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Abstract

This paper explores the suitability of mass customisation (MC) technologies and techniques in order to provide affordable housing solutions for Saudi Arabia. In particular, the paper analyses ten articles filtered through 1.165 publications searched by using the keywords 'mass customisation housing or off-site construction' in the databases Scopus, CumInCAD, ScienceDirect, and Engineer village and categorised them based on their suitability for the Saudi Arabian context. Our findings include a comparative analysis chart evaluating workflows, tools and technologies on their suitability for the MC design and an MC workflow proposal for including parametric design and digital fabrication tools and techniques.

Keywords

Mass customisation; housing; off-site manufacturing; client involvement

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A CRITICAL REVIEW

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ABSTRACT

This paper explores the suitability of mass customisation (MC) technologies and techniques in order to provide affordable housing solutions for Saudi Arabia. In particular, the paper analyses ten articles filtered through 1.165 publications searched by using the keywords ‘mass customisation housing or off-site construction’ in the databases Scopus, CumlnCAD, ScienceDirect, and Engineer village and categorised them based on their suitability for the Saudi Arabian context. Our findings include a comparative analysis chart evaluating workflows, tools and technologies on their suitability for the MC design and an MC workflow proposal for including parametric design and digital fabrication tools and techniques.

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الملخص

تستكشف هذه الورقة مدى ملاءمة تقنيات التخصيص الشامل من أجل توفير حلول إسكان ميسورة التكلفة للمملكة العربية السعودية . على وجه الخصوص، تحلل الورقة عشرة مقالات تمت تصفيتها من خلال ١١٦٥ منشورا تم البحث عنها باستخدام الكلمات الرئيسية "الإسكان، التخصيص الشامل، والبناء خارج الموقع" في قواعد بيانات سكوبس وكيومنكاد وساينس دايركت وانجنير فيليج، وتم تصنيفها بناءً على مدى ملاءمتها لسياق المملكة العربية السعودية. وتتضمن النتائج التي توصلنا إليها مخطط تحليل مقارن يقيّم تدفقات العمل والأدوات والتقنيات المتعلقة بمدى ملاءمتها لتصميم التخصيص الشامل بالإضافة إلى اقتراح سير عمل التخصيص الشامل لتضمين أدوات وتقنيات التصميم المعياري والتصنيع الرقمي.

الكلمات المفتاحية: الإسكان، التخصيص الشامل، البناء خارج الموقع، مشاركة العميل.

1. INTRODUCTION

Mass customisation (MC) is a design and manufacturing approach that focuses on providing customised goods at a low cost (Ganji et al., 2018). Seeking to exploit mass customisation concepts such as modular standardisation, configuration, and flexible manufacturing requires the use of several tools to assemble and generate customised items for commercialisation under comparable conditions as serially produced standard products. MC can be applied in various industries, such as product design, vehicle design and architecture. It progresses through principle design, planning, manufacturing, and assembly stages. However, the architectural project's fabrication stage takes place largely on-site rather than in the manufacturer's location (Winch, 2003). MC provides more durability, improved quality, shorter time, and decreased cost. In contrast, mass production commonly results in identical, monotonous homes that no longer satisfy market desires for individualised design (Noguchi and Friedman, 2019). On the other hand, personalised design is a vital characteristic in meeting the individual needs of homeowners, yet, customisation increases design costs (Smith, 1998). It creates mass-produced modular components yet can be constructed into a broad range of final products. That is one of the most thriving standards of MC, and it reduces costs while increasing personalisation (Noguchi and Friedman, 2019). MC integrates mass production through mass design to achieve qualities of customised design at an affordable price. Mass housing production consists of three primary notions. First, it is built utilising standardised design and factory building processes (Altan et al. 2016). Secondly, it is based on state leaders' belief in similar living circumstances as a societal ideal (Urban, 2012).

Finally, it is used to reduce costs in a short period. Consequently, this study explores the state-of-the-art of MC in housing construction, looking at three different aspects: 1) the amount of client engagement in MC, 2) the types of MC, and 3) the manner of MC implementation. It is found that there is considerable potential for MC in the housing construction sector. Despite the number of benefits promised by MC, its application in the home construction sector remains limited, and building solutions, space and choice navigation tools are very deficient. As a reaction to the Fordian paradigm of mass production and standardisation, many researchers see the possibility of delivering diversity and personalisation with efficiency and economies of scale. Discussions on parametric design and fabrication are usually related to 'Mass customisation', as defined by Davis (1987). The latter term, as stated and described by Pine (1993), refers to 'the mass manufacturing of individually personalised goods and services, which combines the idea of personalisation with the economic cost involved with standardisation.

2. A Brief History Of Housing In Saudi Arabia

Over time, dwellings in Saudi Arabia have been modified according to the changing needs of society, technological developments in construction and the available materials. Formerly, Saudi Arabia's traditional buildings were made of bricks comprised of mud mixed with dried hay and water baked under the sun's rays (Al-Hathloul, 2003). Even though there were differences in socioeconomic status, all houses were generally constructed using the same building materials and designs (Chapman et al., 1999). This construction method continued until the introduction of the reinforced concrete structural framework during the late 19th century. Since then, buildings and construction in Saudi Arabia have changed drastically. Foreign companies and construction workers introduced new materials, and new systems gave way to drastic architectural changes. Consequently, due to its durability, reinforced concrete has become the primary structural system solution, replacing load-bearing masonry walls, which allowed the construction of more homes to support the country's massive population growth (Chapman et al., 1999). Even though the idea of using reinforced concrete buildings came from western countries, the local community has used it differently due to its culture and specific religious and privacy regulations (Bahammam, 1987). The changes in the Saudi Arabian lifestyle have also had an impact on the typical dwelling floor plan (Bahammam, 1998). Overall, Saudi Arabian dwellings have been through three stages of building construction types throughout different periods: the traditional, transitional, and contemporary stages (Bahamam, 2018).

