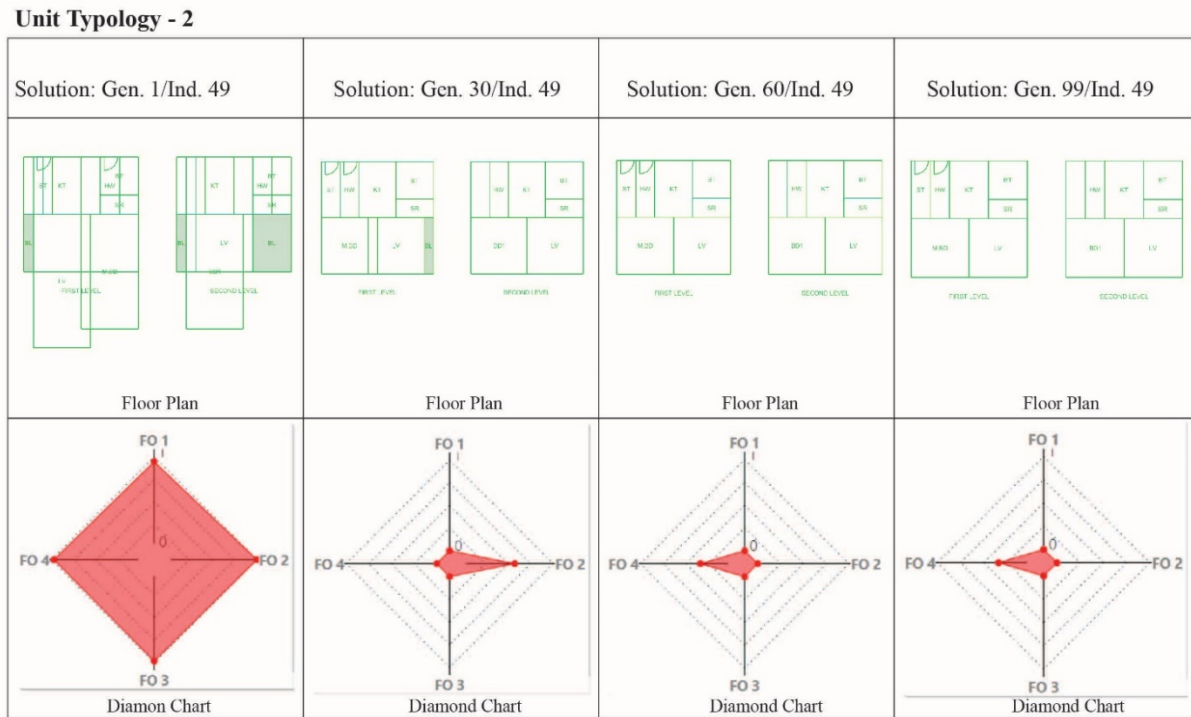


Figure 54: Refined result for unit layout with a second-level rental unit.

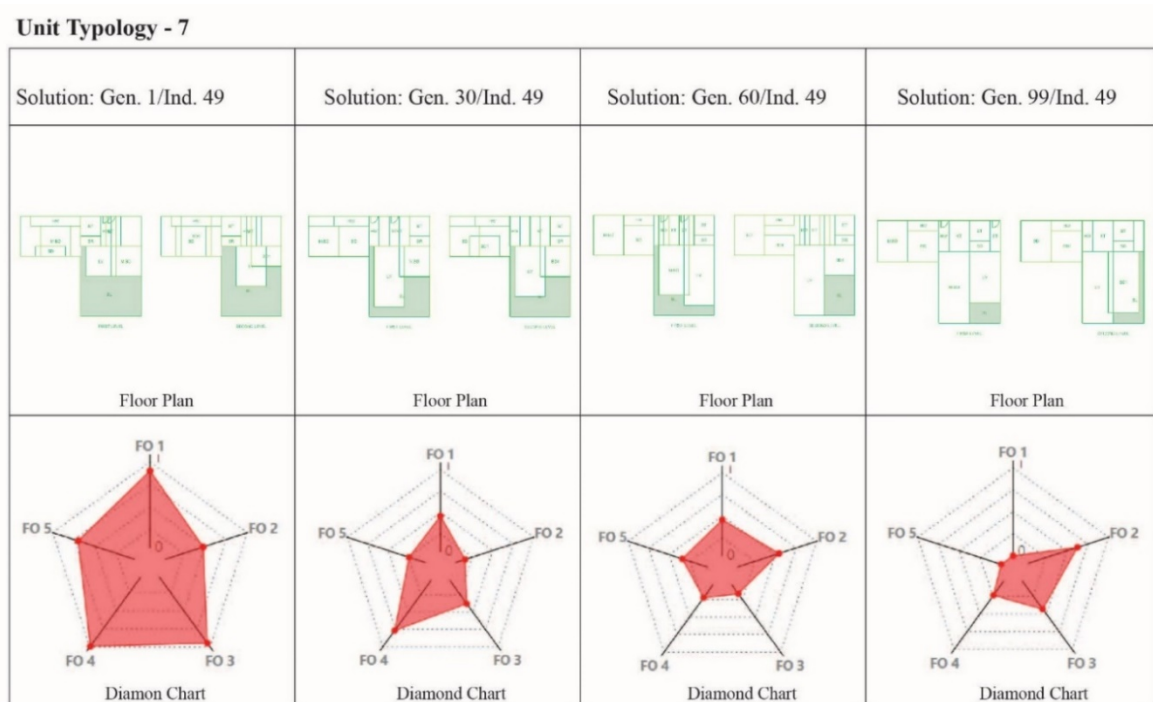
Unit Typology 2: The total typology 2 is 36m² on the first level and 72m² in total. As a result of the unit size, the solution space for space layout arrangement is very small, and the evolutionary algorithm quickly solved the geometric constraint in less than the 30th generation.

Table 13: Solution comparison across different generations for Unit Typology 2



Unit Typology 7: The biggest unit typology and area of the first level is 84m² and 168m² including the upper level. As a result of the size, the solution space is wider than unit types 2 and 3. The chart below indicates the progress of the evolutionary solver over 100 generations, and it did not get stagnant, unlike unit type 2 and 3.

Table 14: Comparison for Typology 7 space layout generation



The GD result from the three-unit typologies reveals that the size solution space is dependent on the size of the unit typology. If all relevant topological and geometric constraints are considered, small area units will have predictable solution spaces compared to larger area units. GD helps designers explore design solution space more efficiently, and depending on the sophistication of the algorithm, and it can reveal unpredictable solutions. GD system only optimizes and does not discriminate like a human designer; therefore, retrieving the best and workable solution heavily depends on the designer.

5.1.3 Mass Customization strategy for Unit Expansion

In this experiment, 1m by 1m modular coordination is used to construct the parametric model and to integrate the MC strategy. The parametric model is devised to work within this grid layout to enable mass coordination. Without getting into the technical details of material and construction, five types of modular wall components are proposed, which can be mass produced and easily configured to construct any orthogonal type - constructed on 1mx1m grid - space layouts.

The proposed strategy help to enhance the 'three capabilities' of mass customizations (Fabrizio et al., 2009). First, it helps to create solution space development by flexibly allowing for generating space layout options. Second, the framework in which the generative design is built has created a robust design process to entertain individual needs while maintaining the integrity of the MC system. Thirdly, through user

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interfaces, the end users can be assisted in navigating choices and making an informed decision. Moreover, the modular framework reduces the solution space and avoids choice complexity.

Due to time limitations, a parametric and GD system is not specifically developed to optimize the space layouts into modular wall components. However, the concept is demonstrated manually to showcase how a particular orthogonal space layout from the previous experiments can be constructed out of the five identified wall segments. Future works can incorporate a parametric model that can convert a wall segment into modular components and a GD system that can select the type and number of modular components to optimize cost.








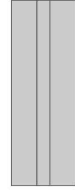




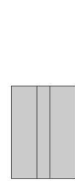


	MC-1	MC-2	MC-3	MC-4	MC-5
PLAN					
ELEVATION	MC-1a 	MC-2a 	MC-3a 	MC-4a 	MC-5a 
ELEVATION	MC-1b 	MC-2b 	MC-3b 	MC-4c 	MC-5d 

Figure 55: Five Modular components that can be reconfigured to create any type of orthogonal room layout.

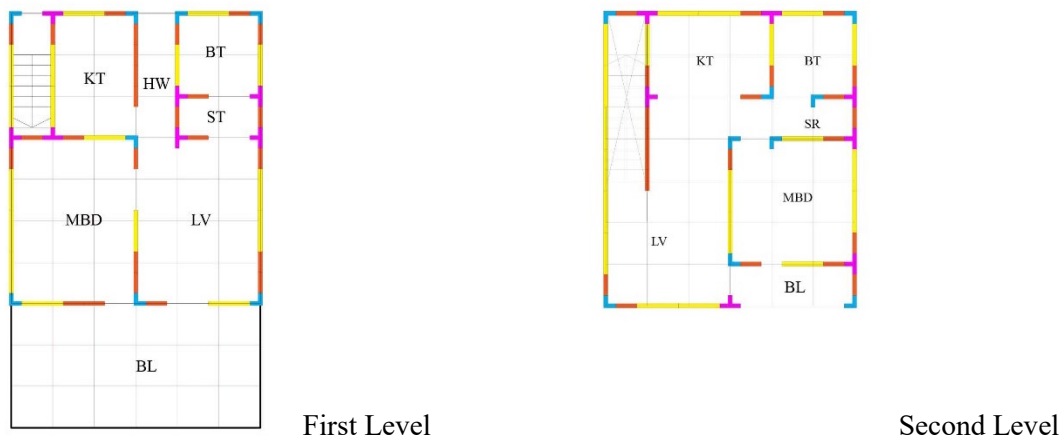


Figure 56: Converting space layout into modular wall components.

From a practical implementation point of view, the size of the modular components is envisioned to be moved and assembled easily by the owner's capacity. The size of modular components strongly affects the accessibility, transportation cost, constructability, and flexibility of the system. Therefore, it is crucial to consider the owner's self-building capacity when designing the mass customization strategy for core housing.

5.2 Discussion

The two experiments on core structure and unit expansion have demonstrated the potential use of GD and MC in the process of CH strategy. The first experiment has demonstrated that GD can efficiently generate customized core structures from elements that can be mass-produced, reconfigured, and optimized based on different fitness objectives. The second experiment on unit layout generation has revealed limitations in solving topological constraints. Regardless, the findings indicate the potential use of GD to create unit layouts within defined regions of the unit. Furthermore, the conceptual propositions of modularization of the unit layout are promising.

This study is conducted to evaluate the potential application of generative design and mass customization to enhance core housing and make it an alternative housing delivery option for Addis Ababa. To effectively fulfill these objectives, three supportive research questions were asked at the beginning of the study. Based on the analysis and result of the research, they are addressed in the following way.

How generative design and mass customization can be used to enhance the process of core housing at the core structure and unit expansion stage?

Findings from literature and contextual review point out that core housing has distinct qualities which distinguish it from other housing delivery methods. The experiments conducted in this study show that the following vital parameters can be enhanced using GD and MC at the core structure and unit expansion stages of CH.

1. Core structure development stage: GD can be used as a design optimization tool to efficiently generate core structure designs at a conceptual level and evaluate them through different fitness objectives. Moreover, modular coordination can be integrated into the GD system parametrically, enabling seamless coordination between the iterative design process and MC, which makes it easy to generate designs that are optimized to different fitness objectives and, at the same time, that are based on mass-producible modular structural elements. This will enhance the decision-making process and create an efficient design process that can address mass needs in customized and responsive ways.
2. Unit Expansion Stage: The second experiment has indicated the potential use of the GD in producing space layouts by optimizing geometric constraints. Even though the possibility of owners

using the GD tools to be able to design space layouts independently is limited, the findings indicate potential alternative strategies and ways forward. Moreover, the suggested MC strategies will enable owners to construct their space layouts out of a limited number of mass-producible modular components.

