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Mass-customisation of dwellings in the Middle East:developing a design-to-fabrication framework to resolve the housing crisis in Saudi Arabia

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The Saudi government is taking the initiative to modernise the country and address critical challenges. One of its primary goals is to relieve the housing deficit. One of the challenges in supplying the houses is that potential inhabitants have denied and refused to accept them due to their design failing to meet their demands. Furthermore, the government suffers from providing high-quality housing in line with people's needs because only a few enterprises can meet the client's needs, but only at the price of lengthy planning and building times, in addition to increased construction expenses. This research aims to propose a mass customisation design-to-fabrication workflow, which targets environmental optimisation, reduction of construction time and reduced cost and incorporates client involvement. Our research method includes conducting a survey with Saudi Arabian architecture firms to collect data about contemporary clients' needs, analysing and reviewing mass-customisation tools & techniques, developing a bespoke algorithm capable of mass-customising housing and evaluating the algorithm through design experiments. Our findings present the advantages and challenges of our tool as well as a shape grammar of mass customised floor plan solutions.

Keywords: *Mass Customisation, Parametric Design, Housing Design.*

INTRODUCTION

The study proposes a design framework that generates housing solutions based on the specifications provided by various user categories and their requirements. Architects should consider future user needs when designing a space to give flexibility, according to Schneider and Till (2005). The design framework is distinguished by a flexible system potentially generating infinite spatial variations through a multi-parametric layout depending on the parameters established by examining the client's needs. These factors are defined in accordance with the findings from the observations and interviews conducted during the field study and serve as the primary criteria that distinguish the solutions by the unique requirements of users. During the interview, it was disclosed that the prevalent causes of people's aversion to government housing projects are attributed to inadequate architectural planning, substandard building quality, and the lack of customer engagement in the design phase.

Field research data are used as input for the design model, while design model outputs are used as inputs for the user interface. Through the use of a multi-parameter layout design, a hierarchical order between all of the acquired data is established, and various fitness functions are developed to produce spatial variations. The spatial variants include several interior models corresponding to various activity sets about the fundamental activities in housing buildings. The users are then shown these modifications via a digital interface. Later, the interface will be set up within a website so that users can see the spatial variations based on their responses via the online platform. The design framework serves primarily as a tool for mass customisation.

The methodology of the paper combines two CAD tools, Revit and Rhinoceros, by utilising the plug-in 'Rhino.Inside' which allows parametric design in the Revit environment. In particular, the design process is split into three sections to manipulate and simplify the design workflow in the most effortless manner (Figure 1).

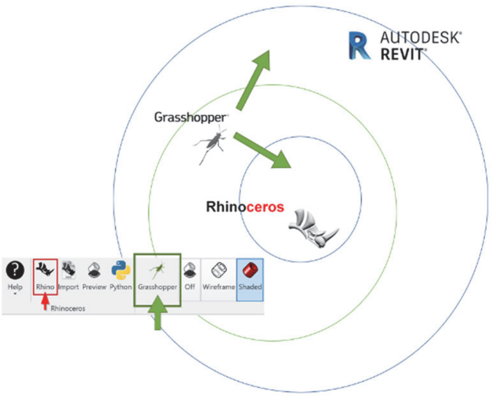

Figure 1
The interface of Rhino.Inside. combines Rhinoceros/Grasshopper with Revit

HOUSING PLANNING PROCESS AND BACKGROUND IN SAUDI ARABIA

Housing planning in Saudi architecture offices is known for its durability. The process revolves around the availability of the office, requiring clients to schedule meetings accordingly. These meetings may be subject to rescheduling or cancellation. Once scheduled, clients meet with an architect, typically taking one to two hours, during this session, the architect gathers the client's information and subsequently, the architect analyzes the data and creates a preliminary scheme. Another meeting is then required to review and discuss this scheme, necessitating the arrangement of a client appointment in the office. Once the client agrees, the actual design process commences. In the event of data-collecting errors during client meetings, the architect must redo the preliminary design. However, our method can expedite this process by over 50%, eliminating delays and rescheduling. Furthermore, data collection remains accurate as no human intervention is necessary.

The social housing system in Saudi Arabia relies on governmental financial support. Essentially, individuals are required to apply for a program known as Sakani. To be eligible, citizens must provide specific documents that serve as housing support requirements, including a family ID card and an employment statement letter from their employer.

Generally, the financial support terms of the Sakani program have undergone several changes. Prior to 2022, the government provided a financial support amount of 500,000 SR, which was equivalent to 133,333 USD. However, the government revised the financial support terms this year, linking them to the beneficiary's total income. This program is intended to assist low to moderate-income citizens, with the maximum financial support amount set at 324,000 SR and the minimum at 100,000 SR. Beneficiaries receive this financial support as monthly payments for a duration of up to twenty years.