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The early traditional buildings were constructed by Islamic rules and regulations and had certain advantages. For instance, building materials such as mud remain cool for long hours inside the wall (Tarrad, 2020). However, some issues emerged in traditional houses, such as maintaining the roof yearly due to rain conditions when clay on the rooftop absorbed the rainwater. Transitional buildings used mixed materials, including traditional materials such as wood, mud and cement blocks, which were more recent. This method produced a better-quality home in terms of quality and less maintenance, especially on rainy existences. At the time, building regulations focused on specific rules such as setback building construction from land barriers and the height of the building.

Contemporary buildings have undergone three periods, early, late, and current. Due to social media and western influences, the Saudi Arabian public has had to change the traditional house styles in a bid to 'move with the times. More recently, building regulations have become more robust after adding new building codes such as fire, construction, and interior codes. By investigating all three stages, every generation has shown different needs in terms of accommodation design according to societal lifestyle changes, the impact of globalisation and technology. Furthermore, Western builders, contractors, and architects have influenced building techniques and ideas by incorporating and sharing their skills and knowledge in the Saudi Arabian context. When foreigners were hired to build large-scale projects rapidly, they erected prefabricated cubic, concrete buildings without aesthetic, contextual or environmental considerations. Governmental regulations in urban planning affected Saudi Arabian society; thus, the subsequent urban form conflict has augmented the gap between members of the public and their urban environment (Al-Naim, 1993).

Furthermore, there is a housing shortage in Saudi Arabia due to a rapidly growing population. Other causes of the housing shortage are construction delays and labour deficits (Alhajri and Alshibani, 2018). In addition, most of the market is still implementing conventional building techniques based on reinforced concrete structures, making housing construction highly inefficient and time-demanding. Still, none of the housing providers has applied client involvement.

Finally, the Saudi housing ministry has the ambition to establish an initiative to facilitate novel construction technologies and made agreements as part of its contribution to the national transformation plan 2030aiming to increase citizens' homeownership from 24% to 52% by 2030 (Overview, 2022).

To solve these issues, mass customisation could aim for affordable, sustainable, context-friendly and user-friendly housing solutions. Therefore, this paper investigates, classifies and compares MC case studies in constructions that could be applied in the Saudi Arabian context. In particular, we will look into the questions:

- Which methods, techniques and technologies are currently being applied globally for mass customisation of housing?
- How can we develop a design framework which can provide mass customised, affordable housing solutions for Saudi Arabia?

3. METHODOLOGY

To answer our questions, we will proceed with a systematic review of relevant literature and then analyse and categorise the related research according to the design and construction customisation methods and the tools and techniques used. In particular, our research method consists of four phases, as can be seen in Figure 1, including 1) searching papers through databases (Scopus, IEEE, Engineering Village, CumlnCAD, and ScienceDirect), 2) screening the selected papers, 3) comparatively analysing and categorising of the papers and 4) evaluating the research in charts and tables. In the first stage, our initial search concentrated on Scopus (Elsevier's abstract and citation database), Engineer Village, CumlnCAD (Cumulative Index about publications in Computer Aided Architectural Design), and ScienceDirect due to their reliability and comprehensiveness. Since the off-site building is a precondition for bringing industrialisation to the market (Gann, 1996), which is necessary for mass customising, the keywords utilised for the search include ‘mass customisation’ and ‘off-site construction’.

The majority of the publications appeared in the database CumlnCAD, which is sponsored by the respective associations ACADIA, CAADRIA, eCAADe, SIGraDi, ASCAAD, and CAAD futures; nonetheless, Scopus and ScienceDirect provide journal articles and book parts connected to our research. Our search has screened 1.165 academic publications consisting of 1,067 conference papers in CumlnCAD, 88 articles and books in ScienceDirect, 20 papers and articles in Scopus, and 10 articles in Engineering village. The articles were screened in the second step by deleting duplicated papers, review publications, and low-relevance articles. The initial filtering was done with the databases’ filtering tools, and 85 items were deleted. Reading the abstracts of the remaining 1,080 papers were used to review them.

The publications on the news, brief messages, and reviews were deleted in the second filtering. Likewise, items not dealing with mass customisation housing (for example, walls, shells, and interior fittings) were eliminated. An extra 1,070 items were deleted in total, resulting in the remaining 10 articles we present here. In the third step, the remaining ten papers were methodically classified and analysed into three parts: 1) levels of client involvement, 2) mass customisation categories, and 3) mass customisation method. The final article selection includes book chapters, journal articles, and conference papers. Lastly, in phase four, the categorised articles are analysed and compared in order to answer our research questions.

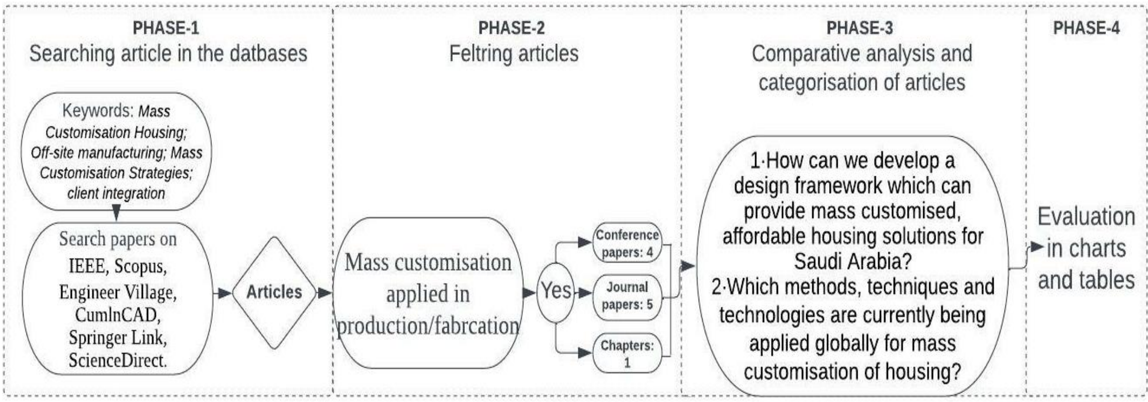

Fig.1: Flowchart of the systematic review process.