To what extent generative design and mass customization used to optimize the goals and objectives of different stakeholders and interest groups in core housing?

The relationship matrix and control distribution of stakeholders and interest groups in the CH indicates three major stakeholders' main interest and control in the core housing process. The study results indicate that GD and MC can optimize the goals and objectives of the three stakeholders in the following ways.

1. For government: The experiment conducted indicates that generative design can be used as an efficient designing and planning tool which enables informed decisions based on the iterative design process and measurable objectives. The GD process will enable the government to give rapid and customized solutions.
2. For owners: The second experiment indicates that generative design can be used to generate space layout options using modular grids and mass-producible wall components. Through the combined use of GD and MC, owners can have the flexibility to produce space layouts that can fit their space demand.
3. For material suppliers: The first and second experiment results indicate that modular coordination can be integrated through a parametric model that enables owners and the government to create various design options using fewer modular components. This integration of modular coordination in the design process creates a chance for material suppliers to enact mass production of a modular component which will increase efficiency and reduce cost.

What are the potential implications of generative design and mass customization-assisted core housing, as an alternative housing delivery option, in the context of Addis Ababa?

The findings from the literature review and contextual study and result of the experiments corroborate that GD and MC enhanced core housing can be an alternative housing delivery option for Addis Ababa for the following reasons:

1. Enhances the government housing delivery capacity: GD and MC assisted CH strategy can enhance government housing delivery capacity by reducing the financial and time burden of producing full housing.
2. It helps to achieve density in CH: Multistory starter unit with an inserted floor expansion can help achieve density in a manageable way. The upper floor can be used as a rental unit, which can generate additional income for the owners and absorb a particular housing demand in the city. This

CH typology creates better urban aesthetics because the individual unit expansion is framed and guided with the core structure; therefore, it can be integrated into a dense part of the city.

3. Helps to create customized mass housing instead of mass-produced housing: GD can be used to create variety and diversity in the housing delivery option. By allowing owners to participate in the housing process, diverse and evolving housings can be created.
4. Affordable housing option: CH reduces the government's financial investment, which, in turn, reduces the housing price. Through MC, the cost of housing production can be lowered without compromising the quality and diversity. As indicated in the first experiment, GD can be used, at a conceptual level, to optimize cost during the design of the core structure.
5. Enhanced quality of design and construction for CH: GD combined with MC can enhance the quality of design through measurable fitness objectives without compromising flexibility. Furthermore, because the design and construction methods are seamlessly integrated, the efficiency and quality of delivery can be enhanced.

5.3 Limitations of the GD Experiments

The following limitations are encountered in this study:

- The size of the modular units (6mx6m) used for the core structure experiment has made the search space manageable. However, for site sizes that are not multiple of 6m, the parametric model created unwanted leftover spaces.
- The unit expansion experiment's findings have shown certain limitations of using generative design to optimize space layout for cases where the topological and geometric constraints are increased to reflect practical design challenges. Furthermore, the consideration of staged expansion makes the design space too small to be navigated by an evolutionary algorithm and produce novel solutions. The consideration of a modular grid layout for the unit helped to create customizable wall segments but, at the same time, has limited the solution space.
- The evolutionary algorithm used in this experiment (Wallacei V2.55) cannot prioritize fitness objectives. As a result, the Pareto front solutions are compromised between the FOs, which have a different level of importance in determining the overall fitness solutions.
- Furthermore, some limitations arise because of the capacity of the programming language used to define the constraints and solution space. In this experiment, a visual programming language (VPL) is used, which does not have sophistication and capabilities compared to 'hard-coding.' As a result, the accuracy and representativeness of the model are limited to a certain extent.

Chapter Six

6.0 Conclusion and Future Work Recommendations

Based on the results and discussion, this chapter makes conclusions and recommendations for future research work. Satisfactory results are retrieved from this study, and several issues and topics are linked, which can be explored and studied further. The process of analytically defining CH, extracting key parameters, and approaching objectives and constraints through an algorithm, has brought a new perspective into incremental self-help housing.

6.1 Conclusion

In this study, one of the old self-help incremental housing strategies, CH, is revisited through GD and MC to propose an alternative housing delivery option for Addis Ababa. After studying CH through literature review, secondary data, and contextual analysis, critical parameters of the process, stakeholders' interests, and morphology of core housing are identified. Out of five stages of the CH process, two of the stages, core structure and unit expansion are selected to be rethought through GD and MC. The parametric model is developed based on a specific type of multi-story and multifamily core housing typology and modular coordination strategy. A multi-objective optimization(MOO) evolutionary algorithm is used to optimize various objectives and goals of selected stakeholders and interest groups in CH.

The result of the experiment indicates that GD can be used to efficiently generate mass-producible core structures that can be customized to different sizes of rectangular sites and optimized for different fitness criteria. On the other hand, with certain limitations, GD can also be used to generate space layouts based on the pre-set modular grid and few modular wall segments. It is indicated in the experiment that by configuring five modular wall segments, any type of orthogonal space layouts can be generated.

This study indicates that, by parametrically combining modular coordination into the GD system, the owner's self-help building capacity can be enhanced. In addition, the quality of construction can be enhanced through the use of mass customized modular components without compromising the owner's control and flexibility to expand their unit. It strikes the right balance between controlled outcomes and customized individuality. It is the right tradeoff between the government's need to control quality and owners' need for flexibility.

Owners have shown incredible self-building capacity, which is testified through a fast proliferation of informal settlements in urban areas and the indigenous self-building tradition in rural areas. It should also be noted that the participation of owners in the housing process creates responsibility and social cohesion. Studies and the current practice have revealed the inadequacy of government capacity to provide full housing. Likewise, the majority of Addis Ababa residents cannot afford the current housing provision.

Moreover, the housing demand increases and the gap between supply and demand grows more expansive year after year. Therefore, a solution that considers housing as a process rather than an end product and coordinates the owners' and governments' potential is essential. As it is demonstrated in this study, GD and MC can create an effective platform that can entertain this process and coordinates the capacity of government, owners, and material suppliers.

6.2 Future Work Recommendations

This study has explored the interdisciplinary boundaries between generative design, mass customization, and core housing to bring a more comprehensive perspective on the housing delivery strategy. Insights are drawn from specialized research of each area of studies, extracted the parameters, and analyzed their connection to develop a solution. However, there is room for improvement of the study and detail analysis of the potential implications. Therefore, the author has identified the following topics to be a potential area for future study.

1. CH starts at selecting the right site with affordable land value and proximity to job places, services, and material supplies. “Selecting the right land for the incremental development of low-income housing is difficult, but it is crucial to the success of incremental housing policy or project.” (Riley and Wakely, 2011) The potential use of GD in assisting the site selection process by optimizing computable parameters is a commendable area of study.
2. Generative design’s potential can be used to optimize block arrangements at an urban scale. Related studies indicate that GD can be used to generate and optimize urban planning and design. Future studies should investigate the potential use of GD to optimize and facilitate the planning and urban block arrangement for CH.
3. In this study, the potential use of GD to generate space layouts is explored, and some limitations are encountered. Future studies can incorporate other computational design strategies, such as machine learning, to efficiently automate the space layout design process. Fast, efficient, and adaptive tools can be developed to enable owners to help design through incremental expansion.
4. An interactive GD tool can be developed and tested by users to study how they interact with it and to gather more data about owners' preferences. In addition, the practical use of GD tools can be tested with the design professionals and material producers to inform practical application. This area of research can be exciting, interdisciplinary, and collaborative research between the architect and software developers.
5. Future studies should be done on the material, production, and assembly processes of modular components to create an efficient mass customization strategy for multistory CH. Two potential areas of studies can be assessed in this regard. The first is to study the construction material supply

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chain and propose a mass customization and production strategy beneficial for private interest groups, government, and donors. The second research area can focus on technical details and assembly strategy, considering the owner's self-building capacity.

PART TWO: PROJECT PROPOSAL

Chapter Seven

7.0 Project Proposal

7.1 Site Selection

Based on the findings of this study, a sample project is proposed on a selected site within the city center of Addis Ababa. The following site selection criteria are used to select a specific site:

- Proximity to job opportunity and city center,
- Potential to create home-based enterprises for the owners,
- The prevalence of incremental self-help building practice,
- Suitability of the urban grid to study the potential of generative design,

Based on the above criteria, three potential sites (‘Cherkos,’ ‘Sebategna,’ and ‘piazza’ area) from three sub-cities were assessed. The site located in Addis Ketema Sub-city, commonly known as ‘Sebategna,’ is selected to demonstrate the practical implementation of the study result.

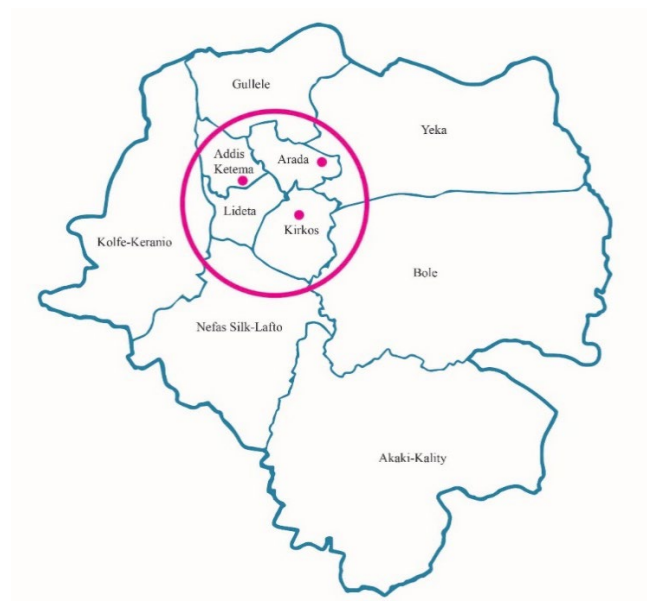


Figure 57: Site comparison.

‘Sebategna’ site is located in the inner-city area, and it has a vibrant and mixed lifestyle. Most of the residents of this area generate their income from small commercial activities happening around the site. The housing units are ‘Kebele Rental Houses,’ but the owners are observed to modify and incrementally expand their housing units through time. This area has repeating rectangular urban blocks and which are

suitable for the parametric model developed in this study. The parametric model for the core structure is developed for rectangular sites, which are multiple of 6m by 6m modular grids.