To apply for the program, individuals must complete an electronic real estate financing form on a government website. Subsequently, they will have access to various projects on the website, allowing them to choose a specific housing unit. Once a unit is selected, it will be marked as a reserved slot. Later, beneficiaries are required to visit a local bank, where the loan amount they are eligible for will be determined. Based on this loan, beneficiaries will receive support through the governmental financial support program.

Dwellings in Saudi Arabia have undergone changes over time in response to shifting societal demands, advancements in construction technology, and the availability of resources. Bricks consisting of mud-dried hay and water that were cooked in the sun previously were used to construct Saudi Arabian buildings (Al-Hathloul, 2003). Besides, Saudi Arabian lifestyle modifications have also had an influence on the typical house layout plan (Bahammam, 1998). Over time, Saudi Arabian buildings have progressed through three stages of building construction: traditional, transitional, and contemporary (Bahammam, 2018).

Saudi Arabia's dwelling deficit is the result of a continuous population increase. Construction delays and labour shortages are two further factors contributing to housing scarcity (Alhajri and Alshibani, 2018). Furthermore, the bulk of the market continues to use traditional building techniques based on reinforced concrete buildings, making house development inefficient and time-consuming. Nonetheless, none of the housing associations has used client engagement. Finally, the Saudi housing ministry aspires to launch an initiative to support innovative building technologies and has committed to agreements as part of its commitment to the national transformation plan 2030, which aims to boost citizen homeownership from 24% to 52% by 2030 (Overview, 2022). Likewise, the Saudi government is taking the initiative to modernise the country and address critical challenges (Overview, 2022). One of its primary goals is to relieve the housing deficit (Alharbi, 2020).

Mass customisation could be utilised to address these problems, aiming for housing options that are inexpensive, sustainable, context-sensitive, and user-friendly (Garip et al, 2021).

Current architects and designers are needed an asset to acquire an understanding of courtyard design as a modern principle and sustainable aspect. As a consequence, this study aims to develop a digital tool capable of generating courtyard buildings and exhibiting their design rules. To generate a parametric modelling tool with educational procedures by scripting, we planned to develop a mass customisation model building interpreted for Grasshopper that could generate design models parametrically. To achieve this goal, the following questions are addressed.

- How can we develop a mass customisation workflow which incorporates environmental optimisation and client involvement in the design phase?
- How effective is such a digitalised workflow in comparison to the current, conventional one?

To answer these questions, we develop an algorithm consisting of three phases: 1) data collection and parametric floor plan design, 2) development of architectural elements and 3) detailing and simulation. We then test and verify the algorithm by generating a set of house designs based on the data collected from our survey, thus we can reach our conclusions.

BACKGROUND AND LITERATURE

We have investigated numerous related research projects to understand the most updated mass customisation methods and techniques (Abdulmajeed et al, 2022). According to Levy and Ellis (2006), there are three steps of the process needed to conduct mass customisation that is input, process, and output. Ma and Ameijde (2022) provided details on the requirements for an adaptive modular building system and a multi- objective optimisation procedure for high-rise buildings. In order to avoid workflow conflicts, they promote the integration of spatial and structural systems with suggests full customisation by the client. They created various dwelling configurations based on various lifestyle preferences using the Rhino/Grasshopper plugin Wallacei. Makki and Showkatbakhsh (2018) used Wallacei to perform simulations using various comprehensive selection techniques, including algorithmic clustering, to