4. MASS CUSTOMISATION METHODS, TOOLS AND TECHNIQUES

This section will describe ten articles, summarising them in a comparative table [Table 1]. It includes several categories, such as MC design, MC type MC, MC applied tool, MC methods, materiality, software and level of client involvement. The MC design category was used to compare how each paper addressed the MC solution. The MC category type was used as a key component in determining the complexity or simplicity of clients' participation in their MC initiatives. The MC tool category was utilised to define the strategy research each project took, ranging from a single element to a complete complex. The MC methods category was used to define the various construction methods utilised in each study, ranging from pre-fabrication to mix customisation. This research looked into the material category to investigate the possible use of innovative materials. The software category was chosen with the goal of discovering new software that could be applied in our future research, as well as the possibility of using multiple software in order to speed up the design process. The level of client involvement category was used to determine the available options of client involvement throughout the design process as well as in each design phase.

Kolarevic and Duarte (2019) noted that one of the crucial points of MC is the neglected social aspect which highlights the lack of cultural characteristics considered in MC. Their MC method enables parametric design and digital fabrication of a table by using an interactive website which allows clients to determine their own desirable individual designs. They suggested the use of local materials to reduce construction costs. Depending on the MC processes employed, structure, enclosure, and partition components may be produced to varying degrees of automation utilising digital fabrication and robotic assembly, such as the one shown in Figure 2.

Fig.2: Various mc Table designs were created by customers using a mobile phone app.

Yuan et al. (2018) developed an adaptive strategy for prefabricated buildings using Building Information Modelling (BIM). The article explains in detail how to solve the problems of manufacturability and assembly of planned systems. Their methodology merges prefabricated dwellings with BIM-enabled parametric design. According to them, Design for Manufacture and Assembly (DFMA)-oriented parametric design needs to be improved regularly to be implemented. As indicated in Figure 3, through DFMA-oriented parametric design, the researchers concluded that incorporating domain experience from the manufacturing and assembly stages can increase the success rate of the design.

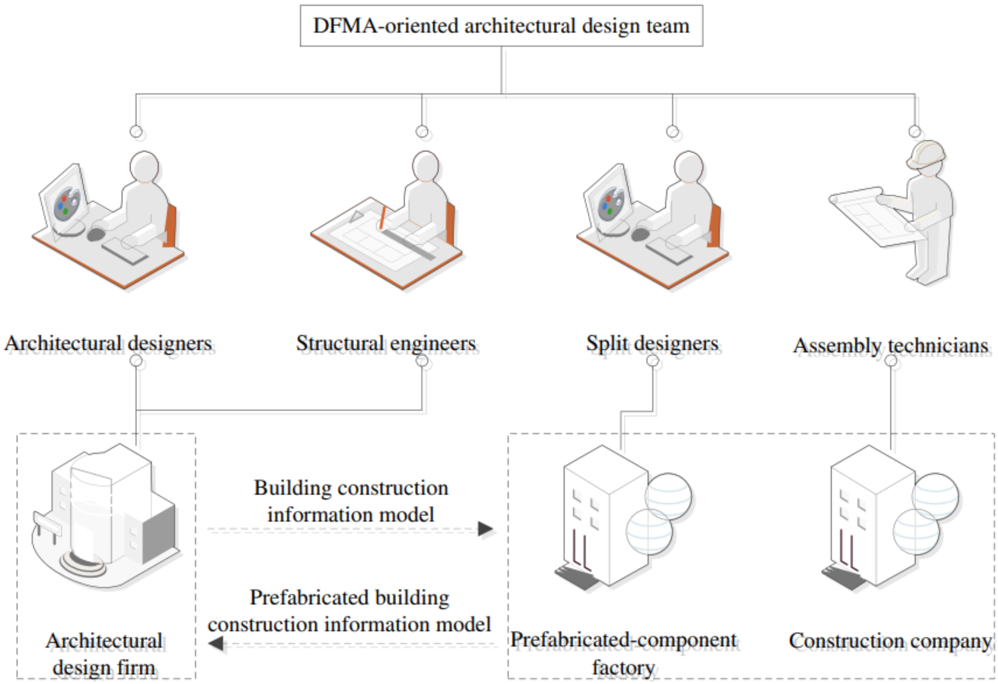

Fig.3: DFMA-oriented parametric design development for prefabricated buildings.

Gazel et al. (2018) designed a partial model using MC for large-scale housing, focusing on principles such as variability, flexibility, and prefabrication. Their methodology includes a modular, parametric system set up in a BIM modelling environment. It allows different spatial arrangements and simulates environmental comfort and construction costs (Figure 4). Their proposed platform also allows client-designer interaction. The software used in their study is Rhinoceros/Grasshopper.

Fig.4: The adaptable layout of a parametric modular system.

Marchesi et al. (2017) suggested adopting a mass customisation method for prefabricated timber frame panel housing, focusing on robustness and flexibility. Their methodology employs developing a so-called Axiomatic Design tool (AD), a systematic approach to examining concepts and efficiently delivering customisable solutions. As shown in Figure 5, the Axiomatic Design is a high-value design approach since it lowers the number of alternative beginning designs to one while using limited resources (Benavides, 2012). The sublayers of walls, windows, floors, and roofs are made of standardised modular panels built into spatial modules based on standard board sizes. These panels can generate a variety of spatial arrangements and can be simply dismantled and replaced without affecting nearby components. The software used in their study is AD.

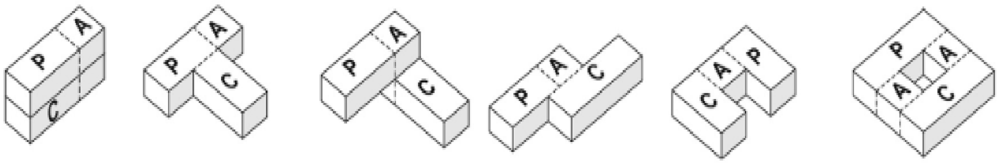

Fig.5: Variation of configuration space moulding by using Axiomatic Design.

