Integrated BIM and DfMA Parametric and Algorithmic Design Based Collaboration Framework for Supporting Client Engagement within Offsite Construction

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Abstract
As a proactive reaction to current ineffective collaboration strategies, this study sought to combine the capabilities of Building Information Modelling (BIM) in the Design for Manufacturing and Assembly (DfMA) method with mass customisation into a framework that enables customers to participate in the offsite construction configuration process. This approach engenders greater customer satisfaction whilst increasing production and construction efficiency. A model capable of facilitating the use of construction information in the proposed framework was developed to implement the proposed framework into practice. Combining the BIM model within the framework provides all project stakeholders with prerequisite information needed for a building’s configuration. This collaborative process utilises an algorithmic composition in which the current assembly information in both the BIM model and framework is used as a controlling factor in the configuration process. The parametric environment of Revit and the algorithmic environment of the Dynamo plugin were used to realise the proposed framework (as a proof of concept).

Keywords: Offsite Construction; DfMA; BIM; Dynamo; Parametric Design; Algorithmic Design; Integration; Collaboration;

1. Introduction
In the past few decades, prefabrication has been heralded as the most effective and efficient construction approach by architecture, engineering, construction and operations (AECO) professionals [1]. Palpable advantages of this construction approach over the conventional onsite construction methods include efficient use of resources, environmental sustainability and higher construction quality control [2-6]. However, due to its complex, distinctive supply chain processes, this construction approach has constantly presented diverse collaboration challenges between different project stakeholders (e.g. designer, contractor and client) [7,8]. A notable area that has received scant academic attention is client collaboration with the offsite construction (OSC) design section. However, project organisations have traditionally kept the client away from the design and construction process, often ignoring their preferences and satisfaction, much to the detriment of future contract success [9]. In addition, compared to conventional onsite construction (OnSC) methods, the design phase in the OSC method is of greater significance because it is less customisable and requires more accurate tolerances. Therefore, high-level collaboration and interaction among all project parties are vital to project success [10]. Hence, an effective and efficient design process requires development that meets customer requirements and preserves a high quality of the design process output in OSC projects.

This study was motivated by an efficient and effective collaborative design. The construction process facilitates information transfer, knowledge development, technical coordination and allocations of resources so that all project parties can function optimally while reducing unnecessary conflicts [11]. Hence, this design approach provides a basis to ensure effective interaction between the client and the design team. Moreover, the customisation strategy is commonly used for augmenting cooperation between two parties which not only enjoys the positive aspects of mass production but also fulfils client’s preferences. However, given the
inherent complexities associated with prefabricated buildings (PBs), such a strategy lacks the
necessary flexibility for clients to choose the components separately without considering the
technical requirements of customised construction. This inflexible approach confuses the client
[12] and reduces customised buildings' design, production, and assembly efficiency. In the design
process of PBs, the design for manufacture and assembly (DfMA) method can provide a reasonable
basis for considering the manufacturing and assembly principles during the early stages of design
to maximise efficiency [12-14].

Similarly, as an environment used to produce and exchange rich construction data, building
information modelling (BIM) with its parametric structure can increase the efficiency of the
building design process. Therefore, integrating DfMA and BIM allows designers to consider the
design, production and assembly requirements more efficiently in the OSC design stage [15].
However, there are no definite mechanisms to ensure client collaboration in selecting and
designing the building elements and components, even in these advanced design approaches.
Therefore, there is still a gap in theory and practice due to the lack of a mass customisation strategy
to help integrate current BIM and DfMA approaches to support the better engagement of the clients
in the decision making processes of offsite manufactured buildings.

As such, this research aims to integrate a BIM-based DfMA approach and customisation to provide
a strategy consisting of complementary stages for optimal customer participation in the design
process of high-performance PBs. Specifically, the work seeks to develop a new design framework
for meeting client preferences based on the production and construction requirements of PBs. A
new information model for the prefabrication information model (PIM) was developed as the
product of this research. PIM gathers all information related to the production, construction and
customisation of all prefabricated elements to enable tailored configuration of PBs to meet client’s
needs. The design data for a building’s elements were then developed into a BIM model. Finally,
in the parametric environment of BIM, a new design algorithm was developed which uses both
models to facilitate collaboration between the client and design team in building a configuration
process. Because this algorithm considers all the functional and physical relationships defined in
the form of PIM, along with all the assembly information produced in the BIM environment, it
automatically limits the choices (options) of the client. Hence, this algorithm allows the client
preferences to be met while reducing production and assembly challenges and rework in the design
and construction stage.

2. Related studies
Two main areas were focused upon to introduce the proposed theoretical and methodological
framework:

1) Prefabrication and production, in which due emphasis is given to the inherent characteristics
of the offsite construction method. Consequently, the three concepts of ‘supply chain
management’, ‘product architecture and modularity’ and ‘client preferences and customisation’
are investigated (separately). This allows prefabrication to be performed from the product-oriented
perspective.

2) OSC design principles, in which due emphasis is given to the efficient OSC design
implementation through investigating the state-of-art solutions in this field. Thus, DfMA as an
2.1. Prefabrication and production

Generally defined, the term ‘prefabrication’ refers to planning, designing, producing and assembling building elements offsite to ensure a fast, efficient construction of a permanent structure [16]. The tangible benefits of the factory-controlled (vis-à-vis OnSC) production of building elements (constituting the different components of a complex product) include lower materials and power wastage, enhanced construction quality, higher efficiency and a comparatively shorter construction process [17,18]. Moreover, since the design and production processes utilised for PBs are product-oriented, other mass production processes (e.g. supply chain management [19]; product architecture and modularity [20]; and client preferences and customisation [21]) can be seamlessly implemented.