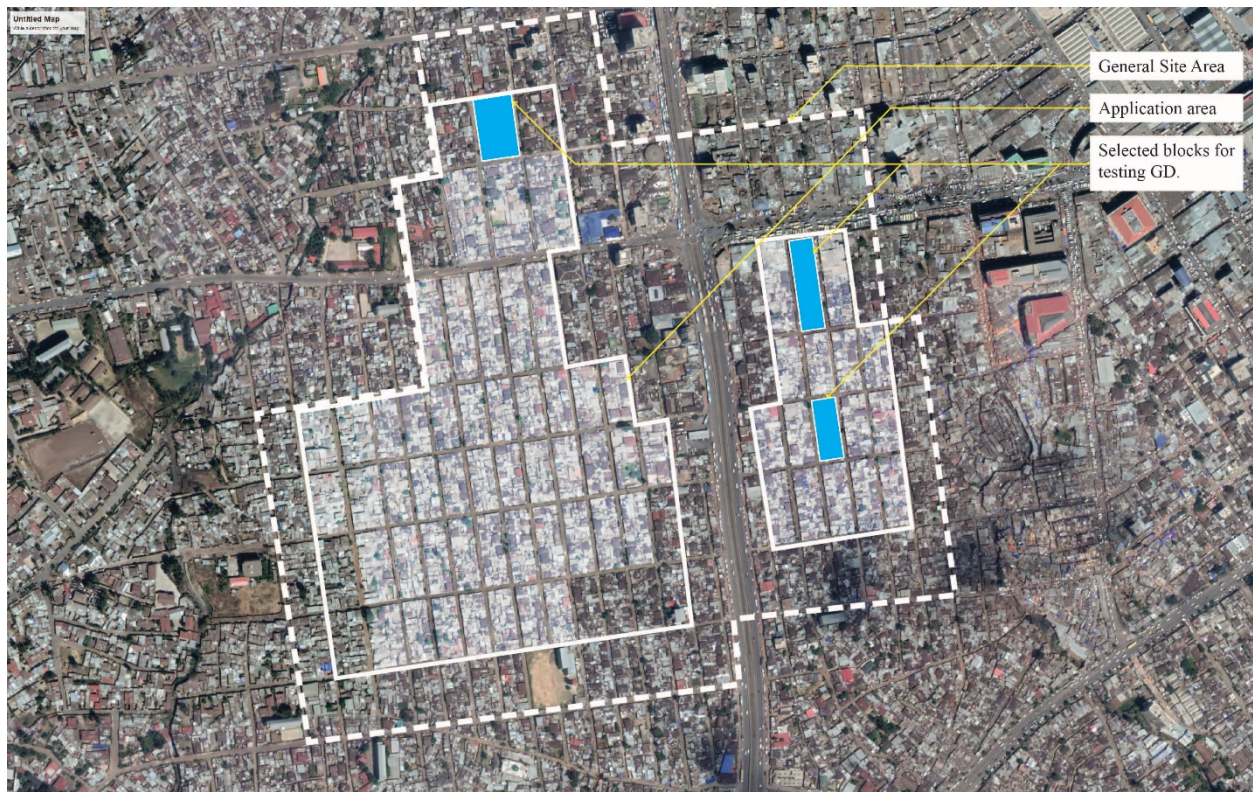


Figure 58: Site Location, the application area of GD, and Selected blocks for testing the GD Strategy.

7.2 Project Development

Based on the study's findings, a multi-story and double-floor incremental unit core housing is proposed for the selected site. The government can mass-produce the starter structural elements and configure them using GD to fit different objectives. The double floor gives the owner space to expand horizontally and vertically and customize their housing unit to match their demand and capacity. The government builds the structure, slab, and walls that divide one unit from the other, and as a result, the structural integrity and safety can be maintained.

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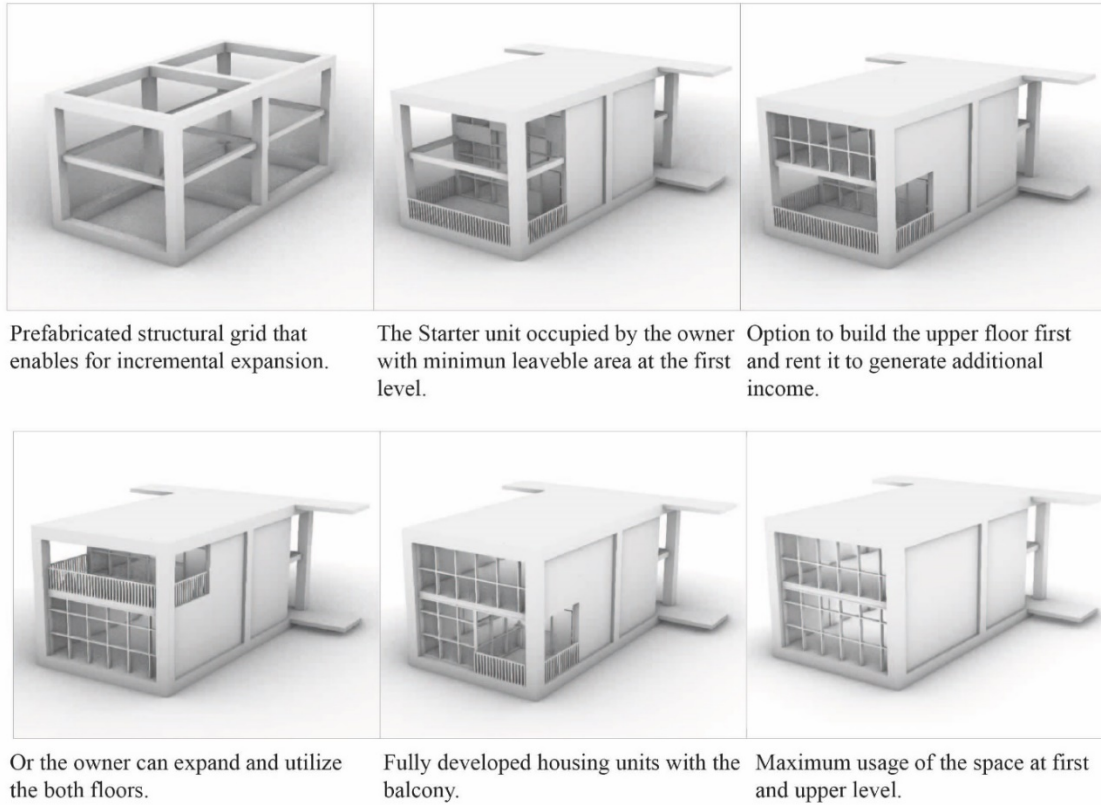


Figure 59: 3D illustration of how a typical unit may expand through time



Figure 60: Ground Floor Plan of the Project Proposal

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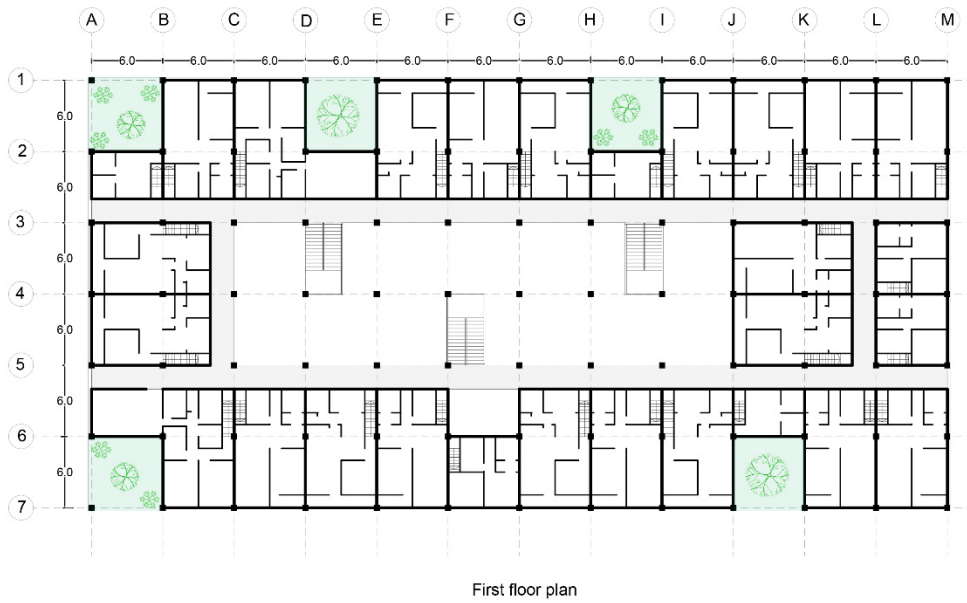


Figure 61: First Floor Plan of the Project Proposal

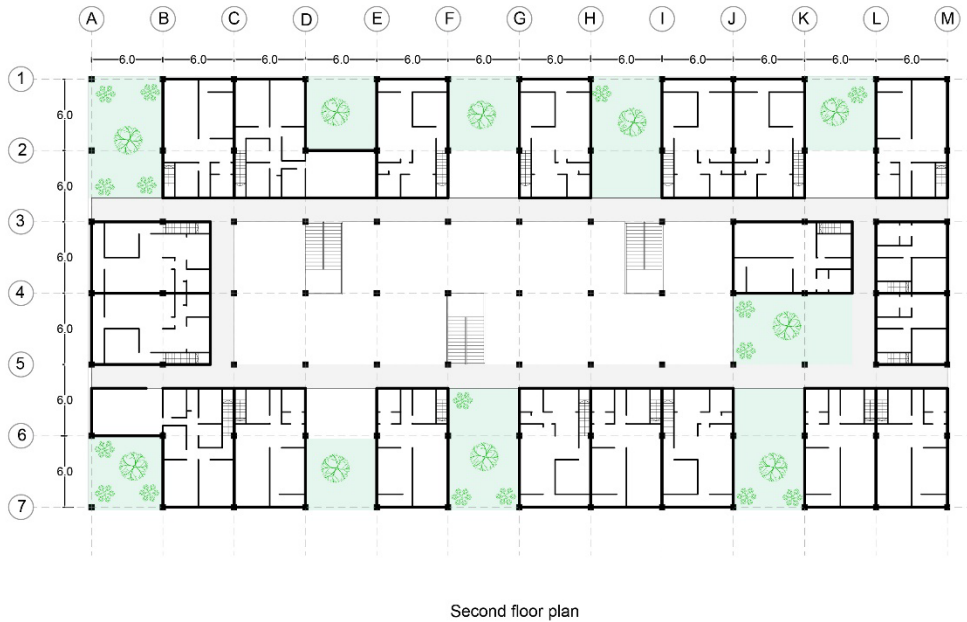


Figure 62: Second Floor Plan of the project proposal

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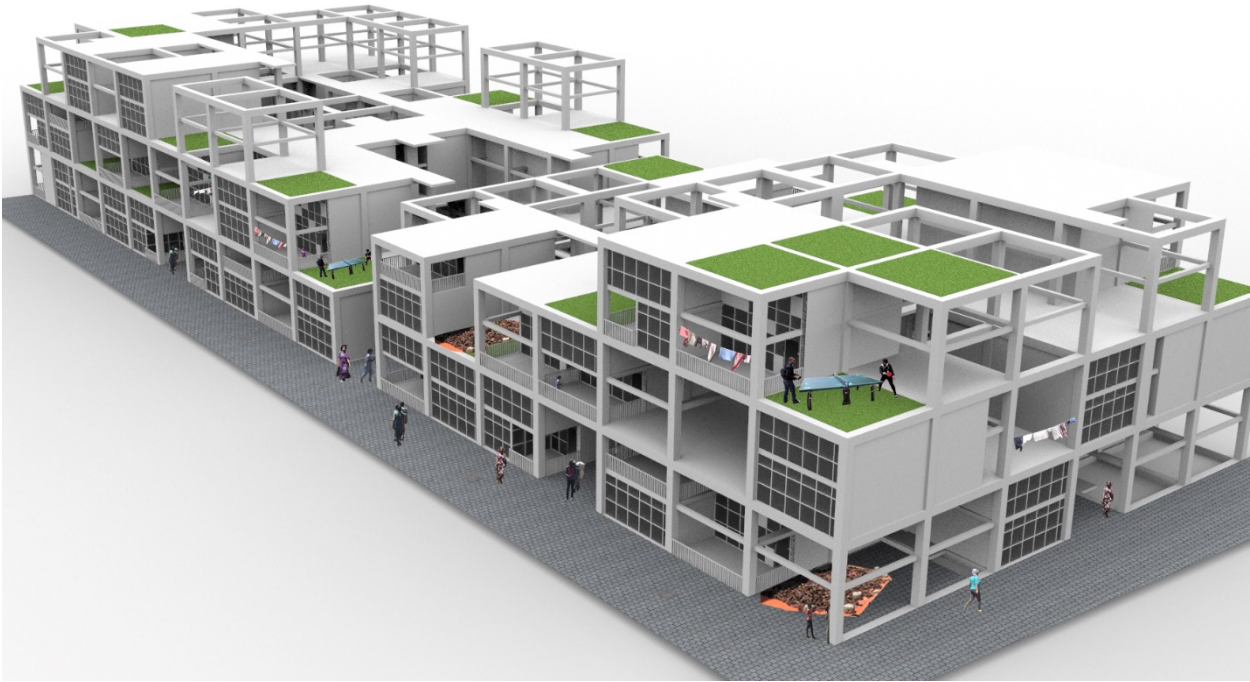


Figure 63: 3D visualization of the proposed urban block



Figure 64: Elevations

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Figure 65: Site plan of the project proposal



Figure 66: Birds eye view of the proposed urban blocks superimposed on the site

7.3 Implementation strategy

Based on the findings of this study and the contextual reference, the following implementation strategy is proposed for the case of Addis Ababa. The implementation strategy considers the three stakeholders; material supplier, Addis Ababa city administration, and residents. A central generative design system or platform that optimizes and mediates the three stakeholder's requirements is envisioned.