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Ma and Ameijde (2022) described the criteria for an adaptive modular building system and a multi-objective optimisation process for high-rise constructions. They encourage combining spatial and structural systems; otherwise, workflow conflicts may occur. Their research suggests full customisation. They utilised the Rhino/Grasshopper plugin 'Wallacei' to develop different apartment configurations based on diverse lifestyle preferences. Showkatbakhsh (n.d) used 'Wallacei' to run simulations using highly detailed rational tools as well as various complete selection methods, including algorithmic clustering, to help users better understand their evolutionary simulations and make more informed decisions throughout the process. It comprises specifying the design challenge, executing the evolutionary algorithm, analysing the results, and picking the required solutions for the outcome. Once a simulation has been finished, users can choose, rebuild, and output any phenotype from the population. Figure 6 presents assemblies of their 'kit-of-parts' system that is used for all buildings, which can be altered and customised to meet the needs of various occupants. Prefabricated components are assembled onto in-situ concrete cast core elements, which serve as the primary load-bearing structure.

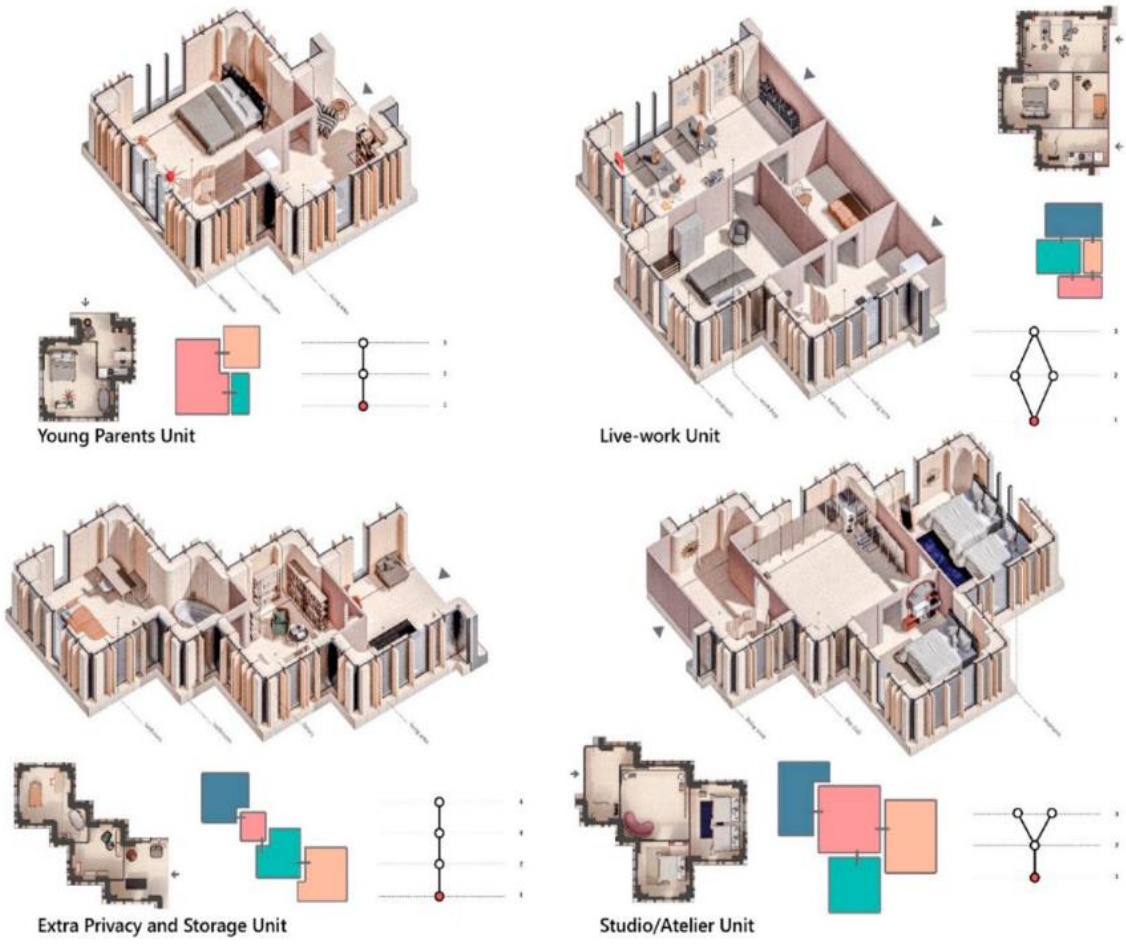

Fig.6: Varied spatial modular shows the flexibility in arranging the sizes

Formoso et al. (2022) attempted to standardise a product that provides affordable accommodation for developing nations (Figure 7). Their methodology is based on an assemblable modular system. Their research focused on small businesses and the MC approach they applied. They found out that the interchangeability of parts of an assembly can lead to various end products implementing MC in affordable house-building projects. Moreover, additional customisation choices were offered in the earlier design stage for consumer involvement in the design. Consequently, the construction firm defined customer order decoupling points in accordance with design phases and client engagement.