2.1.1 Supply chain management

All economic, environmental and social considerations are integrated into a coordinated supply chain through key inter-organisational systems [22-24]. This enables the effective and efficient management of materials, information and financial processes related to the production and distribution of products [25-27]. In so doing, the requirements of all beneficiaries are met, thus augmenting an organisation’s tangible competitiveness and flexibility [28]. The efficient supply chain management of the contemporary prefabricated construction industry as a complex product includes diverse activities. These facilities can provide services, products and materials for supply chain members (viz. suppliers, clients, manufacturers, architects/engineers, general contractors, consultants, subcontractors and developers) [29]. As a result, supply chain management engenders considerable efficiency and cost-effectiveness gains while reducing waste and shortening production processes [30]. However, inherent complications associated with supply chain management in the construction industry creates the omnipresent risk of interruption amongst project stakeholders - thus representing negative drawback related to this approach to construction [31].

2.1.2 Product architecture and modularity

Product architecture allows project management team members to specify the parts and components' specific functions, the product's physical configuration, and the way the parts or components are functionally interrelated after the ultimate product functionality is determined [32]. In modular design, most methods have predetermined modules to eliminate production complications of a given product - particularly in terms of the physical and functional interrelationships between components, while simultaneously increasing the efficiency of customisation, production, assembly, maintenance and disassembly processes of the product [33-35]. Hence, when a modular design is implemented, equal consideration must be given to the methods of planning, designing, production, construction, maintenance, disassembly and reuse [36].

2.1.3 Client preferences and customisation

Customisation within mass production reflects an aura of procurement modernity where contractors equip clients with the flexibility to adjust proposals to their individual preferences [37]. Subsequently, clients can utilise this unique strategic chance to gain a competitive advantage and
considerable economic value [38,39]. In short, this strategy encapsulates the benefit of mass 
production features whilst giving a greater choice to the customer. Furthermore, the customer-
oriented decoupling point (CODP) model developed by Lampel and Mintzberg [40] defined client 
participation in the product supply chain using five different levels ranging from pure 
standardisation to pure customisation. This model allows companies to engage client participation 
based on contractors’ limitations and capabilities in the product supply chain.
Zhang et al. [41] developed a model to investigate the potential effects of the mass customisation 
approach, and product modularity on the integration quality of the product supply chain and the 
ensuing competitive quality secured. Data gathered by 317 international manufacturers on 
different standards (variables) were used to empirically test this model (viz: 1) mass customisation; 
2) product modularity; 3) supply chain quality; 4) internal quality integration; and 5) customer 
quality integration. In their study aimed at increasing production system efficiency, supply chain 
and customisation, Schoenwitz et al. [42] introduced a technique to compare client customisation 
preferences for different categories of PB elements available in its product architecture. Where 
client preferences are incompatible with the company’s priorities, a strategic framework 
implements necessary measures to align these individual preferences.

2.2 OSC design principles
The design phase is of paramount significance towards ensuring construction quality, economic 
efficiency and low environmental impact. Seemingly, in OSC, due attention should be paid to the 
design stage owing to important complexities commonly faced in the different stages of 
production, assembly and supply chain of such buildings [3,10,43]. In response to these 
complexities, the implementation of state-of-art developments in OSC design (DfMA as a 
sophisticated design approach [14] and BIM as a sophisticated design tool [44]) can ensure a high 
rate of quality in all stages in building construction.

2.2.1 DfMA as a design approach
To ensure the effective design for PBs, DfMA considers diverse factors in the design stage as a 
relatively up-to-date PB design method [45]. DfMA primarily seeks to integrate production and 
assembly principles in the product design stage so that the occurrence of potential future problems 
are minimised [12-14]. Because PBs are costly due to their inherent complexities, DfMA can be 
implemented as a highly efficient and reliable approach for the production of PBs. Moreover, 
considering the features mentioned above, it is necessary to implement a suitable strategy that 
responds to the common information requirements determined in the design stage and develops 
the exact product information for each prefabricated element obtained through DfMA 
implementation [15].

2.2.2 BIM as a design tool
BIM has received ubiquitous academic attention due to its potential technical and quality 
hancement capabilities throughout a building’s whole life cycle [46,47]. In relation to OSC, 
many designers and researchers have implemented a BIM parametric structure and its data 
exchange capability to enhance design information production quality and design information 
transfer, thus improving the quality of all the design processes of PBs and their components [48- 
53]. Combining the parametric characteristic of BIM with the capabilities of Application 
Programming Interface (API), unnecessary design repetitions are avoided [54]. This can reduce
the inherent inflexibility in the OSC design stage while meeting the need for high coordination necessary for the OSC design stage [55]. Moreover, the parametric modelling capability observed in BIM can be used as a basis to trigger an innovative workflow in planning modular and prefabricated construction. If the technical monitoring frameworks necessary for such workflows are implemented, waste in such construction projects can be minimised considerably [56]. For example, Ramaji and Memari [36] presented a specific product architecture information model for modular multi-story buildings. To increase design and production efficiency, they employed Level of Details (LoDs) available in BIM to address construction issues encountered in the design phase and align LoDs and different levels of their product architecture model.