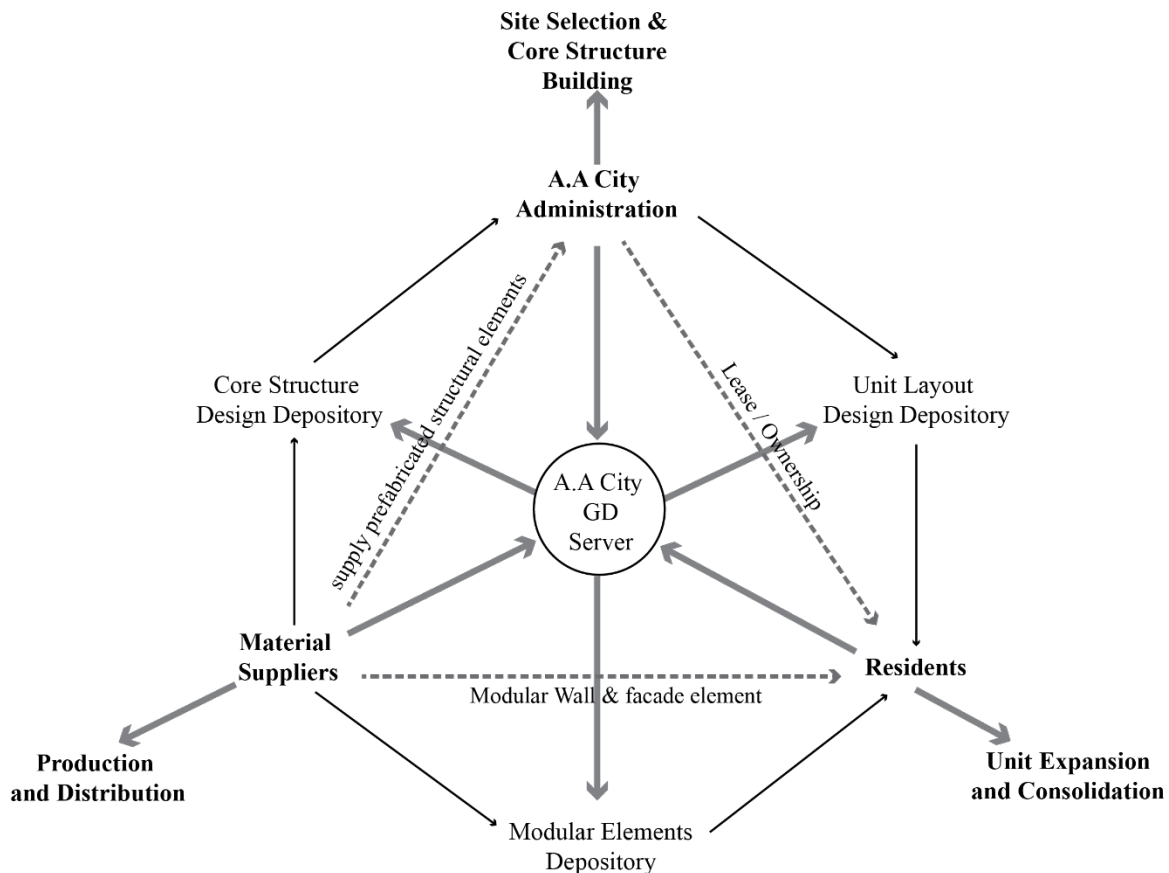


Figure 67: Proposed Strategy for Generative design and Mass Customization assisted Core Housing Strategy

Implementation strategy for City Administration: Because the city administration has jurisdiction to allocate sites and construct the core structure, it should take the central role in facilitating the overall process. A central GD system is envisaged to generate unit layout options, curates them, and stores them in the unit layout depository. Furthermore, the generative design system will search for the best option that fits the residents' requirements.

Implementation Strategy for Material Suppliers: This central system (server) collects data from the material suppliers regarding modular components. This data is used to inform users on the type of modular units they can use during their expansion, and it also collects data from users to inform the suppliers about the type of modular components needed to be produced.

Implementation strategy for Owners: A user interface can be developed to help the owner choose their housing unit and optimize their expansion based on interactive data. The user interface can be integrated with the government’s central server system to benefit from cloud computing. In this way, owners can be provided with up-to-date designs, cost information, and type of prefabricated modular components. At the back end, professionals can collect data from the users to optimize the process further.

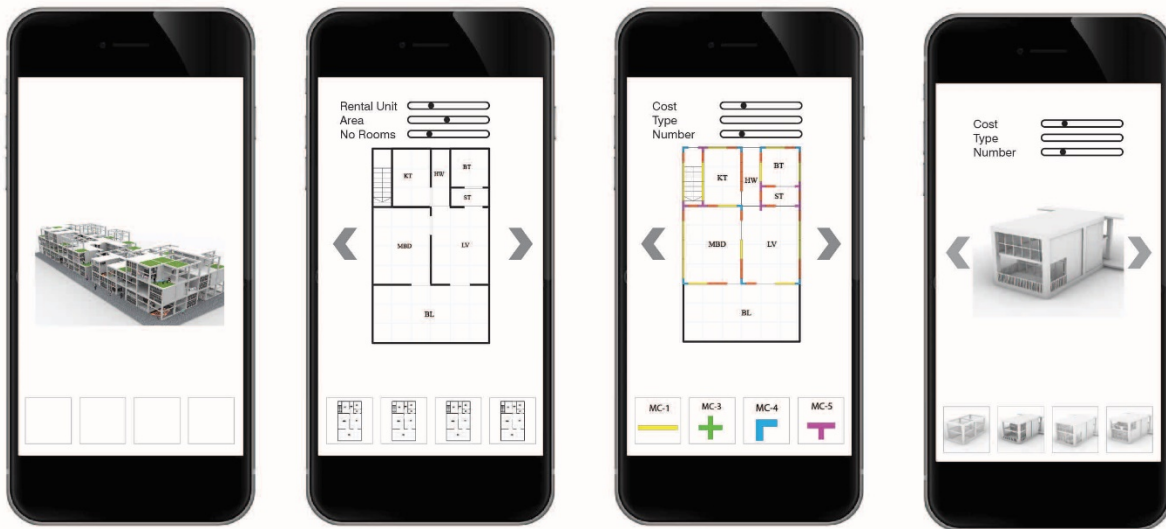


Figure 68: Conceptual illustration for User Interface

7.4 Summary

Digital tools have affected and changed many aspects of our life and have played a significant role in solving problems. They are the most accessible tools, and they are getting even cheaper and more efficient over time. Housing is one of the most enduring challenges of modern society, and leveraging the abundance of digital tools to make housing, as a process, more accessible and democratic is an exciting subject of exploration. This study has explored the potential use of GD as a tool to democratize design and enable self-help housing in current housing practice. In tandem with this, a construction delivery strategy that enables mass production speed of delivery and customizable to allow flexibility is investigated. GD and MC-assisted CH strategy can have a significant advantage for a city like Addis Ababa in many ways.

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CH is a process, and it flexibly adapts to different situations and requirements of various stakeholders. The adaptability of the CH works well for a fast-growing economy like Ethiopia. The proposed housing delivery strategy can last longer than any other mass housing strategy due to the flexibility and adaptability.

Housing projects and neighborhoods must grow and develop over time. There is no such thing as instant environment. What is good today is insufficient tomorrow. Many housing projects that were built in Europe in the fifties and were considered examples for other countries to follow are now obsolete. [...] Being built in concrete these projects are extremely expensive to be renovated or to be demolished. (Habraken, 1988)

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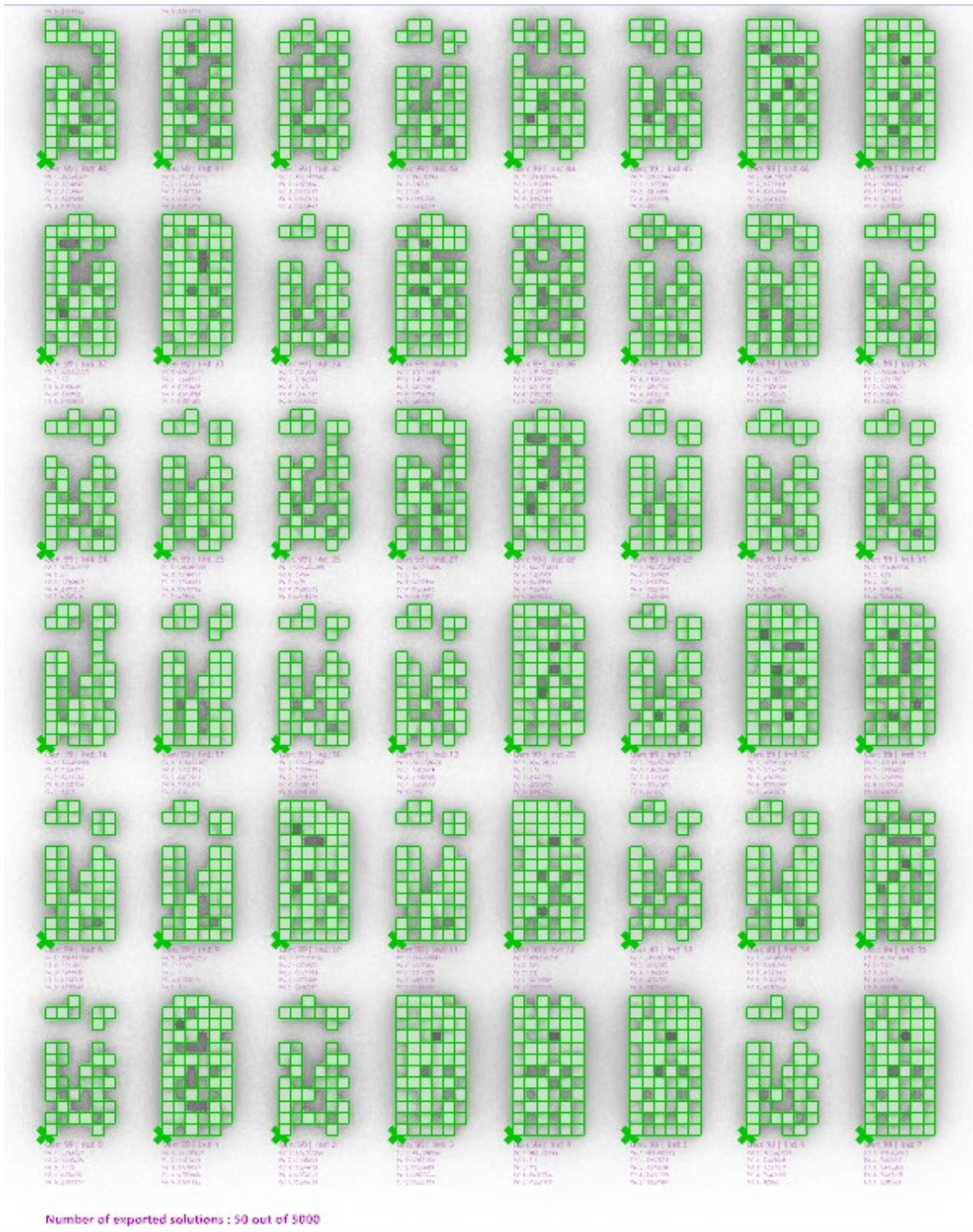
Appendix I

1. Photo collage from 'Sebategna' area.



Appendix II

1. Pareto front solutions Generated for core structure experiments.



2. Selected Solutions for Typology 3 Plan Layouts



Number of exported solutions : 31 out of 5000

3. Selected Solutions for Typology 7 Plan Layouts



Revisiting Core Housing Through Generative Design and Mass Customization

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Abstract: Core Housing (CH) is one of the self-help incremental housing strategies in which government provides an initial starter structure and then resident takeover to achieve full housing incrementally. However, the conventional CH strategy lacks density, standardization, and scalability. This study explores the potential use of Generative Design (GD) and Mass Customization (MC) to upgrade CH strategy. To achieve the study's objective, GD methodology, comprising three steps, is employed. The first step involves analyzing secondary data identifying and defining computable parameters of CH. In the second step, parametric models are developed based on a multistory vertical expansion CH typology using Grasshopper. Lastly, an evolutionary algorithm engine, 'Wallacei,' is used to generate, evaluate, and select design options. Furthermore, a case project is developed demonstrating the result of the experiment on a selected site in Addis Ababa. The results indicate the potential use of MC and GD to create a flexible CH strategy to accommodate owners' incremental participation and mass-producible for speed of delivery.