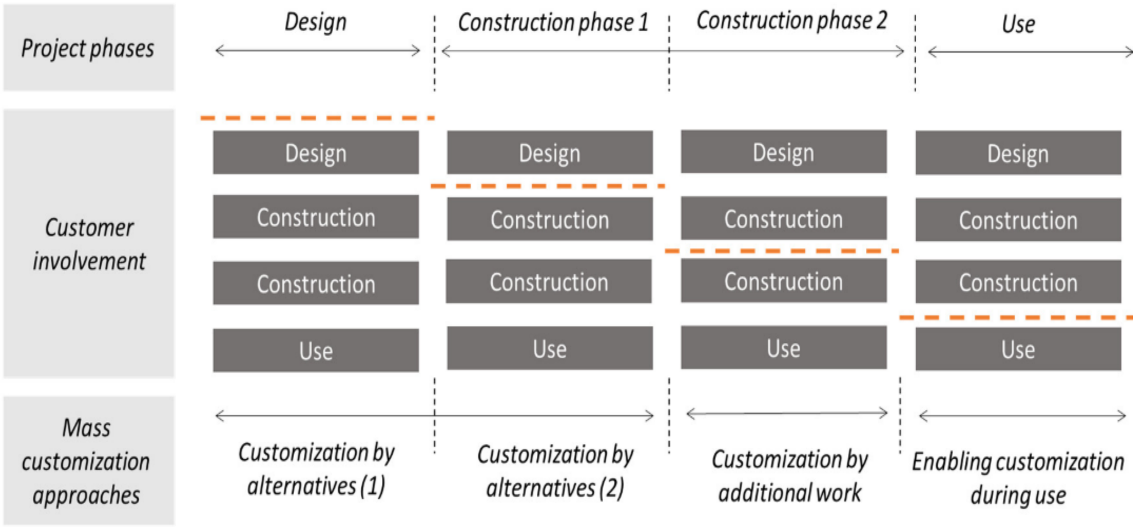

Fig.7: A mixed MC strategy to support customisation

Anane et al. (2022) suggested a modular building framework for design and production. They offered discrete design (DD) as a strategy for MC. They showed how a BIM-driven discrete design method might be used in conjunction with computational design to create modular structures. Their methodology is based on off-site fabrication construction supported by BIM (Figure 8). They suggested a modular system which includes plumbing. Furthermore, off-site manufacturing will use robotic arm cells that can perform cutting and assembly tasks.

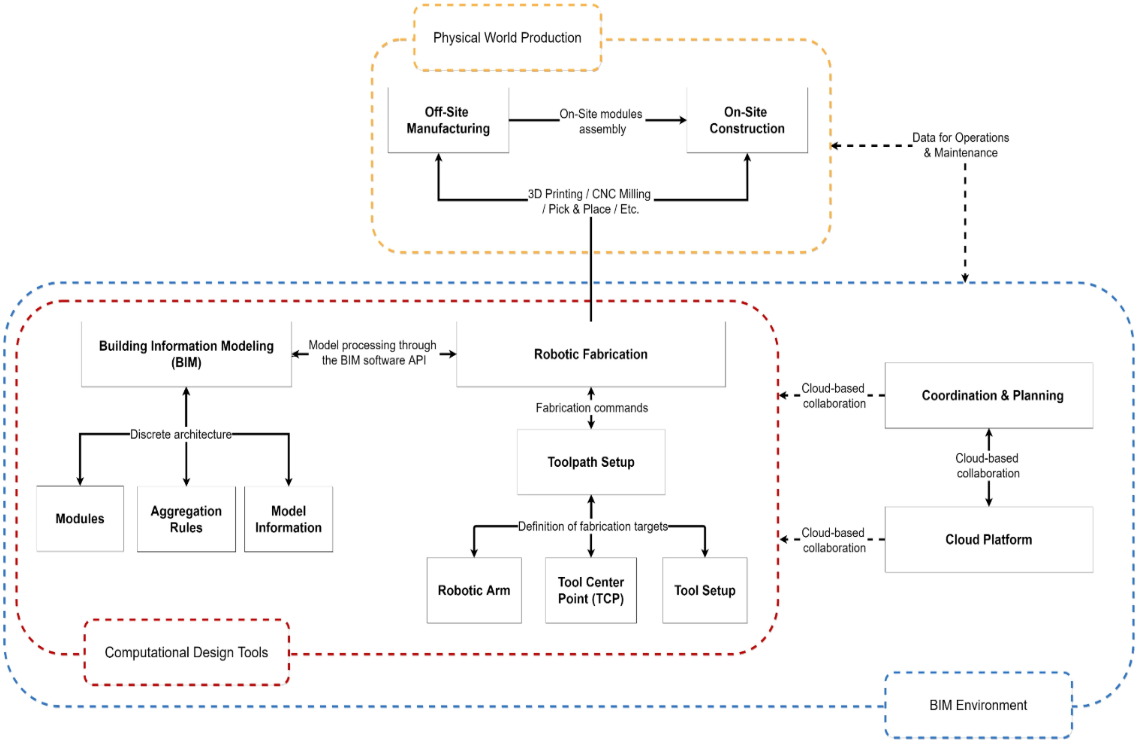

Fig.8: A framework of the DD for modular construction driven by BIM design

Alwisy et al. (2018) presented a systematic methodology for automating the design and fabrication of modular, wood-framed residential buildings based on the platform framing construction method. Building information modelling (BIM) was implemented to facilitate design automation and drafts for manufacturing. They developed the tool Modular Construction Manufacturing Pro (MCMPro), which generates sets of shop drawings and material take-off lists needed for framing module walls, floors and ceilings ready to be used for the production line (Figure 9).

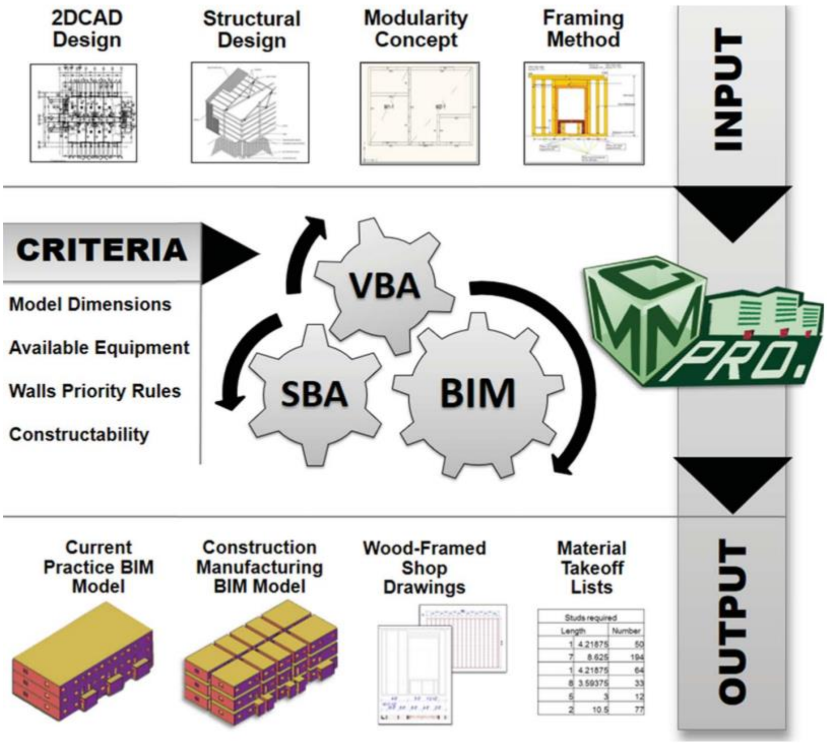

Fig.9: A methodology of the design process

Bakhshi et al. (2022) developed a BIM-related algorithm that allows assembly and customisation in high quality (Figure 10) as well as the participation of the client in the building configuration process based on assembly limitations. They claim that compared to the current strategies offered to implement prefabricated construction, their 'Prefabricated Information Model' provides marketing experts with a product and building-oriented understanding.