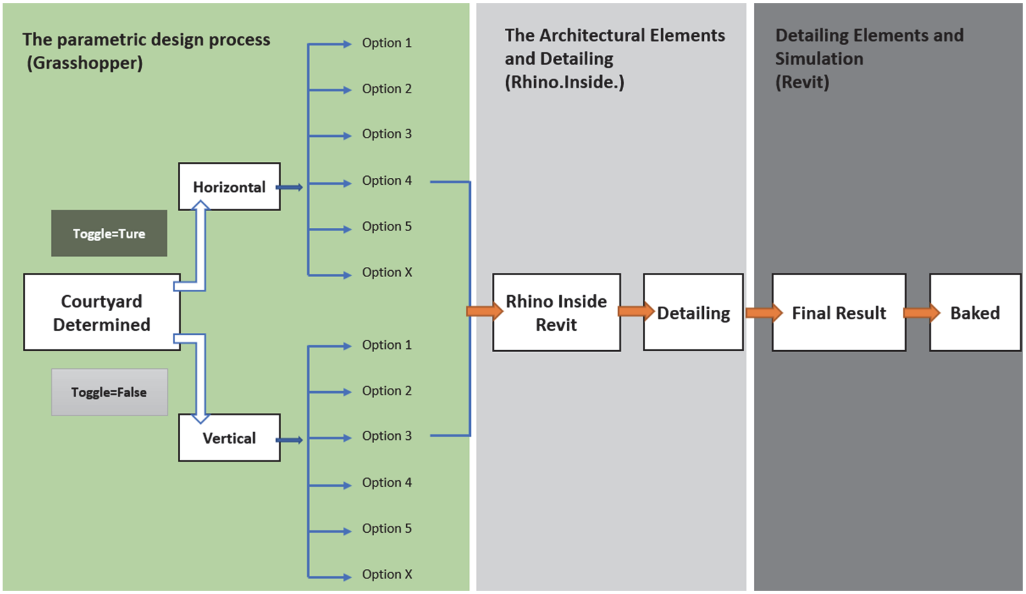

Figure 2
Flowchart of three phases in design

assist users in understanding better and making informed decisions during the evolution process. It means defining the design problem, running the evolutionary algorithm, evaluating the outcomes, and selecting the necessary solutions for the result. After a simulation, users can choose, reconstruct, and output any form from the sample. Mass customisation has many methods to be applied; one of them is client involvement and the degree of flexibility approach. As part of the prefabrication parametric design, Bakhshi et al., 2022 proposed choosing options from a set of choices for the client and involving them in the design using BIM software. Marchesi et al (2017) proposed mass customisation of prefabricated panel housing, focusing on robustness and flexibility. The study method used Axiomatic Design (AD) to determine the capability to explore ideas to find concerns for producing efficiently customisable explanations. The most regarding points are the reduction of building cost and construction duration. Kolarevic and Duarte (2019) reported that one of the essential points of MC is the neglected social aspect, emphasising the absence of cultural characteristics considered in MC. Their MC method allows parametric design and digital fabrication of a table by using an interactive website which allows buyers to select their own desirable personal designs. They proposed the use of local materials to decrease construction prices. Leaning on the MC processes utilised, structure, enclosure, and partition components may be produced to varying degrees of automation utilising digital fabrication and robotic assembly.

MATERIALS AND METHODS

We develop a design framework for mass customisation and test its effectiveness in generating various types of housing layouts. the design workflow includes three phases: 1) Parametric floor plan design, 2) Development of architectural elements, and 3) Detailing elements, and simulation (Figure 2). Furthermore, our proposed algorithm can be operated in three steps

1) determining initial parameters, 2) computing, and 3) and generating 2D-3D models (Figure 3).

Phase 1: Parametric floor plan design

In phase one, the floor plan can e generated in accordance with the client's needs. The client's involvement takes place in the early design phase to accelerate the design procedure in the mass customisation plan layout. In this step, users will be given editable initial input parameters such as plot size, building area, number of rooms and size, and courtyard area.

Phase one's computational process takes place within the Grasshopper interface. To expedite the process, we utilise a principal element with three-digit secondary components to regulate and adjust room sizes within the confined length and width parameters, ultimately reducing processing time during this stage.

The algorithmic process starts with the plot size, the building area, the courtyard space, and each room's size. Then the input result shows a plan within multiple layout options that will satisfy the clients, allowing them to choose from the different options and make modifications if needed. After clients choose their desired plan, they can submit a desired design through a cell phone application or website. Finally, the designer will provide the simulation and visualisation for the last phases of the design process.