Key Words: Core Housing, Generative Design, Mass Customization, Incremental Housing, Self-help Housing, Genetic Algorithm

Introduction

Since the modern programmable computer development, professionals and academicians in design and architecture have been using computers in various ways. Even though the computational power and versatility have been exponentially growing, computers in architecture are primarily focused on drafting, visualization, and information modeling. Following the fast development of Artificial Intelligence (AI) in recent years, computation to advance the design process is gaining traction. Computer scientists, programmers, architects, and companies in the Architecture, Engineering, and Construction (AEC) industry are taping computer's immense potential to develop computational design tools and solve design problems. Generative design (GD) is considered to use computers beyond the 'traditional' drafting aid or visualization tool. "GD is the process of defining high-level goals and constraints

and using the power of computation to automatically explore a wide range of design space and identify the best design options." (Vilaggi, 2020)

Simultaneously, the first personal computer is being developed; some scholars like John Turner (1965) and Charles Abrams (1964) were proposing a self-help housing strategy as an alternative housing delivery option for third-world countries. Following the decolonization, the failure of the modern housing strategy adopted from the Colonies, and the subsequent proliferation of informal housing in the urban area of third-world countries have initiated the idea for a self-help housing strategy (Napier, Mark, 2002). Core housing (CH) is one of the self-help housing strategies in which the government provides a starter structure, and then the owner expands the unit incrementally to consolidate full housing. Many case studies indicate that self-help housing has made housing accessible to most low- and moderate-income families in third-world countries. Given the starter structure, owners displayed the enormous potential of housing themselves without government involvement or minimum government involvement.

Mass customization is a concept that combines two seemingly opposing theories of mass production and customization (Maria et al., 2019). It is a business strategy to manufacture a personalized design at the lower price of mass production and provide a customized solution. The emergence of GD and other computational tools has made MC palatable, especially in industrial and product manufacturing. These concepts are also experimented with and tested to alleviate the housing design delivery strategy.

Some studies and practical applications have explored the use of MC and GD to solve housing problems in the context of Addis Ababa. A computational design strategy is suggested to efficiently plan mass housing for Addis Ababa (Martin Bielik, 2013). In this study, a GD tool is proposed to effectively address the planning and designing capacity deficiency and rapid housing demand. The potential use of Building Information Modelling (BIM) integrated with mass customization is explored for 40/60 Integrated Housing Development Program (IHDP) condominiums in Addis Ababa (Shikur, 2016). Facade element prototypes are developed to demonstrate the result. Participatory and incremental housing, which uses fabricated construction elements produced by residents, is proposed, and tested in some parts of Addis Ababa (Dirk Donath, 2015). This project's scalability to meet the density requirement of Addis Ababa city is not effectively investigated. There is a lack of study, which explores the potential use of computational tools to enhance self-help CH strategies in conjunction with MC in the context of Addis Ababa.

Currently, the Addis Ababa city administration does not consider CH as a part of the current housing delivery option. The difficulty of scaling this strategy is one of the critical challenges of adopting CH as an alternative housing delivery option for Addis Ababa. It is challenging for the government to control construction and design quality without infringing the flexibility and control of owners in incremental housing. A new approach and strategy are required to scale up the CH strategy and effectively coordinate the owners' self-building potential with the government's effort to make housing accessible for the mass. Furthermore, CH is a suitable strategy to address this.

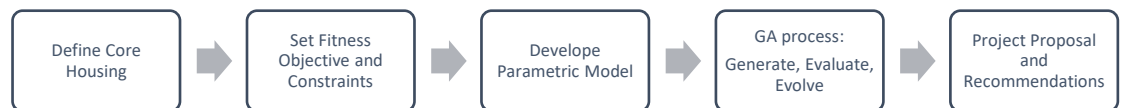
Ethiopia needs to deliver 73,000-151,000 formal housing units annually to meet the housing demand (UN-HABITAT, 2011). In the year 2012, the backlog of housing demand in Addis Ababa was 230,000 units, and it is estimated that annually the demand increases by 10,000 units (Gebremedhin, 2016). As result, Addis Ababa has the highest housing demand ratio, 361 per 1000 people, than other urban areas in Ethiopia (Housing in Ethiopia an Overview, 2017).

Bringing density to self-help housing is crucial to make it a feasible housing delivery option in Addis Abba. However, upgrading CH to accommodate the need for density brings an extra challenge in design, coordination, and delivery mechanism. One of the challenges come from coordinating resident's ability to incrementally expand their units while at the same time producing quality building structure or urban block. This contradiction between the need for flexibility, owner's control on the one hand, and the requirement for standardized quality and speed of delivery on the other is an exciting challenge that requires an innovative design and construction delivery strategy.

Method of Study

Two research methods are used in combination to achieve this study's objective and explore GD and MC's potential use to enhance CH. The first method employed a qualitative study of secondary data about CH using a framework analysis strategy. Then, the result of the qualitative study is used as groundwork to develop a GD methodology. Thus, the whole process mainly entails four stages. Furthermore, in the end, a conceptual architectural design project is developed to demonstrate the result.

Figure 1: Method of study.



Defining Core Housing

Several International literature and contextual reviews are studied, and three thematic frameworks are identified which define the key aspects of CH.

- Core housing as a process
- Stakeholders control distribution in the CH process
- Morphology of core housing

Core Housing as a Process

The process of CH is simplified into four key stages: Site selection and planning, Block/Plot arrangement, the building of starter structure, and expansion of the living units. Except for the unit expansion, all have defined starting and completion times. Site planning and block arrangement are common in typical mass housing strategies, but the development of starter structure and unit expansion are the two unique characteristics of CH. Hence, this study focuses on starter structure development and unit expansion stages of CH

Stakeholders Control Distribution

For this study, the stakeholders are simplified into three fundamental elementary groups. It is considered that the three stakeholders can representatively absorb the role of the remaining stakeholders. The minimization of the stakeholder number is adopted to economize the GD simulation. The importance of material suppliers is emphasized to link the relevance of MC in the process of CH. Studies indicate that (Dirk Donath, 2015) (Goethert, 2019) (Laura Sara Wainer, 2016) (Mota, 2019), material suppliers integral part of successful self-help incremental housing projects.

Typologies of Core Housing

Studies indicate that proactively designed CH dictates the nature of the starter structure and the process of incremental expansion. For this study, based on the type of starter structure and the consecutive expansion process, nine types of CH morphologies are identified. Furthermore, each type of morphology is then evaluated based on four criteria to determine the level of appropriateness in the context of Addis Ababa.

Figure 2: Selected CH Typology

Description	Starter/Core Structure	Expansion	Reference Cases
Multi Storey Vertical Expansion Multi Family			Mkales Project, Beirut, Lebanon (Source: Multi Story Incremental Housing at the World Urban Forum, Naples, 2012. P.30)
Evaluation			
1. Affordability			
2. Significance for Gov.			
3. Density			
4. Flexibility			

In this study, this typology is selected for the development of GD simulation for the following reasons:

- The expansion is made vertically within the unit, and the cumulative result incrementally creates density without changing the original structural framework.
- Compared to other multistory and multifamily core housing approaches, this gives better flexibility for expansion.
- Moreover, this typology is convenient to convert the upper floor for rental.

Based on the above-selected CH typology, two experiments are conducted to explore the potential use of GD and MC at the development of starter/core structure and unit expansion stages of CH.

Defining Constraints and Objectives for Core Structure

Constraints:

- Site boundary: the simulation for this site is developed to work on sites with orthogonal edges.
- Building Setback and allowable building height are dependent on the adjacent road width.

- Construction technology: A Modular construction system with reconfigurable structural elements is selected.
- Allowable structural grid: only a 6m by 6m structural grid is considered for this study.
- Floor to floor height: 5.4 m height which allows the owners to insert floor at 2.7m.
- Vertical circulation type for core structure: U-shaped stair with total width of 3m and 6m length, including the landings. Elevators are not included considering that it will be walkable housing.
- The cost of construction: the real-time cost of the structure is not calculated for this experiment, but the cost efficiency in relation to the building shape is considered below.

Objectives/Goals:

1. Maximize density: A given site density is governed by total gross floor area (GFA) divided by total site area (TSA).

Indicator: The commonly used indicator for density is Floor Area Ratio (FAR)

$$FAR = \frac{GFA}{TSA}$$

Goal: Government prefers to maximize the number of residents that settle in a specific area to justify the land, infrastructure, and starter structure cost.

2. Minimize Cost: For this study, cost efficiency at the conceptual level is calculated based on the building shape. Different types of indexes determine the relationship between building shape and cost (Stainislaw Belniak, 2013).

Indicator: Compared to others, the W/F index is found to be the most sensitive index for building shape (Stainislaw Belniak, 2013). Since the floor-to-floor height is fixed for this experiment, the shape-sensitive index is preferred against volume-sensitive indexes. The W/F index specifies the ratio between the wall surface area and floor surface area in which a smaller index's value indicates cost-efficient building shape. The following formula expresses the W/F index:

$$\frac{W}{F} = \frac{L - L_s}{L_s} * 100\%$$

L: Building perimeter calculated from the contour of the outer walls, L_s: Perimeter of the square of the same surface as the building being compared (Stainislaw Belniak, 2013). Square is the most cost-efficient shape.

Goal: Creating a cost-effective starter/core structure is the preferred goal of government. It also affects the affordability of the housing provision hence affects owners indirectly.

3. Maximize courtyard space: A courtyard will be generated for block size greater than the allowable space depth (12m from exterior surface assumed) from both sides.

Indicator: Total area in m² of the generated courtyard space.

Goal: maximize courtyard space to allow natural light and ventilation.

4. Minimize solar radiation received by the structure at certain hours of a day: Shape and orientation influence the amount of solar radiation a building receives at a specific duration.

A plugin called Ladybug is used to calculate the total amount of radiation that a building surface receives during the daytime from 12:00 pm up to 5:00 pm.

Indicator: Kilo-wat per hour (Kw/hr.) received by the external surface of the structure external envelop.

Goal: Create self-shading to minimize the amount of solar radiation that falls on the total massing by diversifying the structure height.

5. Connectivity of circulation on the second level: Avoid disconnected circulation routes.

6. Flexibility for unit expansion: Flexibility of the starter structure is essential for the residents during the expansion of the unit.

Indicator: The simple indicator for space flexibility is avoiding columns that will be created inside the starter unit space.

Goal: maximize the spatial flexibility by creating column-free space, which will be helpful for the owners during space configuration.

7. Mass customization of construction elements: This is the ability to create as minimum variants of structural elements as possible and at the same time be able to produce as many variety design options as possible using those elements.

Indicator: Total number of variants of construction components or prefabricated modular elements and potential for configuration.

Goal: minimized elements of construction components to increase the efficiency of the mass production.

Defining Constraints and Objectives Unit Expansion

Constraints of this stage are essentially related to spatial design problems and construction systems.