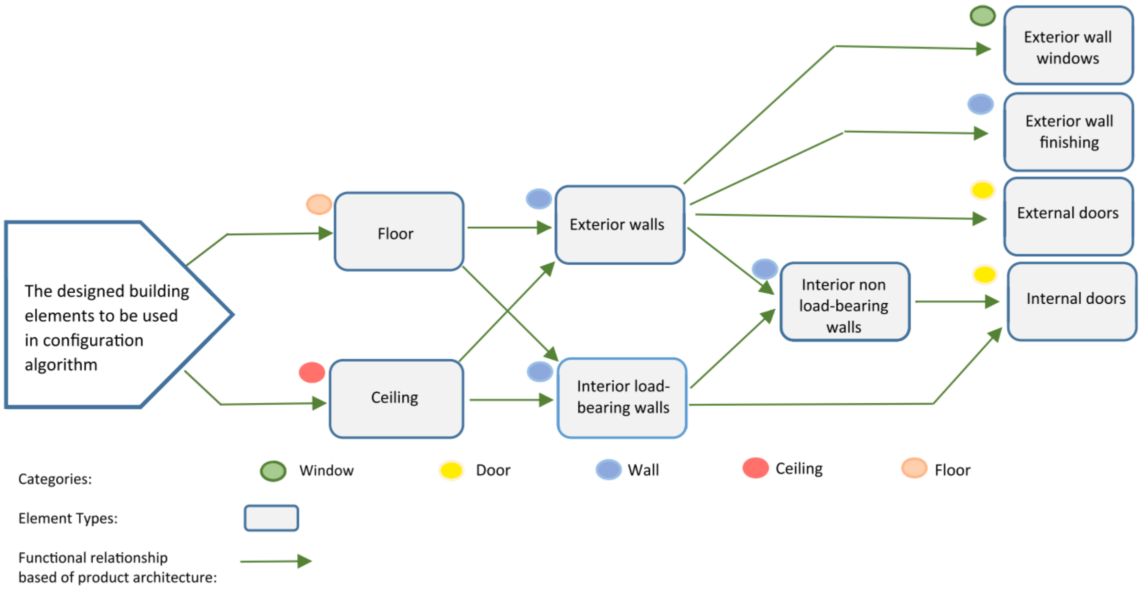

Fig.10: The notion of housing configuration algorithm and choice limitations

Wang et al. (2022) proposed a 'skeletal' parametric scheme for generating building layout variations to optimise a performance-based design (Figure 11). Their skeletal parametric scheme tool was used to generate building layout configurations. It can create plan/construction variations utilising a collection of skeletal lines based on numerous architectural features aligned with parameters like sidewalks, space, and setback regulations. They claim that using parametric models will optimise the design and increase the overall construction quality providing designers with various design possibilities. The software used in their study is Rhinoceros/Grasshopper.