Other research studies focused on the maximum increase of design process efficiency through implementing BIM parametric design tools in developing designs based on a DfMA method; where all the requirements in ‘design’, ‘production’, and ‘assembly’ of PBs are achieved to prevent repetitive work in these three stages. For example, Yuan et al. [15] proposed an innovative framework for DfMA implementation using BIM parametric modelling for domestic housing. Once modelling was completed, the production information model of the house was optimised. If all the production and assembly requirements were met, the model was sent to the production unit. Such a framework can use the BIM family templates and API to create the needed elements and assembly functions not existing in BIM as BIM-redevelopment. The newly created elements are subsequently added to BIM standard parametric prefabricated component library. Following a lean construction and DfMA methodology, Gbadamosi et al. [57] proposed an effective method for optimising the assembly process of prefabricated elements. In their study, Revit software along with a Dynamo algorithmic environment was implemented to benefit from the parametric modelling capability of BIM and to transfer design information using Industry Foundation Classes (IFC) format.

Similarly, Li et al. [58] emphasised the need for an integrated conceptual framework to understand present studies and signpost future research based on BIM capabilities. Moreover, it can simplify the process of decision making by OSC stakeholders. In their proposed framework, the parametric capabilities of BIM and data exchange through information format constitute a key role. This framework was used as a basis to develop a design for X(DFX) strategy.

2.2.3. BIM as a collaboration tool

The built environment has been perennially caught up in a low productivity problem for a long time [59]. Poor collaborative processes and lack of productive information exchanges have been identified as primary reasons for this [60,61]. In addition, the discontinuity between design and construction has been cited as a significant contributor to this problem [51,62-68]. However, it has taken major developments in digital technologies like the Internet, project extranets, BIM, and the Internet of Things (IoT) to generate the kind of optimism that the industry has never experienced before. The built environment is not alone in sharing the excitement around these technologies. These technologies have captured the imagination of just about every industrial sector. But, of course, no technology can result in addressing the challenges of any industry on its own. A set of complementary processes [61,64] needs to be developed in tandem for the technologies to enable change effectively. Quite encouragingly, such processes have been developed recently, particularly in information management and collaborative working in the built environment sector.
These are positive developments and whose integrity and effectiveness will be tested over the next few years.

Meanwhile, the wider world (including the built environment) is experiencing a paradigm shift due to the industry 4.0 revolution. Recent technological and other process-based advances and innovative technologies in the built environment mentioned above have a key role in this process. As widely reported in the popular and scientific media, the nine pillars supporting Industry 4.0 are 1) The Internet of Things, 2) Big Data, 3) Augmented Reality (AR), 4) Advanced Visualisation, Virtual Reality (VR) and Simulation, 5) Additive Manufacturing, 6) System Integration, 7) Cloud Computing, 8) Autonomous Systems, and 9) Cybersecurity.

In the built environment sector, these nine pillars can be underpinned by BIM, widely regarded as the tool of choice to address key issues as industry fragmentation, value-driven solutions, decision making, client engagement, and design/process flow to name but a few. Therefore, it could be argued that Construction 4.0 has ten pillars, including the nine Industry 4.0 pillars and BIM [69]. Exemplars from other industries such as automotive, aerospace and oil and gas currently demonstrate the power and application of these technologies. However, the built environment has only just started to recognise terms such as “golden key” and “golden thread” as part of BIM processes and workflows. Construction 4.0 offers a portfolio of potential solutions to bridge the knowledge and information gaps between design, construction and operations [70,71].

This has led to the emergence of a series of cutting edge technologies in the AEC realm, including but not limited to virtual reality-based collaboration technologies [63], artificial intelligence-based optimisation [72], data-driven decision support [73], smart data modelling [72], blockchain and distributed ledger technologies [74], and computer vision and graphics [75,76]. For example, these advancements can now assist decision-making in predicting the cost and performance of optimal design proposals [77].

Advancements in cryptography and read-only data management optimisation are paving the way for fully-fledged distributed ledger technologies for digital twinning and asset lifecycle management. Previous research has demonstrated real-time centralised solutions for openBIM. Collectively, these developments are forcing a paradigm shift in design from asynchronous to real-time data exchanges. This ultimately can improve inter-organisational perceptions of social presence [78] and imbuing confidence in the design shift expected of openBIM standards and the neutral information format of IFC [79,80]. Consequently, several research studies have sought to increase the quality of collaboration in the design stage. For example, Rahimian et al. [63] enhanced the quality of client collaboration in the design section in OSC, implementing open-BIM standards, IFC format, along with BIM parametric characteristics (attributes) to transfer neutral design information to a BIM server and to connect (relate) the information to the Unity environment. This enabled the graphical information of buildings and their elements to be visualised and displayed in immersive environments such as VR and AR for the client, thus providing effective interaction with low latency with the design team. Apart from these technical characteristics for fostering collaboration between the client and design team, the PAS 1192-2 standard [81] offers guidelines under the title of a common data environment (CDE), which describe how the different parts of the design team interact with one another and with the client.
These guidelines are provided to engender systematic interactions during the various stages of designing buildings.

In summary, in addition to the parametric capabilities to increase supply chain process efficiency in general and the design process of PBs, BIM can facilitate collaboration between project stakeholders [4,59,75,82-84]. Furthermore, BIM can support participatory working during design and decision-making processes thanks to the inherently systematic and ontological information representation structures.

2.3. Summary of the literature

Collecting, processing and integrating multi-aspect information from construction projects is vital for meeting sustainability metrics and cost and time related Key Performance Indicators (KPI) [63]. This needs to fully cover design decision drops, technical specifications, client preferences, building materials and assembly. Yet, as stated in Section 2.2.1, due to the complex supply chain issues, there is always the risk of the disrupted flow of information among the various stakeholders involved in PB projects.