Constraints:

Constraints in spatial design problems can be divided into two; topological and geometrical. Topological constraints describe the relationship and adjacency between rooms. Geometric constraint describes the area, proportion, and orientation of the rooms. Based on this, the following topological and geometric constraints are developed for unit expansion of core housing.

Topological Constraints:

- The entrance to the building should be from the corridor.
- The location of the internal stair should be determined based on the owner's preference to rent the upper floor of their unit.
- If the upper room is going to be rented, then the stair should be located near the corridor for direct and separate tenants' access.
- If there will be no rent, then the stair can be placed in any part of the room.
- The kitchen and bathroom should be adjacent to the corridor for easy access to utility,
- The living room and main bedroom should be adjacent to the outside, at least on one edge.
- The hallway should be adjacent to all rooms.

Geometric Constraint

The geometric constraint is described below with the rooms' minimum and maximum size in the X and Y direction. The room areas and sizes are selected for the case of the experiment.

Table 1: Geometric Constraints for Unit Expansion

Tag	Room Name	Min-Max (X)	Min-Max (Y)	Rotation	Required Area (m ²)
HW	Hallway	[1m-1m]	[1m-10m]	0 (no rotation)	Not fixed
ST	Stair	[1m-1m]	[4m-4m]	0°, 90°, 180°, 270°	4
BT	Bathroom	[1m-2m]	[1m-4m]	0° or 90°	2
KT	Kitchen	[1m-2m]	[2m-4m]	0° or 90°	6
LV	Living Room	[3m-4m]	[2m-6m]	0° or 90°	12
MB	Master Bed Room	[2m-3m]	[2m-4m]	0° or 90°	9
B.1	Bed Room 1	[2m-3m]	[2m-4m]	0° or 90°	6
BL	Balcony/Expansion	[0m-6m]	[0m-6m]	0 (no rotation)	16-20 (not fixed)
			Total		59
			Total Space Available on first level.		60

Objectives/Goals for Unit Expansion Stage:

- The residents' goal, once their unit boundary is decided, can be categorized into two phases. The first phase is to minimize the initial cost and create livable space. The second phase is gradual expansion by adding room numbers, expanding room areas, rearranging rooms, and upgrading material types.
- For material suppliers, the modularization of the design elements is essential because it enhances mass production. A generative design can help residents to create a preferred design layout based on the mass-produced modular elements.

Based on the above methodology, the topological and geometric objectives are specified below:

1. Geometric Objectives: This objective determines the size, orientation, proportion, and location of a room.

Indicator 1: Ensuring rooms are not intersecting. The intersection area between the rooms must be minimized or avoided.

Indicator 2: A list of required areas for each room is prepared and is compared against the generated room areas result. The absolute area difference between the two is calculated, and the fitness objective is set to minimize the difference between the two lists to match the initial requirement.

2. Topological Objectives: This objective determines the adjacency between the rooms.

Indicator: minimize the distance between the rooms required to be in proximity and maximize the distance between the rooms required to be far apart.

3. Mass Customization Strategy: The plan layouts are constructed on a 1mx1m modular grid. The goal is to create a flexible plan layout that respects the modular layout. The modular layout is constructed from modular wall segments(components) combined in a different configuration to achieve the generated room layouts automatically.

Developing Parametric Model For Customized Core Structure

Based on the defined constraints, a parametric model is developed to generate a hypothetical core structure. For this experiment, the parametric model is developed to function on a

rectangular site with an average size of an urban block. The following steps are undertaken to develop the parametric model.

Input: Site Boundary polyline.

Step 1: Construct the setback. Based on the regulatory requirement, the site boundary is offset inward from each direction.

Step 2: Divide the site into modular rectangular sizes. A 6m-by-6m square size is used to divide the site in x and y-direction.

Step 3: Assign a height value that is controlled by a discrete value parameter. Based on the selected double floor morphology, the height value is a multiple of 5.4m. The height of each module multiplied by 0, 1, 2, and 3 values gave the result of 0m, 5.4m, 10.8m, and 16.2m. For this parametric model, a maximum height of 16.2m is considered to avoid lift requirements.

Step 4: Generate a courtyard. Modules located two blocks away from the exterior boundary are part of the courtyard.

Step 5: Generate floor plate: Contour the overall volume by 5.4m interval starting from 1.5m height. It gives the floor plate layout at each level and indicates GFA (Gross Floor Area) result.

Step 6: Locate the horizontal circulation (corridor) at each level. It is an offset from the exterior surface of the volume considering the maximum allowable depth of the living unit, which is 10m.

Step 7: Locate the vertical core (stair). Divide the horizontal circulation spine(corridor) into a certain number of points that indicate the stair location. It is controlled by a continuous positive rational number value, and it distributes a certain number of stairs along the corridor length.

Step 8: Calculate the Radiation amount that falls on the surface (top and side) of the mass.

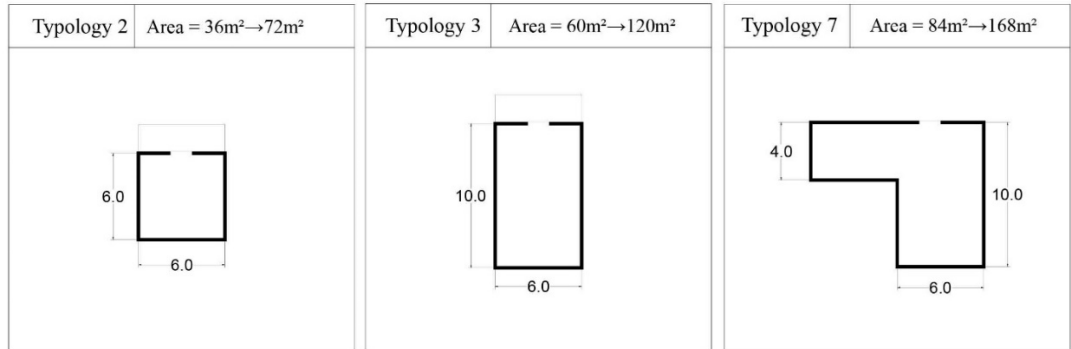
Step 9: Divide the floor plate generated at step 5 by a line, which delineates the corridor and unit spaces.

Step 10: Generate conceptual structural grid and beam layout and extrude according to the height of each module.

Developing Parametric Model for Unit Expansion

For this experiment, three typical starter unit typologies from the result of the first experiment are selected to develop the parametric model.

Figure 1: Selected Units for space layout generation



To illustrate the parametric process, typology 3 will be used, but the experiments are done for the three units, and the analysis and result are discussed in the next chapter.

Step 1: Define a fixed boundary of the unit at the first and second levels. The boundary will be the edge of the unit layout for the first level, but it will be the extent of the built area of the first level ceiling for the second level.

Step 2: Divide the region into Wet areas (kitchen and Bathroom) and living areas (where living, dining, bedrooms, and balcony)

Step 3: Define the initial starter space and future expansion area. In a real case, this can be negotiated between the provider of the starter structure and the owner, taking the initial cost and the associated premium payment into consideration. In this experiment, for levels 1 and 2, the expansion area is defined as a balcony. Therefore, during the initial stage, the balcony will be oversized, and it will get smaller as the unit expands.

Step 4: Define the access points from the corridor for the first level and second level. For the first level, the access should always be from the corridor, but for the second level, it varies depending on whether it is rented for additional revenue or fully utilized by the owner. In the first case, the - upper level rented – the stair is preferred to access the corridor directly. In the second case, the stair can be located anywhere in the room.

Step 5: Convert the geometric constraints into a parametric model using a domain size. The domain size in X and Y determines the minimum and maximum area of the room and proportion. The location of each room is measured from its centroid. The room size is developed based on 1m*1m modular grid. All rooms except the hallway and balcony can rotate 90 degrees during the optimization process to qualify the fitness objective. Only one type of stair with a single flight is used in this experiment, considering that it is simple for construction.

Step 6: Compare the area of the rooms that are generated using the X and Y parameters with the list of area requirements and find the absolute difference. This difference will later be used as a fitness objective. Before starting this process, it should be checked that the sum of the required area list should not be more than the total available amount of unit area at the first and second levels.

Step 7: Generating floor plan for the second level. Because the two levels are linked by stair and wet rooms, the location of these rooms will be like the first level. Therefore, if the owner

prefers to rent the second level for revenue generation, the space layout program will be like the first level. However, if the owner prefers to utilize both the levels, the kitchen does not need to be repeated on the second level; instead, more bedrooms will be added.

Results

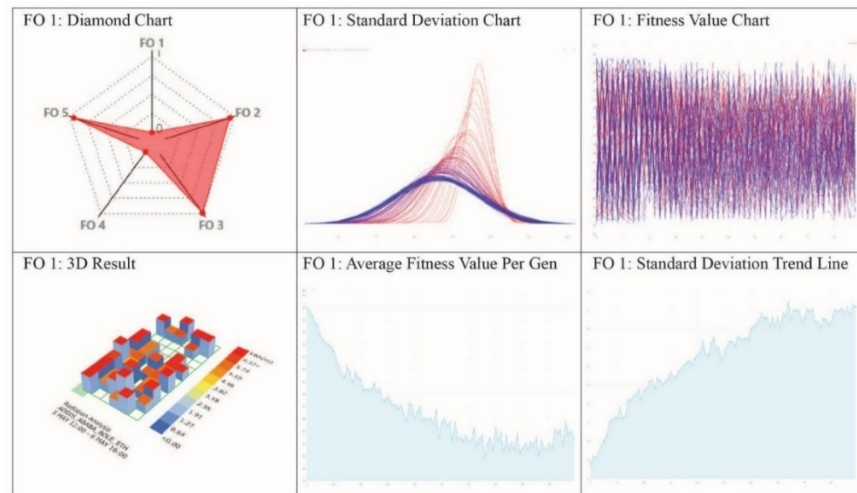
Results of Core Structure Experiment

The first experimental results are presented below by making comparisons for selected fitness objectives (FOs.) and extracted Pareto front solutions. The highest rank of each FO is extracted to demonstrate the capacity of the evolutionary solver in optimizing the objectives separately. The overall result of the highest rank of each FOs demonstrates the evolutionary solver capacity in selecting the best individual solutions for a given number of generations and population sizes. On the other hand, the Pareto front solutions are not as satisfactory and palatable as is expected. The possible reasons are the immense size of the solution space, the inability of the evolutionary solver to discriminate between the FOs, and the inefficiency of the coding.

FO1: Minimize Solar Radiation

The highest rank is generated in the 94th generation and at the 4th individual solution. The fitness value is 312.289216, and it is ranked at 0/4999. Besides, the standard deviation has indicated variance, and the graph has shifted to the left, which indicates that fitter solutions are generated in the process. The 3D solar radiation result shows that this value is achieved by varying the block height to create self-shading and eliminating some of the blocks to minimize surface areas that receive radiation.

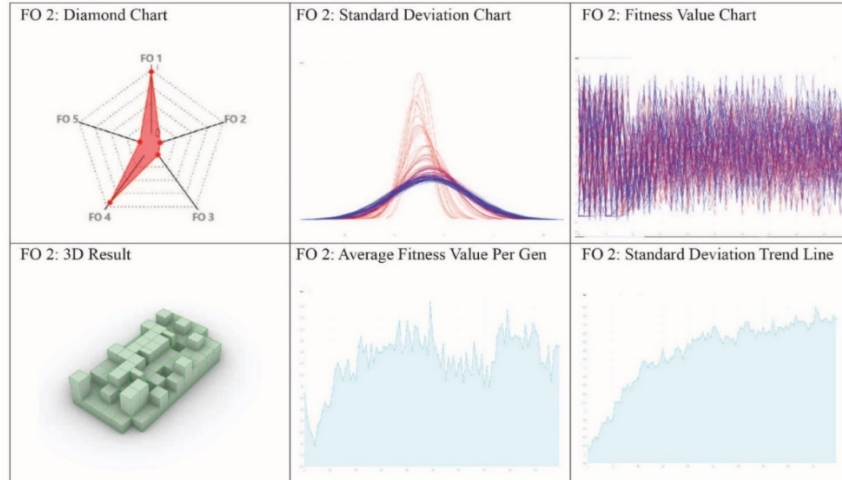
Figure 4: Result for FO1 (Radiation) optimizations



FO 2: Minimize the cost Index.