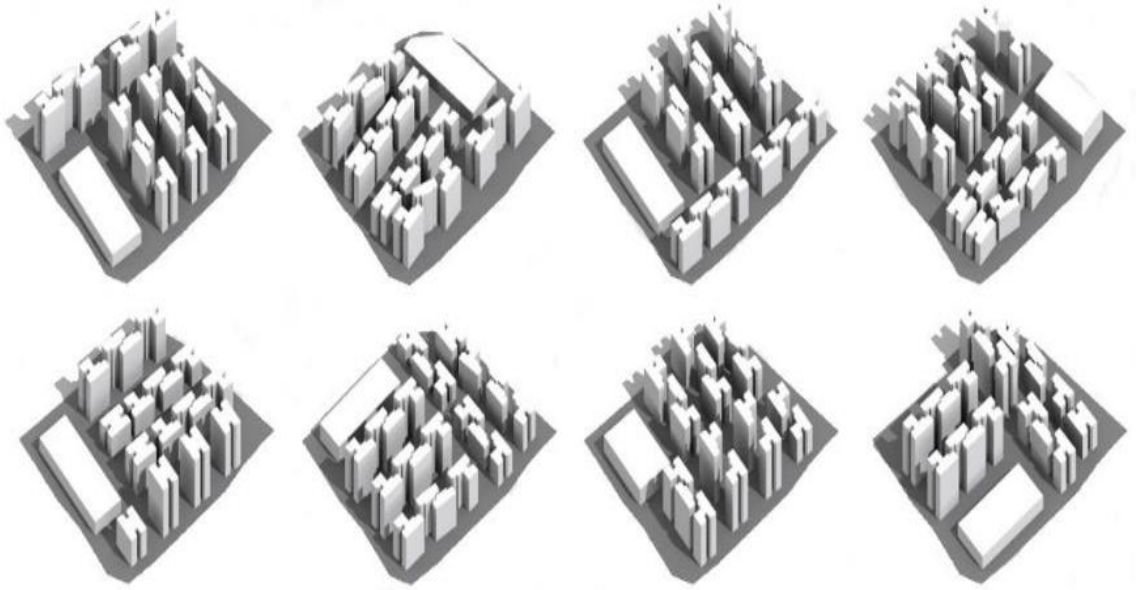

Fig.11: Variety building layout ‘skeletal’ parametric scheme

5. FINDINGS

Our findings are collectively illustrated in Table 1. Consequently, we can observe that MC interactive products should not be fully customised, and the level of customisation could be between customised standardisation and tailored customisation (Kolarevic and Duarte, 2019, Rocha et al., 2016). The three primary deciding factors—time, cost, and building quality—are also considered advantages of modular construction. The modular building technique is a crucial breakthrough that promises to provide the construction industry with contemporary ways to build dwellings quickly and effectively to satisfy demand. Due to the higher initial costs needed during the planning and design phases, which were out of the reach of conventional builders, the cost was frequently perceived as a barrier to off-site activity (Young et al., 2020). Similarly, the majority of recent studies have shown that parametric tools may help the MC process by reducing the design process time and data storage (Kolarevic, 2015). (Kolarevic and Duarte, 2019, Rocha et al., 2016, Gazel et al., 2018) noticed that the simplicity of design for MC is essential. Visualisation and simulation appear to be of great importance in the majority of studies because it increases clients' satisfaction. MC helps to reduce construction time due to efficient workflows and doesn't rely on weather conditions (Kolarevic and Duarte, 2019, Rocha, 2016). OSM housing approach mainly facilitates the construction process to occur concurrently, reducing the time necessary for the construction, cost and quality (Seidu et al., 2021).

In general, we have identified two types of MC: full customisation and part customisation (Figure 12). Full customisation allows the client to be involved in the entire design process, while part customisation tolerates the client to be involved in the segment design process customisation is limited. Based on client preferences, manufacturers can provide a degree of flexibility for users in the design, from simple to complex. Client involvement can take place in different ways and starts from pure standardisation, segment standardisation, customised standardisation, tailored customisation and pure customisation, as shown in Figure 13.

Table 1. The ten articles are analysed on the side of MC design and optimisation.

Mass Customisation design	Type of MC	MC tools	MC method	Material	Software	Level of client involvement	Type of article	Reference
Building a modular model in mass housing scale with principles in terms of variability, flexibility, and prefabrication	Part Customisation	Parametric Modelling	Prefabrication Modular Model	Steel Frame	Grasshopper	Choice Options	Conference	Gazel et al. (2018)
Adopting the mass customisation of prefabricated panels housing	Full Customisation	Systematic Approach.	Prefabricated Housing	Timber	Axiomatic Design (AD)	Full Involvement	Journal	Marchesi et al. (2017)
Parametric provides a viable method to produce building layout configurations.	Part Customisation	Parametric Modelling	Analysis of Two Cases Design Optimisation	N/A	Grasshopper	Layout Variations	Conference	Wang et al. (2022)
An off-site robotic prefabrication proposal for a modular home using discrete architectural ideas	Full Customisation	Discrete Design.	Discrete Aggregation Tools	Composed of Wooden Parts Interlocked	BIM	Full Involvement	Conference	Anane et al. (2022)
Using interchangeable elements of a fully prefabricated system of modular building	Full Customisation	Kit-of-part' Systems Genetic Algorithm	Panel Systems	Composition of in-situ cast concrete and precast elements	Wallacei Plugin	Full Involvement	Journal	Ma and Ameijde (2022)
Practical integrated methodologies for implementation in the OSC industry, combined with a design framework	Part Customisation	Parametric Modelling	Prefabrication	N/A	BIM	Choice Options	Journal	Bakhshi et al. (2022)
Design for Manufacture and Assembly (DFMA) into the design of prefabricated buildings	Full Customisation	DFMA-Oriented Parametric Design	Prefabrication and Assembly Method	Composition of off-site cast concrete and precast elements	BIM	N/A	Journal	Yuan et al. (2018)
Standardise a product of affordable accommodation projects in developing nations has been challenged	Part Customisation	Analysis of customer demand for customisati on	Mixed Customisatio n Levels	Traditional Building Technologies	N/A	Custom Choice	Journal	Formoso et al. (2022)
Design parametric goods with increased functional performance and customer satisfaction	Part Customisation	Parametric Design	Prefabricated Housing	N/A	N/A	Dialogue Options	Book	Kolarevic and Duarte (2019)
BIM-based automation of design and drafting for manufacturing panels for modular buildings	Full Customisation	Modularity Approach	Panel systems	Wood Panel	BIM	N/A	Journal	Alwisy et al. (2018)

The tailored customisation could provide design selection, layout choices, finishing, materials selection, and catalogues. Tailored customisation could be applied conventionally by a face-to-face meeting with the client or online by giving options to the client, such as an open design involving, design selection, layout choices, dialogue, finishing, materials selection, and catalogues.

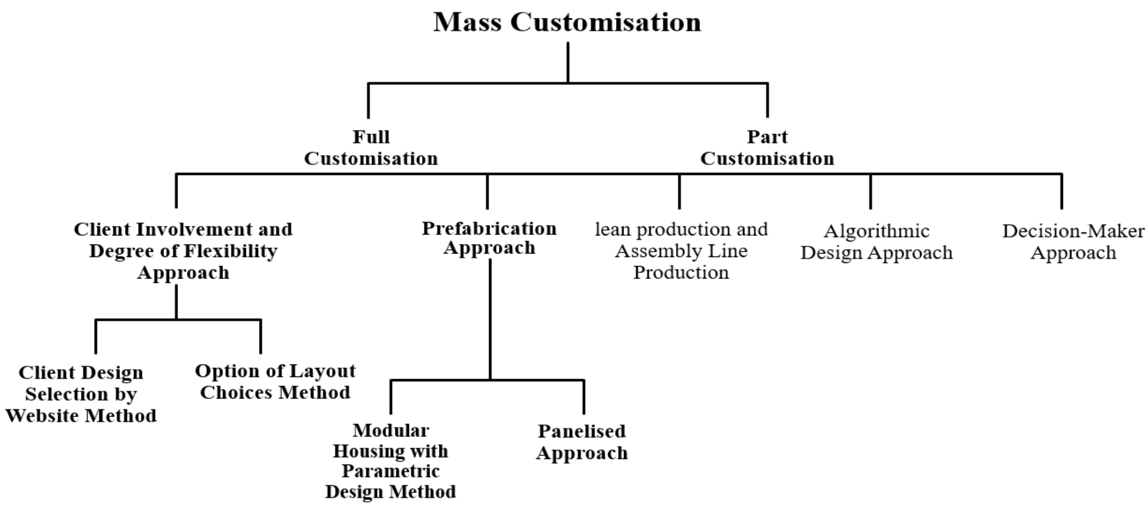

Fig.12: Categories of Mass Customisation made by the author.