A review of extant literature suggests that the design stage in OSC is of paramount significance partly because of the unique characteristics of PBs. If undertaken properly and efficiently, it can prevent cost escalation and project overruns in the design stage and, consequently, all supply chain stages. Moreover, it was emphasised that a hybrid combination of DfMA and the capabilities of BIM tools in the design stage could both facilitate the design process and increase the efficiency of the manufacturing and assembly stages in OSC. However, although many studies are completed on increasing design efficiency and mass customisation in OSC, there seems to be a shortage of studies aimed at studying customer satisfaction during the design stage in OSC projects. Moreover, scant research has investigated how the client can collaborate effectively in the design stage of PBs and their elements. In more specific terms, despite a myriad of capabilities offered in BIM applications for leveraging collaboration among different stakeholders of construction projects, there is still a practical and theoretical gap in the body of literature for supporting clients' engagement within the process of customising PBs. The lack of research in these areas substantiate the primary motivation for the present study.

3. Research methodology and framework

3.1. Research methodology and design

This study adopted a sequential mixed research methodology comprising five phases: 1) Identifying the client engagement issues in the OSC design stage 2) Establishing customisation principles 3) Developing a new design framework 4) Developing a proof of concept prototype 5) Evaluating the results through discussions. Further details of these five phases are depicted in Fig. 1 and the subsequent paragraphs.
In the first phase, the current issues in the OSC industry (including limitations and complications experienced in the prevalent customer requirement-oriented methods) were diagnosed using an extensive literature review. Then, focusing upon achieving effective client intervention in the design process as one of the most important variables influencing PBs’ design [85], and effective design procedure for PBs was developed in this study. This was achieved by examining the inherent potential of the OSC process for client intervention in the design process of such buildings to establish a new framework. Such a framework adopts the principles of OSC to maintain a high-efficiency rate in OSC but also an anticipated increase in customers’ satisfaction with the final product. Additionally, automation of the configuration process was undertaken to enhance the design quality of PBs, which can engender higher production and assembly qualities [57,86].

The proposed framework with the features above can boost the market share of OSC in the AECO industry through implementing a purposeful client collaboration and ensuring a high-efficiency rate for companies providing PBs. However, it must be emphasised that tackling this problem in OSC through lean design methods (which emphasises both production efficiency and customer satisfaction [87]) is an enormous and challenging undertaking. PBs are considered a sophisticated product is comprising diverse, complex elements. Therefore, an abundance of choice per se is not considered an advantage. Conversely, facing too many options sometimes does not necessarily manifest as customer’s satisfaction. Rather it may cause customer confusion, impacting their decision-making process negatively to own a PB [42].

Several studies focus upon client requirements in the OSC design process. However, there is a shortage of theoretical and practical studies to develop an effective BIM-based framework for the design process. As a result, the client requirements and needs for element customisations and building configuration have seldom been systematically considered in the design process of such buildings. Mohammed [87] presented a data-rich BIM design environment integrated within an expert system to develop a set of rules (principles) relevant to the design requirements of PBs, and to examine these rules throughout the design process. Although design principles developed in this study were based on the client design requirements, the solutions proposed were limited only to the Engineer-to-Order (ETO) level of COPD. Li et al. [58] presented a framework in which the BIM capabilities were implemented in the production of PBs to facilitate data exchange and collaboration throughout the supply chain process using three integrated intelligent solutions. Yuan et al. [15] implemented a DfMA model for designing PBs and sought to increase the efficiency of the design process using BIM’s parametric capabilities. However, this study [15] did not focus on managing client requirements or intervention in the design process. All three studies mentioned above implemented BIM capabilities to develop effective frameworks and solutions that facilitate design information flow to improve the efficiency of the design and production processes for PBs. Despite this scientific advancement, there remains a notable lack of a BIM-based framework which incorporates the design and production requirements of PB but also embraces the client’s requirements related to different levels of customisation. To develop a balanced relationship between these three areas, the present study primarily aimed at developing a sound theoretical foundation underpinning an applied framework for client collaboration in
design process, and to implement some integrated strategies to realise it in such a way that all these
three key areas are considered from the early stages to the final stages of design. Fig. 2 illustrates
the three objectives of the present study viz. ‘customer’s satisfaction’, ‘sophistication in design’
and ‘production efficiency’. These objectives respectively seek to improve the quality of the three
key areas of marketing, construction and production in the OSC industry.

Considering the objectives set and based on the research gap diagnosed in the first phase, the
second phase of this study developed principles (regulations) controlling the client collaboration.
These principles hinged around three key constructs, namely customisation approach, customisation levels, and customisation stages. A BIM-based DfMA design framework was
developed in the third phase to incorporate the established principles in designing PBs. In the
fourth phase, to examine the practicality of the proposed collaborative design framework in the
real AECO world, a Prototype was developed in Revit environment. The integrated approaches
proposed in the present study were implemented to put the present client-intervention oriented
framework into practice. In the fifth phase, the results were discussed against the studies conducted
on the design process in PBs, and client collaboration.

3.2. Establishing customisation principles
For this present study, a customisation approach was considered as one of the most fundamental
guiding principles. Consequently, the allowable rate of client customisation (to control the degree
of client collaboration in the design process) needed to be determined as a second principle.
Notably, however, the customisation rate allowed for the different building elements by the
company is different from the approach the company follows for the customisation of its products.
Finally, the customisation stages which are to be integrated into the design process were
determined as the third and last principle based on the two principles developed already, in which
the stages of the customer’s interaction and needs for customisation are determined

3.2.1. Customisation approach
Collaborative customisation [cf. [88]] was used as a basis for the client customisation. According
to the approach, companies providing customisation OSC services first gather detailed information
concerning the client customisation requirements and then create various building element models
based on these requirements. These models can be adjusted and customised to a limited extent
based on customer requirements. In addition, the company enables the customer to participate in
the building’s configuration within a controlled range, allowing them to choose from the models
provided before.