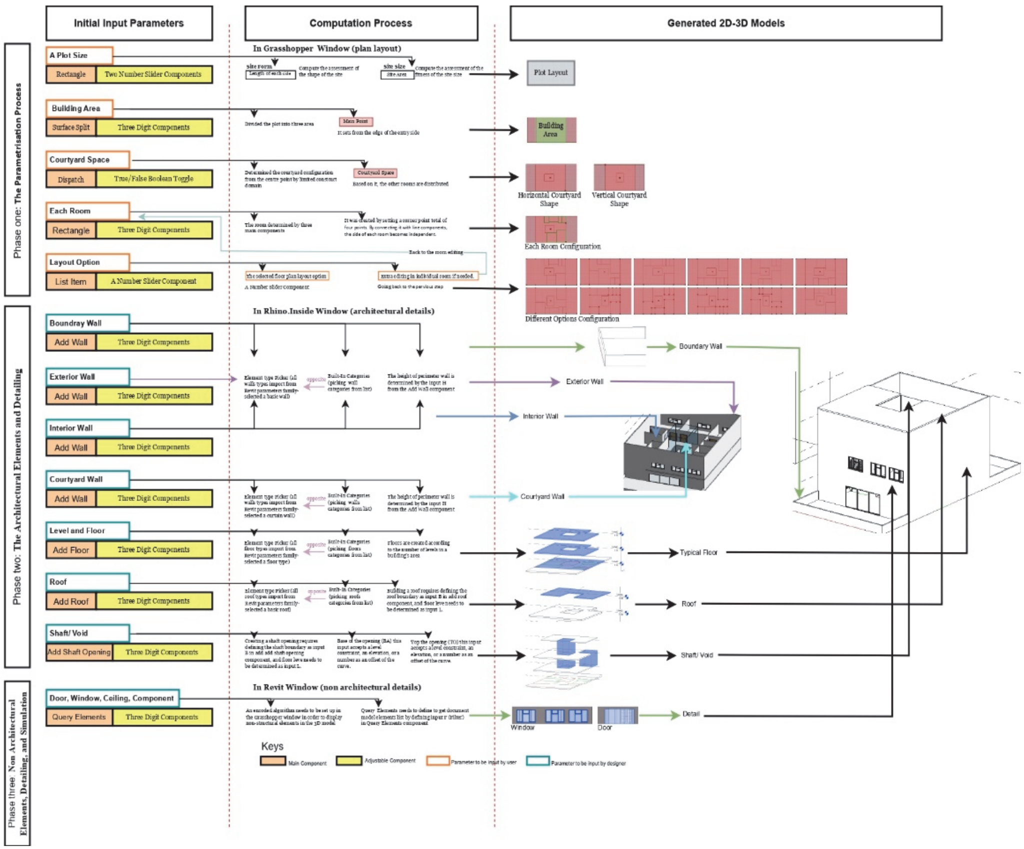

Figure 3
Flow chart of the design framework

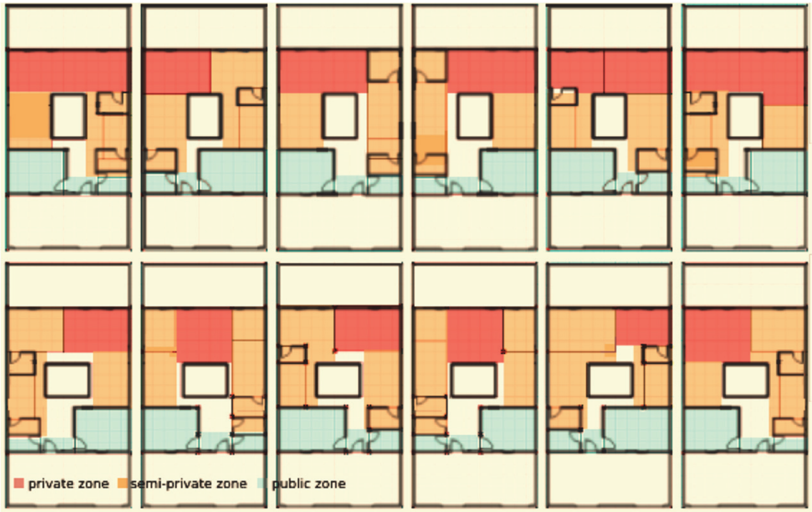

Figure 4
Configuration layout options generated by the algorithm with different courtyard forms

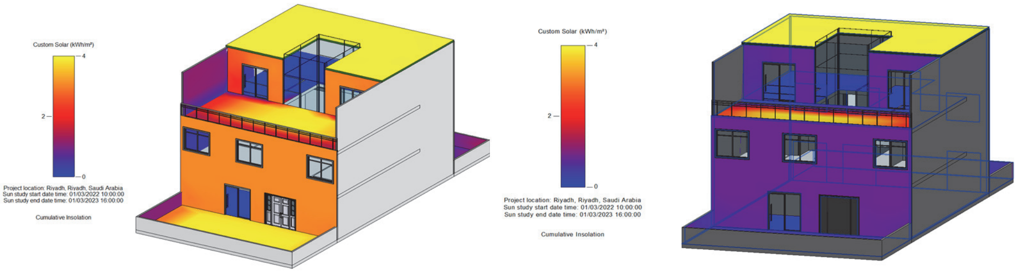

Figure 5
Solar energy analysis

Phase 2: Development of architectural elements

In this phase, the Rhino.Inside tool is used to create the essential building elements with actual wall thickness, like walls, floor slabs, and roofs. The walls are divided into four different types to differentiate between the internal and external wall thickness: boundary wall, interior wall, exterior wall, and courtyard wall. For instance, the building boundary walls' height is between 1.5m to 2.0m, and the thickness is 30cm. The exterior walls' height is between 3.0m to 3.2m, and the thickness is 30cm. The interior walls' height is between 3.0m to 3.2m, and the thickness is 20cm. The courtyard wall height of the panel is between 9m to 12m and is categorised as a curtain wall, which is double glassed with a thickness of 24mm to 28mm.