The highest rank is generated at 95 generations and four individual solutions. The fitness value is 0.931469, and it is ranked at 0/4999. The inverse value is 1.073. The standard deviation chart indicates variance, but the fitness values are not getting better. This is also reflected in the average fitness value per generation and the 3D.

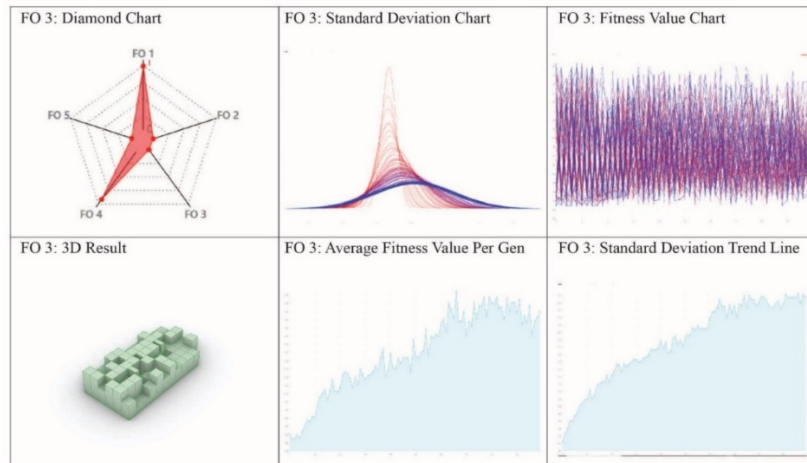
Figure 5: Result for FO2 (Cost Index) optimizations



FO 3: Maximize FAR

The highest rank is generated at the 75th generations and the 5th individual solutions. The fitness value is 0.473684, and it is ranked at 0/4999, which yields FAR: 2.11. The Standard deviation chart and average fitness values indicate that the values have variance, but they are not fittest.

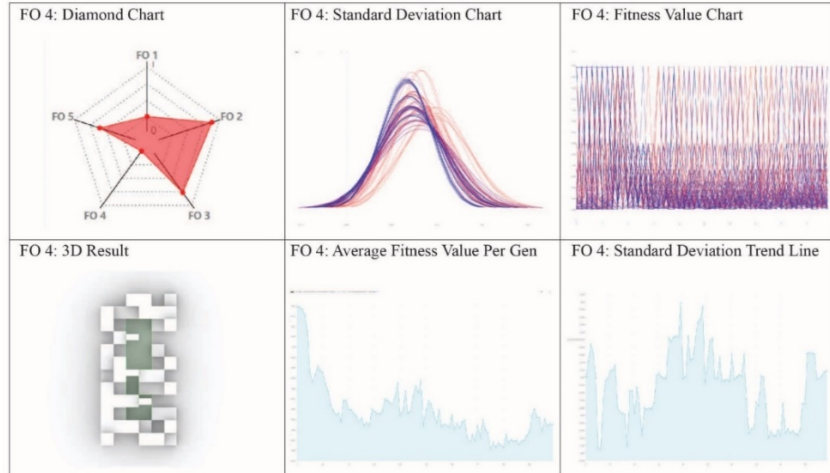
Figure 6: Result for FO3 (Maximizing FAR) optimizations



FO 4: Maximize Courtyard Space

Highest rank is generated at 83 generation and the 7th individual solution. The standard deviation chart indicates that there is convergence, but the values are getting fitter. The average fitness value and the 3D confirm this.

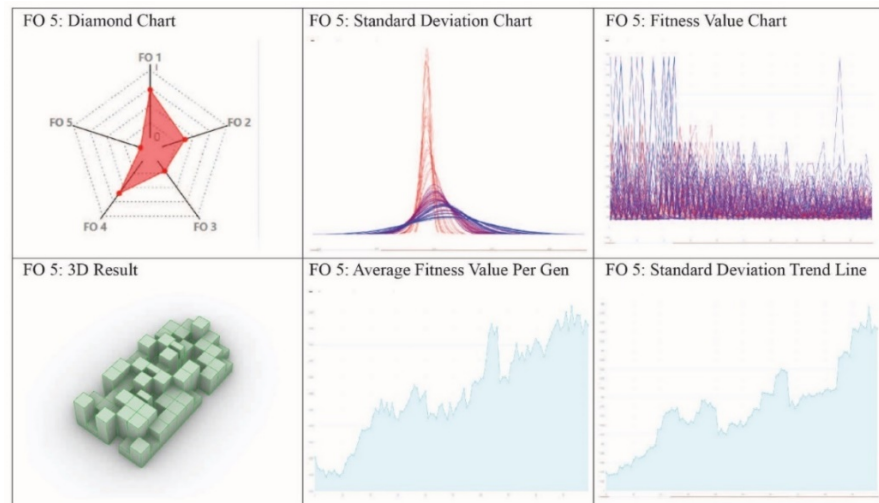
Figure 7: Result for FO4 (Maximizing Courtyard Space)



FO 5: Maximize Circulation Connectivity.

The highest rank is generated at the 7th generation and the 3rd individual solution. The maximum fitness value is 0.007353, and it is ranked at 0/4999. It indicates that the initial random position of the model has created a fitter solution.

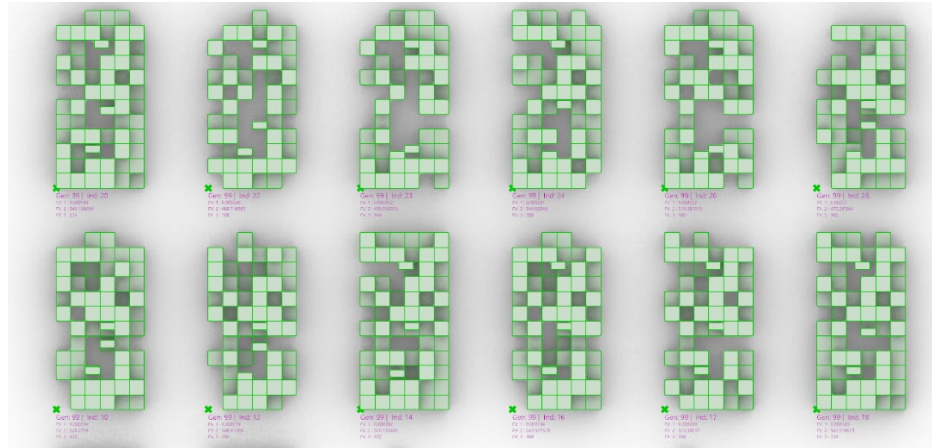
Figure 8: Result for FO5 (Maximizing Circulation Connectivity at 2nd level) optimizations



Pareto Front Solutions

The Pareto Front solution indicates the compromise between the other five fitness values to achieve the best individual solutions that satisfy all the FOs. The pre-conceived solutions for the design problems and the GD generate solutions are found to be different. For example, in the first experiment, the pre-conceived massing of the core structure is a courtyard in the middle and the floor massing in the periphery. The GD produced design solutions that distribute the courtyards (open spaces) differently. It can be considered as the advantage of generative design in producing unpredictable results.

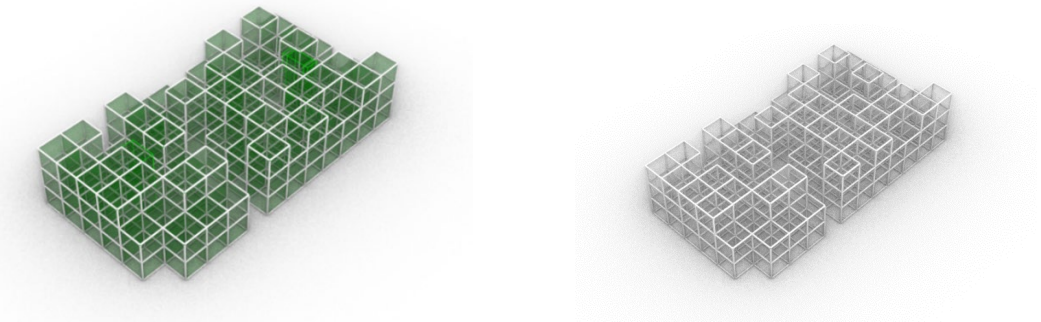
Figure 9: Top view of Pareto Front Solutions with 3 FO in consideration



Mass Customization for Core Structure.

The parametric model is developed based on the modular volume of 6mx6m and height of 5.4m, making it possible to be produced out of mass-customized and mass-produced modular structural components. In addition, the parametric model can automatically generate a schematic layout of the structural elements (beams, columns, and slabs) for quick visualization. Moreover, the number of modular components can be easily accounted for, which will help optimize elemental cost at the early conceptual stage of the design.

Figure 10: Modular Structural Elements of the Core Structure



3.2 Result for Unit Expansion Experiment

Room layout optimization is conducted for the three selected unit typologies based on the topological and geometric constraints developed according to the methodology described in the previous section.

Table 2: Fitness Value and Phenotype Comparison between randomly selected generation and individual solutions.

Unit Typology - 3





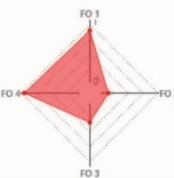
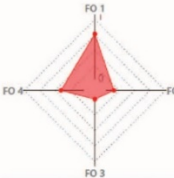
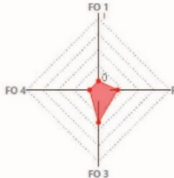

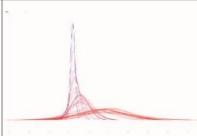
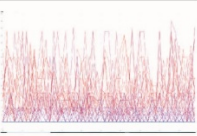


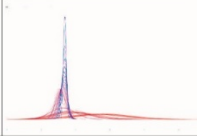
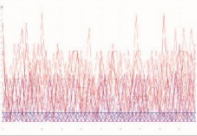


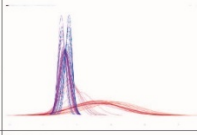
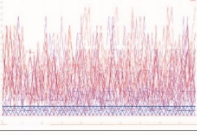
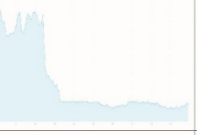
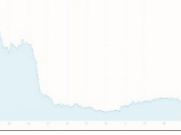
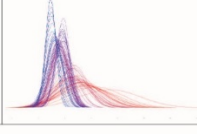
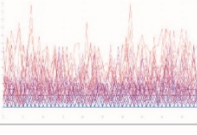
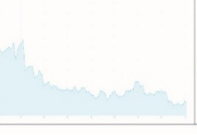
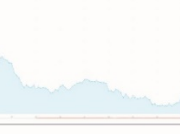
Solution: Gen. 12/Ind. 32	Solution: Gen. 32/Ind. 46	Solution: Gen. 80/Ind. 46	Solution: Gen. 96/Ind. 46
 Floor Plan	 Floor Plan	 Floor Plan	 Floor Plan
 Diamond Chart	 Diamond Chart	 Diamond Chart	 Diamond Chart
FO1: Minimize Starter Unit Geometric Constraint Fitness Value: 7 Fitness Rank: 4510/4999 FO2: Minimize 1st Floor Geometric Constraints Fitness Value: 3 Fitness Rank: 828/4999 FO3: Minimize 2ndFloor Geometric Constraints Fitness Value: 1.5 Fitness Rank: 1731/4999 FO4: Minimize Expansion Area Geometric Constraints Fitness Value: 10.5 Fitness Rank: 4785/4999	FO1: Minimize Starter Unit Geometric Constraint Fitness Value: 2 Fitness Rank: 3835/4999 FO2: Minimize 1st Floor Geometric Constraints Fitness Value: 3 Fitness Rank: 828/4999 FO3: Minimize 2ndFloor Geometric Constraints Fitness Value: 0 Fitness Rank: 0/4999 FO4: Minimize Expansion Area Geometric Constraints Fitness Value: 3 Fitness Rank: 2035/4999	FO1: Minimize Starter Unit Geometric Constraint Fitness Value: 0 Fitness Rank: 0/4999 FO2: Minimize 1st Floor Geometric Constraints Fitness Value: 3 Fitness Rank: 828/4999 FO3: Minimize 2ndFloor Geometric Constraints Fitness Value: 3 Fitness Rank: 1886/4999 FO4: Minimize Expansion Area Geometric Constraints Fitness Value: 0 Fitness Rank: 0/4999	FO1: Minimize Starter Unit Geometric Constraint Fitness Value: 0 Fitness Rank: 0/4999 FO2: Minimize 1st Floor Geometric Constraints Fitness Value: 3 Fitness Rank: 828/4999 FO3: Minimize 2ndFloor Geometric Constraints Fitness Value: 3 Fitness Rank: 1886/4999 FO4: Minimize Expansion Area Geometric Constraints Fitness Value: 0 Fitness Rank: 4785/4999

Table 3: Fitness objectives and the associated analytic chart for space layout.