3.2.2. Customisation levels
The theoretical continuum with five mass customisation strategies (from pure standardisation to
pure customisation) proposed by Lamper and Mintzberg [40] was used to classify the
customisation levels allowed for the client. This theory provides the company with a basis for
determining the CODP of building elements flexibly that considers diverse variables such as
resources, economic and technical considerations.

3.2.3. Customisation stages
The three different stages of customisation in the OSC design process are shown in Fig. 3. In the first stage of the proposed procedure, the company’s customisation strategies for various building elements are determined. In the second stage, the company allows the customer to determine their customisation requirements based on the customisation limitations specified in the first stage. The client requirements are classified into different customisation levels. Based on the client customisation requirements in the third and final stage, the company provides various building element models and the necessary information concerning their assembly and production. The company then develops the building configuration by selecting from among the alternative building element models provided.

<Insert Figure 3 about here>

### 3.3. Proposed design framework

The DfMA framework proposed by Yuan et al. [15] was employed as a basis for the design approach developed in the present study. The customisation principles introduced in Section 3.1.3 are integrated with this DfMA process to establish a new design framework. The customisation principles found in the previous section were then incorporated with the DfMA framework. In line with this integration, some rules have been added to this process and some need to be changed. To implement the first stage of customisation, the company must provide customisation services for PBs to determine the desired amount of customisation for all elements used in the building design. Since this determination depends on the company resources, this stage must be performed without the direct participation of the customer and by the company’s marketing strategists. However, the company can use surveys of its target market before determining its marketing strategy. However, they must consider the average level of customisation that people apply in the preceding cases and build their strategy based on it. It is also necessary for this strategy to be flexible so that if the market tastes change, the strategy will adapt to the market's new needs. In the next stage, which begins with a contract between a customer and the company, it is necessary to extract the customer’s customisation needs within the customisation constraints set by the company before starting work on the design of building elements. These needs are categorised at different levels of customisation for each of the elements used in the building configuration. After this stage, various prefabricated building design experts begin to provide complete design information for these elements. As a result, a comprehensive model of each of these elements is available in building configuration. Finally, in the third and final customisation stage, the prefabricated building is configured using the mentioned elements with the customer's participation. The final model of the configured building is made available for final technical tests. Fig. 4 depicts the developed DfMA framework in this study. The stages directly dealing with the three customisation stages proposed are specified with dashed lines.

<Insert Figure 4 about here>

### 4. Prototype development

The proposed DfMA framework (section 3.2) and solutions to implement its stages, especially those which involve the presented customisation stages in the design process, constituted the basis for a prototype development using Revit software. The prototype served two simultaneous purposes: 1) introduce research solutions to put the proposed framework into practice; and 2) examine the framework’s practicality in a real-life project that utilised a BIM tool. A complete
realisation of the proposed framework is beyond the scope of the present study due to the diversity of building elements in PBs. Therefore, the windows category was used as an illustrative sample to examine the customisation and design functions. In addition to Revit software, the Dynamo plugin available in this software was used for the configuration algorithm’s implementation in the building design process. Moreover, when some of the required functions were unavailable in Dynamo or their production was complex and time-consuming, Python script was used in Dynamo to tackle the problems.

4.1. Determining customisation information

4.1.1 The company’s customisation strategy

The PIM hierarchical model was used as a basis to determine the company’s customisation strategy; this model aligned product architecture levels of each building with their corresponding LoDs. More specifically, the building and category levels were aligned at LoD 100 and LoD 200, respectively, and element type and component levels, which are related to the physical parts of the building, were aligned at LoD 300. Mass customisation was considered the third parameter in the proposed model to determine the company’s CODP levels. Thus, based on the proposed model, the company can simultaneously determine the CODP for each potential element and component from the production and design perspectives. The company’s general customisation strategy assumed that it considers a customised standardisation level as the maximal customisation allowed for window types level with LoD 300 when determining the window specifications. In other words, at the highest level of customisation, the customer can make minor modifications in the standard components of the window, replacing choices made with common structural components and ironmongery.

Moreover, by limiting the window component level with LoD 300 to pure standardisation, the company allows the customer to customise the window components in terms of features. Customers have to choose among the available standard components offered to them. Determining the company's CODP for windows mass customisation is the first of three customisation stages are presented in section 3.1.3.

4.1.2. The client’s customisation requirements

It is assumed that the customer’s needs for customising windows have been extracted as customer employer’s information requirements (EIR) through questionnaires and have been classified in PIM by customisation experts. Based on this classification, the customer wants the design section to select two of the four building windows related to a living room. Thus, the company classifies these two windows as pure standardisation. However, if the client chooses windows for the rooms from commercially available designs, the company classifies the room windows as segmented standardisation. Moreover, it has been assumed that based on the information available in the EIR, the customer wants the two identical windows for the building’s public space and the other two windows of the two rooms to be identical too. Therefore, in the final model, there are only two types of windows to be used. This is the second stage of the customisation process presented in section 4 above.

4.2. Design and customisation process
4.2.1. Specifying design information for configuration stage

Once the non-prefabricated construction information model was developed and the DfMA and Split Design analyses were conducted, the exact window specifications to be used could be determined. The window models were designed using the proposed DfMA framework in the BIM environment according to the LoD 300 considered in the PIM model. Because the customer’s potential choices are limited to the standard commercially available windows, their Revit models, including their graphical model and manufacturing and assembly information, are downloaded from their manufacturer’s websites and imported into the Revit library. Fig. 5 reveals that the final output of the stages completed so far was four different window models from four different types. As mentioned in section 4.1.2, only two of these four window types were used in the building. Finally, it should be noted that if the customisation level considered for the elements is customised standardisation or more, it is necessary to exclusively design the needed elements based on the client requirements for the window elements, which were already provided in the form of EIR.