Furthermore, the building floor slab is created as a separate level, excluding the ground floor, within the encoded algorithm, with a thickness of 20cm to 30cm. The building roof is also separately created to differentiate between a roof and a floor slab with a thickness of up to 30cm. Each level is independently treated because it has a different layout. Building shafts for staircases and courtyards are defined in the algorithm script as well.

Phase 3: Detailing elements, simulation, and environmental effect

Our algorithm reads the building's windows, doors, and ceilings as secondary structural elements. It visualises and utilises them for environmental simulation in the Revit interface. If the simulation result is satisfactory, the finalised building will proceed to implementation and all required construction documents will be produced. If the result is unsatisfactory, the design process will return to phase 1.

To assess the environmental impact of our model, we utilised the Revit solar analysis tool. The process involved first creating a detailed model of the preferred house option using the options available in the Grasshopper script. Subsequently, we performed a solar analysis by clicking on the corresponding option, which opened a solar analysis table. We then selected an exterior wall and a roof for analysis. Finally, by clicking on the "Update" button, we obtained the complete solar analysis results, as depicted in the figure below (Figure 5).

VERIFICATION

We verify our tool by generating various dwellings by setting parameters deriving from our initial user survey. The ground floor plan divides into three zones: the public zone for guests in blue, the semi-private zone for services in orange, and the private zone for the family area in red (Figure 4). The most critical components used in the Grasshopper script are the move component and the number slider component, allowing for individual control of each space.

By controlling three parameters (move, number slider, and direction) for each room, we ensure that the scale relationship of generated rooms around the courtyard complies with the general plot area constraints, specifically the building area. However, we noted that some floor plan patterns could not be created due to circulation issues around the courtyard.

By using Rhino.Inside, we can generate a variety of plan layouts within seconds and clients can modify any option they choose as they prefer.

Overall, our algorithm, with the help of specific parameter components in the Grasshopper script and the Rhino.Inside tool, has successfully generated various house layouts (Figure 4). However, the aspect of user interaction is not addressed in the current paper, as it will be the focus of future research.

FINDINGS

Our design is achieved in accordance with our survey data. Based on the analysis, the floorplans are designed in a rectangular shape. We found multiple configurations that can be easily produced by the algorithm.

However, some floor plan outlines could not be created due to circulation restrictions around the courtyard. The Rhino.Inside tool utilises parametric algorithms for building design and layout planning. Once the desired outcome is achieved, the model can be rendered in both the Rhino and Revit interfaces.

Furthermore, a drawback of the tool is that, when reopening a Revit file, level numbers must be deleted to prevent overwriting the existing script file. By dividing the workflow into the steps of data collection and parametric floor plan design, development of architectural elements, and detailing and simulation, user-friendliness has increased. Ultimately, in the Revit interface, the building is visualized and used for simulation, and if the analysis is satisfactory, the final output proceeds to the construction document phase. If the analysis is unsatisfactory, adjustments must be made in the Grasshopper script, and the process must be repeated.

CONCLUSIONS

Our conclusion will focus on answering our research questions: How can we create a mass customization workflow that integrates environmental optimisation and client involvement?

The plug-in Rhino.Inside was very useful in achieving our mass customisation workflow. The algorithm was easy to use and has successfully generated multiple dwelling solutions.

How effective was our parametric workflow compared to conventional design methods?

Our findings indicate that obtaining data online and involving clients leads to a faster design process with a satisfactory outcome compared to the conventional and time-consuming manual design approach. The traditional planning process in Saudi architecture offices is notoriously time-consuming. However, our approach has the potential to reduce it by over 50% this can be accomplished by eliminating in-person meetings while also minimising delays and rescheduling. Likewise, the accuracy of data collection is guaranteed as it remains untouched by human intervention.

However, we encountered some limitations in the project. Certain floor plan patterns could not be created due to circulation issues around the courtyard. When reopening a Revit file, level numbers must be deleted to prevent overwriting the existing script file.

In conclusion, our study proposes a mass customization workflow incorporating environmental optimisation and client involvement in the design phase. The three-phase algorithm we developed improves workflow efficiency and generates affordable, sustainable, and user-friendly housing solutions. Our future objectives involve conducting experiments to enhance client involvement and design flexibility, as well as exploring the feasibility of using robotic technology to create more complex and reliable components.

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