	Standard Deviation Chart	Fitness Value Chart	Standard Deviation Trens Line	Average Fitness Value Per Generation
FO1: Minimize Starter Unit Geometric Constraint				
FO2: Minimize 1st Floor Geometric Constraints				
FO3: Minimize 2ndFloor Geometric Constraints				
FO4: Minimize Expansion Area Geometric Constraints				

The standard deviation chart indicates convergence at the younger generation, but the shift to the left indicated that the solutions fitter. Besides the standard deviation trend line and average fitness value graph line. In the case of FO1(Minimizing the starter unit geometric constraint or

the intersection between the rooms), the solutions stagnate at the early stage. The experiments have revealed that the limitation of a genetic algorithm in tackling space layout design problems to a certain extent. It should be noted that only visual programming language is used in these experiments, and certain limitations come with it.

Mass Customization strategy for Unit Expansion

In this experiment, 1m by 1m modular coordination is used to construct the parametric model and integrate the MC strategy. The parametric model is devised to work within this grid layout to enable mass coordination. Without getting into the technical details of material and construction, five types of modular wall components are proposed, which can be mass-produced and easily configured to construct any orthogonal type - constructed on 1mx1m grid - space layouts.

Due to time limitations, a parametric and GD system is not specifically developed to optimize the space layouts into modular wall components. However, the concept is demonstrated manually to showcase how a particular orthogonal space layout from the previous experiments can be constructed out of the five identified wall segments. Future works can incorporate a parametric model that can convert a wall segment into modular components and a GD system that can select the type and number of modular components to optimize cost.

Figure 11: Five Modular Components that can be configured to create any type of orthogonal room layout.

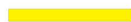




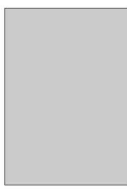

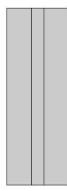




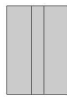

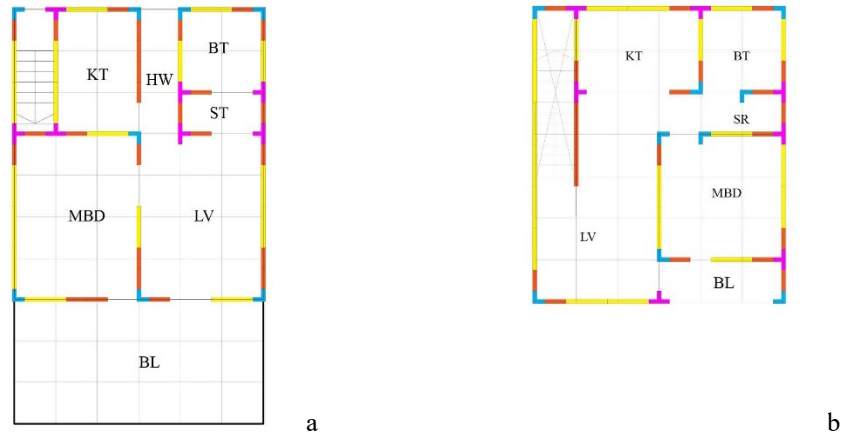
	MC-1	MC-2	MC-3	MC-4	MC-5
PLAN					
ELEVATION	MC-1a 	MC-2a 	MC-3a 	MC-4a 	MC-5a 
	MC-1b 	MC-2b 	MC-3b 	MC-4c 	MC-5d 

Figure 12: Converting space layout into modular wall components. a: First level b: Second level



From a practical implementation point of view, the size of the modular components is envisioned to be moved and assembled easily by the owner's capacity. The size of modular components strongly affects the accessibility, transportation cost, constructability, and flexibility of the system. Therefore, it is crucial to consider the owner's self-building capacity when designing the mass customization strategy for core housing.

Project Proposal

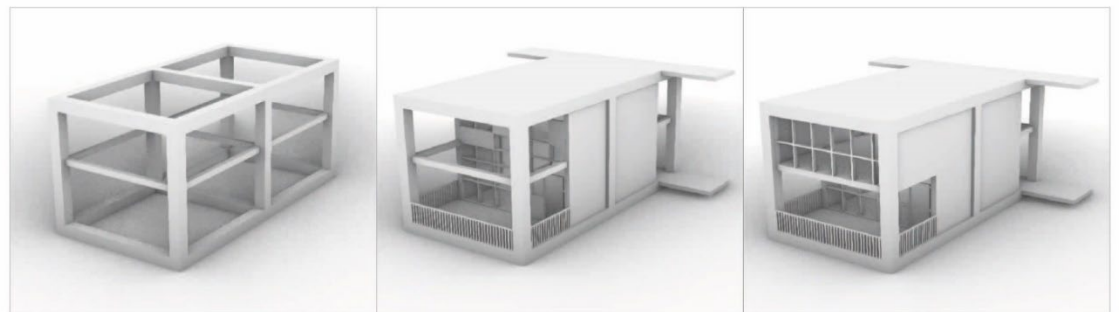
Based on the findings of this study, a sample project is proposed on a selected site within the city center of Addis Ababa.

Figure 13: 3D visualization of a typical urban block of GD and MC assisted CH design.



Figure 12: 3D visualization of the project proposals..

Figure 13: 3D visualization of a typical unit expansion.



Prefabricated structural grid that enables for incremental expansion.

The Starter unit occupied by the owner with minimum liveable area at the first level.

Option to build the upper floor first and rent it to generate additional income.

1. Discussion

The two experiments on core structure and unit expansion have demonstrated the potential use of GD and MC in CH strategy. The first experiment has demonstrated that GD can efficiently generate customized core structures from elements that can be mass-produced, reconfigured, and optimized based on different fitness objectives. The second experiment on unit layout generation has revealed limitations in solving topological constraints.

Findings from literature and contextual review point out that core housing has distinct qualities which distinguish it from other housing delivery methods. The experiments conducted in this study show that the following vital parameters can be enhanced using GD and MC at the core structure and unit expansion stages of CH.

1. Core structure development stage: GD can be used as a design optimization tool to efficiently generate core structure designs at a conceptual level and evaluate them through different fitness objectives. Moreover, modular coordination can be integrated into the GD system parametrically, enabling seamless coordination between the iterative design process and MC.
2. Unit Expansion Stage: The second experiment has indicated the potential use of the GD in producing space layouts by optimizing geometric constraints. Even though the possibility of owners using the GD tools to be able to design space layouts independently is limited, the findings indicate potential alternative strategies and ways forward. Moreover, the suggested MC strategies will enable owners to construct their space layouts out of a limited number of mass-producible modular components.

The relationship matrix and control distribution of stakeholders and interest groups in the CH indicates three major stakeholders' main interests and control in the core housing process. The study results indicate that GD and MC can optimize the goals and objectives of the three stakeholders in the following ways.

1. For government: The experiment conducted indicates that generative design can be used as an efficient designing and planning tool which enables informed decisions based on the iterative design process and measurable objectives.
2. For owners: The second experiment indicates that generative design can be used to generate space layout options using modular grids and mass-producible wall components.
3. For material suppliers: The first and second experiment results indicate that modular coordination can be integrated through a parametric model that enables owners and the government to create various design options using fewer modular components. This integration of modular coordination in the design process creates a chance for material suppliers to enact mass production of a modular component, increasing efficiency and reducing cost.

The findings from the literature review and contextual study and result of the experiments corroborate that GD and MC enhanced core housing can be an alternative housing delivery option for Addis Ababa for the following reasons:

1. Enhances the government housing delivery capacity: GD and MC assisted CH strategy can enhance government housing delivery capacity by reducing the financial and time burden of producing full housing.

2. It helps to achieve density in CH: Multistory starter unit with an inserted floor expansion can help achieve density in a manageable way. The upper floor can be used as a rental unit, which can generate additional income for the owners and absorb a particular housing demand in the city. This CH typology creates better urban aesthetics because the individual unit expansion is framed and guided with the core structure; therefore, it can be integrated into a dense part of the city.
3. Helps to create customized mass housing instead of mass-produced housing: GD can be used to create variety and diversity in the housing delivery option. By allowing owners to participate in the housing process, diverse and evolving housings can be created.
4. Affordable housing option: CH reduces the government's financial investment, which, in turn, reduces the housing price. Through MC, the cost of housing production can be lowered without compromising the quality and diversity. As indicated in the first experiment, GD can be used, at a conceptual level, to optimize cost during the design of the core structure.
5. Enhanced quality of design and construction for CH: GD combined with MC can enhance the quality of design through measurable fitness objectives without compromising flexibility. Furthermore, because the design and construction methods are seamlessly integrated, the efficiency and quality of delivery can be enhanced.

2. Conclusions

In this study, one of the old self-help incremental housing strategies, CH, is revisited through GD and MC to propose an alternative housing delivery option for Addis Ababa. After studying CH through literature review, secondary data, and contextual analysis, critical parameters of the process, stakeholders' interests, and morphology of core housing are identified. Out of five stages of the CH process, two of the stages, core structure, and unit expansion, are selected to be rethought through GD and MC. The parametric model is developed based on a specific type of multistory and multifamily core housing typology and modular coordination strategy. A multi-objective optimization (MOO) evolutionary algorithm is used to optimize various objectives and goals of selected stakeholders and interest groups in CH.

The result of the experiment indicates that GD can efficiently generate mass-producible core structures that can be customized to different sizes of rectangular sites and optimized for different fitness criteria. On the other hand, with certain limitations, GD can also be used to generate space layouts based on the pre-set modular grid and few modular wall segments. It is indicated in the experiment that by configuring five modular wall segments, any type of orthogonal space layout can be generated.

This study indicates that the owner's self-help building capacity can be enhanced by parametrically combining modular coordination into the GD system. In addition, the quality of construction can be enhanced using mass customized modular components without compromising the owner's control and flexibility to expand their unit. It strikes the right balance between controlled outcomes and customized individuality. It is the right tradeoff between the government's need to control quality and owners' need for flexibility.

Owners have shown incredible self-building capacity, which is testified through a fast proliferation of informal settlements in urban areas and the indigenous self-building tradition

in rural areas. It should also be noted that the participation of owners in the housing process creates responsibility and social cohesion.

Studies and the current practice have revealed the inadequacy of government capacity to provide full housing. Likewise, most Addis Ababa residents cannot afford the current housing provision. Moreover, the housing demand increases and the gap between supply and demand grows more expansive year after year. Therefore, a solution that considers housing as a process rather than a product and coordinates the owners' and governments' potential is essential. As it is demonstrated in this study, GD and MC can create an effective platform that can entertain this process and coordinates the capacity of government, owners, and material suppliers.

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