Post window models’ design and manufacturing information were determined through a DfM process (implemented in the BIM environment). The assembly information is derived from the DfA process in the same environment. The proposed framework’s DfA process consisted of two main steps: 1) determining assembly limitations; and 2) determining assembly requirements. Accordingly, the proposed prototype examined the assembly limitation between windows and their host wall. Before the configurations process, the allowable choices for windows could be specified based on the host walls. In this way, the host walls could be considered a limiting factor in selecting window types from among the choices offered - assembly limitations are shown in Table 1. Because BIM supports the assembly requirements of all four types of windows through Assembly Code Parameter (Fig. 6.), there is no need to redefine this parameter for these types of windows. In addition to windows, the assembly requirements of their host walls are also defined by the same parameter.

As it can be seen in Fig. 7, the company’s CODP for determining the customisations limits for the building windows (discussed in section 4.1.1) are shown with a solid red line in the PIM model. This model also shows the classification of customer customisation requirements based on CODP levels (discussed in Section 4.1.2). In addition to customisation information, the names of the four suggested windows in which their design models were produced previously in the BIM environment (section 4.2.1) are shown in this figure. More specifically, so far, in addition to the graphical model of these four windows, their manufacturing and assembly information, along with the assembly requirements of their host walls, have been determined by the BIM authoring tool. Now that their BIM and PIM (containing information concerning window customisation and functional relationships of building
components) models have been determined, all the necessary information is accessible to develop the building configuration algorithm for customising windows.

4.2.2. Customisation through configuration algorithm

In this stage, it was necessary to develop an algorithm based on two key pieces of information. First was the building product architecture which provides information about the functional relationship among all building elements. The second was the DfA information which provides details about assembly limitations between elements and assembly requirements of each element. For further clarity about the presented configuration algorithm, the following paragraph provides an overview of the development strategies of this algorithm how it relates to these two pieces of information.

First, the architecture of the PIM model is used to assess the existing functional relationships between the various elements of the building. Second, suppose a functional relationship was determined between a host element (e.g. element A) and a mountable element (e.g. element B). In that case, the technical assembly considerations of each element will be loaded from the DfA section of the design framework. These will set up limits for their assembly relationship. If, in light of the assembly constraints, it is possible to connect or place element B on element A (i.e. there is no limit to the assembly), the assembly information related to the relationship between the two elements will be precisely defined and formulated. In this case, whenever element A is selected as the “host element”, element B will be considered as a “customisation option”. Otherwise, element B will not be introduced as an option for assembly on element A. Consequently, there will be no need to define and formulate the relationship between the two elements. This process is illustrated in Fig 8.

<Insert Figure 8 about here>

However, providing a configuration algorithm for a whole PB entails a comprehensive understanding of relationships among all building components. Therefore, an algorithm based on the product architecture information available in the PIM (as discussed in Section 4.2.2) specifying the exact functional relationships between the different prefabricated elements was used to develop an integrated strategy for the proposed design framework. The functional relationship available in the product architecture determined the connections between the nodes of the algorithm, which constitute the element types of different categories (refer to Fig. 9). Therefore, choices in the element type section can limit the selection of element types that are functionally related to those choices.

<Insert Figure 9 about here>

Moreover, the Dynamo plugin available in Revit software was implemented so that the proposed algorithm could be used to configure the building and its designed window models in this prototype. This configuration process (which is based on the inputs needed to execute the function of creating a window on a host wall in Dynamo) consists of determining three main steps: 1) the host wall; 2) the location of the window on the host wall; 3) the window type. However, to help secure a better grasp of the innovative limiting mechanism as the main functional feature of this
algorithm, it was assumed that the first two steps were completed, with the primary focus being on the last step of determining the window types. Thus, in the limiting mechanism developed, the input nodes include the host wall and the list of available window types. At the same time, the output contains a filtered list of windows based on the assembly limitations of the selected host wall. Because the necessary function for the extraction of all windows available in the Revit family was not available on Dynamo and its packages, it was required to use Python scripts to create such a function.

Moreover, to create a node with the function of the limiting mechanism, an attempt was made to define a specific number of window assembly codes for all assembly codes of the host wall choices. Once a given host wall was selected, a list of window types (which have assembly codes matching with the assembly code of the wall) resulted in the output of this node. Fig. 10 shows how Python script was used to develop this function.

After a list of windows is designed based on the customer's customisation needs and the manufacturing and assembly requirements of PBs are provided, the customer can choose a preferred window type available in the configuration algorithm. Thus the last of the three stages of the customisation supplied in the proposed DfMA framework is completed. Fig. 11 summarises how the window types are selected in Dynamo and installed on the host wall in the Revit environment. This figure reveals that according to the client customisation requirements translated in the form of customisation levels in PIM (Fig. 7), the two southern windows of the living room are selected by the design section. In contrast, the client can decide on windows 3 and 4 from among the four suggested choices. Moreover, because the client’s customisation requirements in PIM entail windows 1 and 2 to be of the same type and windows 3 and 4 similar, the algorithm is programmed to select these windows two by two.

The proposed algorithm provides a flexible framework for the configuration because its parametric structure allows the design section to make necessary changes even after the customisation stages are completed. If the client decides to change their choices, the proposed algorithm can incorporate the new selections automatically based on the assembly requirements. Moreover, the design section introduces new window types and host walls so that the new choices can be easily added to the Revit Family environment. The new elements are inserted automatically into the relevant inputs available in the Dynamo environment. After the limiting mechanism is updated based on the assembly codes of the newly added elements in the configuration algorithm, they will be available to be selected by the customer or the design section.