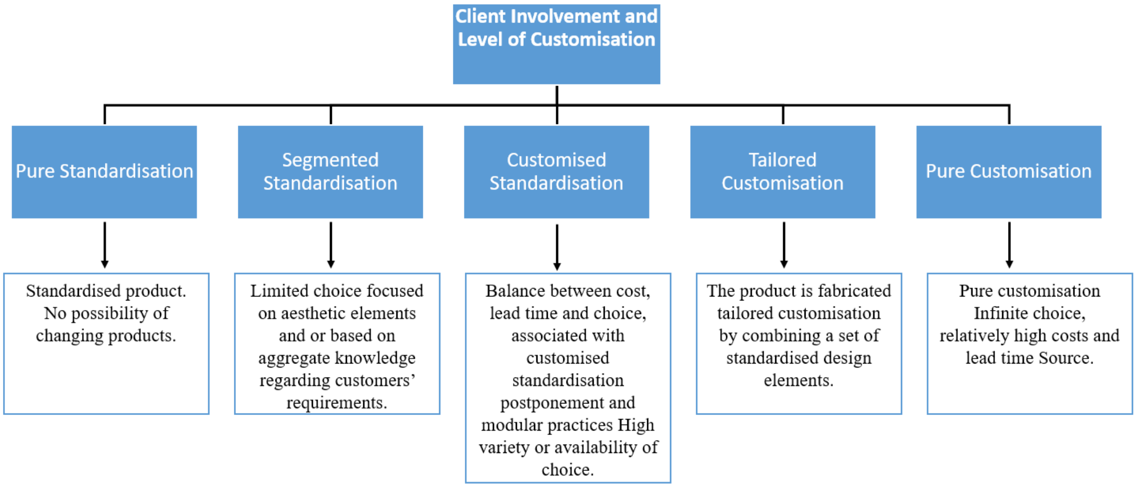

Fig.13: Client's integration level of mass customisation made by the author.

Consequently, we propose a novel, parametric MC method, as shown in Figure 14. It allows the involvement of both designer and client via an interactive interface linked to floor plans, room sizes, elevations and courtyards. All data will become available to the designer via a data cloud; thus, he can start the design process. The interaction will continue in all design and construction phases. The proposal has made an easy platform to be accessible for architects and non-architects to be used without complexity. For instance, in the first stage, an interface will be provided on a website which would be easy for anyone to use. The page interface will provide basic information about the plot's dimensions. The clients can determine the number of stories, rooms and the courtyard. In the second phase, all data will be used for processing and creating plans supported by an algorithm. The date will be made available to the designer via a could database. The last phase will include alterations and finetuning of the drawings up to completion.

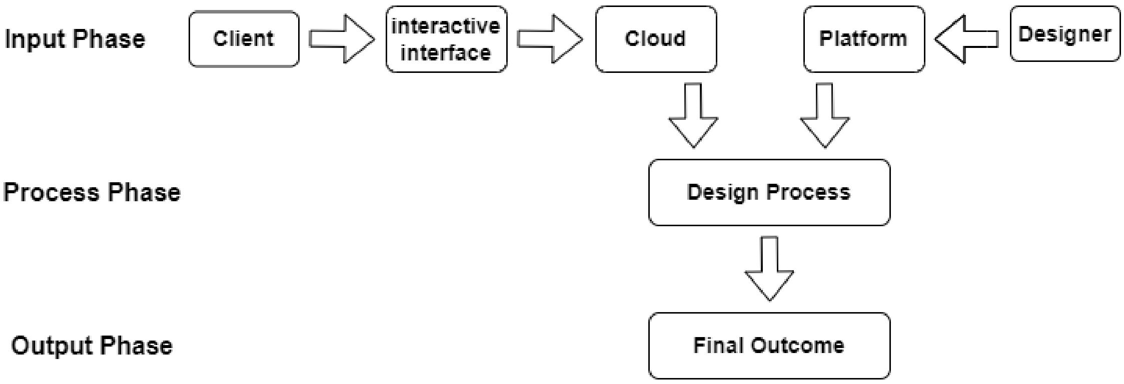

Fig.14: Arthur proposed a methodology for MC.

6. CONCLUSION

This paper contributes to the Saudi vision by using such technology with building structure elements. It focuses on using technology software with offsite structure elements that will help the high demand of housing in the country. Looking at our findings, one can see that MC was difficult to achieve up to recent years. It was implemented by conventional methods, which are inefficient due to the required time for data processing and labour. However, emerging tools and techniques such as data clouds, smartphones, parametric design and digital fabrication have enabled new possibilities. Client involvement may occur even in preliminary design stages via internet browsers or phone applications.

Furthermore, there is a plethora of websites and design communities where designers exchange their knowledge, designs, and scripts. In this regard, Hippel (2005) argues that clients who design can develop precisely what they desire instead of depending on producers to function as their (sometimes very inadequate) agents.

Additionally, parametric tools are among the most effective ways of achieving MC. Kolarevic (2015) suggests that a customisable mass house should be parametrically specified, interactively planned (through a website or an app), and digitally built, employing file-to-factory procedures in order to achieve ‘real’ personalisation.

Combining the structural system with the spatial design system of a house through parametrisation is an efficient way to obtain and optimise MC production. There were numerous implementations of MC in the last decade, which did not engage with layout and structural systems but only allowed client involvement on exterior applications and finishing materials. As a consequence of our analysis, we identified the need for a novel file-to-fabrication framework utilising parametric tools and responding to the stakeholders’ needs and allowing their involvement to participate creatively in the design process.

In our future work, will focus on developing a tool which will allow the involvement of the client in the design process alongside the designer, aiming for a faster and more efficient designer-client collaboration.

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