After the configuration and optimisation steps, DfMA tests are performed on the building model again. If the results are confirmed, reliable information on PB's customisation, design, and production is provided in PIM and BIM models. Therefore, the construction and production sections can access the needed information included in these models before projects commencement.

5. Discussions
Over the last few decades, many research studies have emphasised the importance of customer intervention in the design stage, presenting innovative approaches to facilitate customer collaboration [21,89-92]. Because BIM has proved effective in reducing rework and the economic and environmental costs caused by the waste of materials [93-95], it can be implemented as a design tool to simultaneously meet the customer’s requirements and those of the OSC industry [96,97]. In this regard, the literature reviewed uncovered that an increasing body of research studies have emphasised the unique technical data exchange capabilities of BIM along with immersive technologies such as AR and VR through open BIM standards and IFC information format [4,29]. Numerous studies reveal that these capabilities can create innovative solutions for the collaboration among individuals and different parties engaged in such buildings [63,98-100].

However, a notable dearth of studies sought to provide a design framework for these buildings; a framework in which due attention is paid concurrently to these buildings’ customer requirements and construction efficiency. More specifically, delineating how the customer collaborates with the design section from the early to final stages of the sophisticated design process. One solo research project in this area presented a solution based on providing different building configurations by various pre-designed components and building assemblies designed according to production, construction, and assembly [101]. Yet despite this research, the focus of attention predominantly is upon customer requirements at the configuration level, ignoring the basis for the customisation of building and its components throughout the design process.

The design framework presented, along with the practical integrated approaches for implementation in OSC industry, can be used as a foundation to determine the client collaboration with the design section of this type of building. Consequently, the results obtained in the present study are relevant to the stages before data exchange between the client and design section and advance previous studies conducted in this area. Compared to the collaboration process defined in BIM standards such as CDE available in PAS 1192-2-2013 standard [81], the collaboration framework proposed is developed specifically for prefabricated buildings and their elements. Moreover, since the present framework enables users to take advantage of an algorithmic process for building configuration with the customer collaboration, many design rework items commonly experienced in traditional client collaboration processes can be avoided. In addition to this, due to the parametric configuration algorithm available for selecting the elements, the time and economic costs imposed by possible future changes are minimised. Finally, because all the assembly requirements are observed in this algorithm, the risk of error occurrence in the assembly stage is minimised. Consequently, the need for design and production rework is considerably reduced.

However, there are some practical and functional limitations with the research presented. For example, although there are solutions to customise the elements in the proposed framework, it lacks solutions for customising the building layout. The present study’s primary purpose was to develop a theoretical framework for the collaboration of the customer with the design section. Consequently, a prototype was created to examine the proposed model’s practicality. However, the study presented lacks empirical data obtained through implementing the proposed framework in different case studies. Consequently, usability, advantages and disadvantages require future testing on real-life projects.

Future studies should provide a digital information model that can integrate the PIM model developed with the BIM Model. Integration of the information gathered from the beginning to the
end stage of the design process can make access to information related to the production, assembly, and customisation of the elements (and their relationship with other elements available in the product architecture) easier all stages the design process. Moreover, cloud-based environments can provide zero-latency communication between the customer and the design section [102]. When the design and customisation information of the elements and the configuration algorithm developed based on the framework proposed is uploaded onto the cloud-based environment, a user interface can be created in the background, which can offer easy access to, and use of, the configuration algorithm for the customer. Moreover, BIM and blockchain technology [103-105] can be combined to facilitate smart contracts and payments for the customisation activities in an automated peer-to-peer method. In this way, a customer’s confidence will be augmented like the collaboration offered by the present framework. In addition, to automate OSC industry [106], it seems possible to provide strategies in which the production and assembly information present in the PIM and BIM models can be automatically prepared and exchanged for robotic manufacturing and assembly processes after the design process is completed.

6. Conclusion

This research makes several contributions to the fields of digital design and marketing in the OSC industry. First, a DfMA-based framework was provided and based upon customisation principles, thus enabled simultaneous emphasis to design principles of PBs, and customer satisfaction so that the client can customise building elements and components to the extent permitted by the company. Second, the proposed framework for the building design customisation stage contains an algorithm that allows the client to participate in the building configuration process based on assembly limitations. Third, in addition to the theoretical framework offered, this research study uses the BIM environment for the element design and building configuration process. Moreover, an innovative information model for gathering different types of information concerning PBs and their elements (including customisation, product-oriented and building construction information) was developed to relate the theoretical concepts with these fields' practical and technical issues.

Compared to the current strategies offered to implement prefabricated construction frameworks, the PIM model provides marketing experts with a product and building-oriented understanding. This feature enables them to determine the company’s customisation strategy for the products they offer from a more comprehensive perspective and to define and classify the acceptable levels for client customisation based on this customisation strategy. Furthermore, the product architecture levels available in this model enable the experts in the DfA section of prefabricated buildings to determine all the available information concerning the functional relationships between the elements and the physical components, which can be used in the design process. In addition, the general information about the elements and components used in this product architecture can guide building element(s) and component(s) design throughout the design process. Finally, the customised PB’s product architecture information and manufacturing information in the BIM model can be used as reliable information to start the production process.

Moreover, the design experts can use LoDs to determine the level of work and care needed to deal with the design details in the design process of elements. Upon conclusion of the design process, the LoDs of the different elements and components included in the product architecture of the customised building can provide reliable information for the construction process to start. The idea of a configuration algorithm was developed to properly use assembly and customisation
information inside the innovative model to achieve high-quality output. In addition, the assembly
requirements determined in the BIM model for the elements were used to automate the provision
of customer choices to enhance their satisfaction and mitigate the risk of production and assembly
errors (mistakes) caused in customisation and design processes. Indeed, the ultimate purpose of
the strategies offered for the best implementation of the present theoretical framework was to
courage customers in the construction market to opt for OSC through meeting their preferences
(requirements) while minimising material and time waste. The strategies' practicality was
examined by developing a prototype for customising building windows considered a sample
category. It was observed that all the proposed methods in the framework for the design and
configuration of elements using the Revit tool (considered as the most commonly employed BIM
tool) and an intermediate level of coding showed good usability.

Despite the considerable positive aspects of the present study, there are several limitations.
Foremost, this study exclusively focuses on expediting client engagement within PB design, whilst
other projects have similar needs and requirements. Although it would be great to generalise the
developed framework and algorithm to all types of buildings design, this wasn't feasible to do it in
a single study as the fundamentals of collaboration for PBs differ from any other kind of building.
This is due to the DfMA approach being a prerequisite of this kind of buildings so that it
encompasses all vertical and horizontal relationships among various building elements. Due to this
fact, the designed algorithm could not be applied in designing any other kind of building. Second,
there is no customisation framework for building layout that considers all the construction
requirements and is integrated with other design stages. Nor does a suitable user interface exist
that can be used to examine the practicality of the client collaboration with the design section in
building configuration. Hence, it is suggested that a communication server and a visualisation
environment be used along with a new version of the proposed framework and upgraded strategies
such as a simple interface that customers can use with ease to receive immediate feedback on their
selections. Finally, it is suggested that the PIM model be digitalised to be fully integrated with the
BIM model, which can facilitate the flow of information along with the proposed framework, in
general, and in the configuration stage, in particular.

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Fig. 1. The five-step sequential mixed research methodology and design

Phase 1
- Identifying the customer collaboration issues in OSC design stage
- Using an extensive literature review

Phase 2
- Establishing customisation principles
  - Customisation approach
  - Customisation levels
  - Customisation stages

Phase 3
- Developing a new design framework
  - Selecting a reference framework
  - Matching the reference framework with the customisation principles

Phase 4
- Developing proof of concept prototype
  - Using Revit software as a parametric environment and Dynamo plugin as an algorithmic environment

Phase 5
- Evaluating the results through discussions
  - Using related studies conducted on the OSC design process

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Fig. 2. Areas and objectives of current research and the desirable relationship between them
Fig. 3. Intended stages to customise prefabricated building

Stage 1
Determining the company's customisation strategy

Stage 2
Determining client’s customisation requirements

Stage 3
Performing collaborative customisation
Fig. 4. The proposed DfMA framework for achieving research objectives
Fig. 5. Various types of windows usable in the building
Fig. 6. Determining the assembly requirements for the windows using assembly code parameter
### Table 1 Assembly limitations of different window types and their host walls

<table>
<thead>
<tr>
<th>Host walls</th>
<th>Windows to be assembled</th>
</tr>
</thead>
</table>
| EXT _ Timber Frame - 250mm - Filled | a) M_Fixed_0915 x 1830mm  
                      | b) Intakt-inward_opening_window_2+1_glass_3-light_with_mullion-middle open  
                      | c) Window-Horizontal_Sliding-PlyGem_WC-LessHalf_Vent |
| EXT _ Composite - 250mm - Filled | a) M_Fixed_0915 x 1830mm  
                      | b) Intakt-inward_opening_window_2+1_glass_3-light_with_mullion-middle open  
                      | c) Window-Horizontal_Sliding-PlyGem_WC-LessHalf_Vent |
| EXT _ CLT - 150mm | a) M_Fixed_0915 x 1830mm  
                      | b) Intakt-inward_opening_window_2+1_glass_3-light_with_mullion-middle open  
                      | c) Window-Horizontal_Sliding-PlyGem_WC-LessHalf_Vent  
                      | d) Window-Solar_Innovations-Tilt_Turn_SI7251 |
| EXT _ Light Gauge - 200mm - Filled | a) M_Fixed_0915 x 1830mm  
                      | b) Intakt-inward_opening_window_2+1_glass_3-light_with_mullion-middle open  
                      | c) Window-Horizontal_Sliding-PlyGem_WC-LessHalf_Vent  
                      | d) Window-Solar_Innovations-Tilt_Turn_SI7251 |
### Fig. 7. The PIM model of the building windows

<table>
<thead>
<tr>
<th>Product Level</th>
<th>Category Level</th>
<th>Element Type Level</th>
<th>Component Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure standardisation</td>
<td>Segmented Standardisation</td>
<td>Customised Standardisation</td>
<td>Customisation</td>
</tr>
<tr>
<td>Prefabricated Building</td>
<td>Window category</td>
<td>Window number 1, Window number 2, Window number 3, Window number 4</td>
<td>Window Components</td>
</tr>
</tbody>
</table>

**Fig. 8. The concept of the assembly limitation between building elements**

- **Step 1**: Checking functional relationship based on building product architecture
  - Element A
  - Functional relationship with
  - Element B: Valid
  - Element C: Invalid

- **Step 2**: Checking assembly limitation based on technical considerations
  - Does element A limit the choice of element B?
    - Yes
      - Element B as an option
    - No
      - If element A is selected do not return element B as an option
Fig. 9. The concept of building configuration algorithm and choice limitations
Fig. 10. Executing the limiting function of the windows based on the host wall using Python script
Fig. 11. Selecting the preferred windows using configuration algorithm created in Dynamo and the resulting output