# Sum of the Parts: Leveraging BIM to achieve effective delivery of mass customised housing

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## Abstract

The UK housing market has, over the recent 5 years experienced considerable economic pressures both from the market place and from the construction sector. The need for an economic and mass produced housing type that specifically targets the market to achieve the balance for the need of affordability and the benefits of mass customisation is a key focus for delivery.

This study sought to deliver a mass produced housing system that could also deliver a high level of customisation. Historically housing that has been mass-produced to ensure affordability, has removed a high level of customisation to ensure that the final costs were controlled. This paper also examines the design factors that are integral to the process of delivery affordable housing, and observe the gaps between affordability and mass customisation of a modern method of construction delivered project. The move away from traditional methods of delivery and a shift in the procurement of the design for such housing typologies.

## Keywords

*Mass custom design; architecture; low-cost; UK; Modern Methods of Construction; timber frame; off-site.*

## Introduction: Housing delivery in the UK - from traditional delivery to off-site construction methods

In 2006 the BoKlok approach to affordable housing was launched in the UK to great acclaim. As the name suggested BoKlok literally translated means live smart. The concept was created originally in the 1990s by the joining of IKEA and Skanska in Sweden. The fusion of these two large companies brought together a strong design company that understood the market place and customer needs for affordable housing, with a construction company with over 100 years constructional experience.

*Image 01: Initial Concept for BoKlok UK House types, Architect: David Morton. (Image: D.Morton)*

BoKlok's parent company IKEA are an organisation that are strongly orientated towards its market. The products designed, produced and delivered to IKEA stores is based on needs, demands and selection criteria of their customer base. The products sold within the stores are developed from the initial idea to product launch in house involving economic, technical and market driven factors derived from analysis of the companies' clients and customer base. This approach allows the company to learn from its customers' needs and buying behaviour and predicting to some extent, the potential needs and requirements that may well occur in the future. This is analysed and structured through use of both the Manufacturer-Active and Customer-Active Paradigm. The Manufacturer-Active paradigm (MAP) and the Customer-Active Paradigm (CAP) were originally defined by Eric von Hippel in 1978. These paradigms explain a structure of opportunities that could be utilised by an organisation that arise from the market the company supply, for generating new ideas with the customers input and feedback from the initial stages of development. Customer feedback can create better market intelligence that can increase market strength in the short term, followed by market predictions in the long term.

*Image 02: Completed BoKlok UK Housetypes, Architect: David Morton. (Image: D.Morton)*

Founded in Malmo in 1987, Boklok was formed with the aim of unifying the use of technology to deliver both a system of delivery for mass produced housing whilst retaining the individual need, from the customer perspective, of customisation. The original concept for BoKlok as a direct response to the market need for low priced housing in Sweden in the mid-1990s. For a period of 10 years prior to the Millennium, there very limited private housing built even though demand was high. In 1995, the BoKlok concept team was formed and later, in 1997, the initial BoKlok houses were completed. The concept was then extended to other Nordic Countries and in 2006 launched in the UK. The BoKlok house types are known collectively as 'Generations' or Gen1 for the apartment type blocks and Gen2 the first BoKlok housing, developed in conjunction with British Architects. The design approach allowing for an open plan flexible living format on one or two floors, with kitchen, dining and wet rooms providing the serviced spaces.

## Theoretical Background

The proposed theoretical model for this study has its origins in the automation of fabrication and design. Duarte and Simondetti (1997) implemented the original model initially. This model was further developed with the introduction of the generation of 3D abstract objects that allowed for the fabrication of these models utilising rapid prototyping. Wang and Duarte (2002) developed the computer programme that allowed the generating of the abstract objects and codification of the models elements. Duarte (1995) proposed the first general model for integrating housing design and production as one combined approach. The fundamental element of the model was in the codification, creating a series of house types.

*Image 03: BoKlok Generation 1 Apartments timber framing system under construction (Image: D.Morton)*

The underlying paradigm that architects have persistently endeavoured to solve is the standardisation of components and the systemisation of the construction process, the combination of which was seen as the panacea to affordable housing. The primary issue with this paradigm in past endeavours was that it created minimal customisation. Mass production is not new in many not construction industries, such as motor vehicle manufacturing. Historically, Henry Ford, who mass-produced the Model T in 1910, created the concept of mass production in this industry. The famed quote of Ford at this time was that you could purchase a Model T in any colour as long as it was black. Many researchers' have taken this as to offer one colour was inherently cheaper to produce. The actual reasoning behind this choice was the fact that black paint was faster drying, so the production line could be operated at faster rates.

Such combinations of factors that look at design, materials and processes have yet to be used in the broader observation of the affordable housing market. For example, current purchasers of motor vehicles today are offered many customised options such as trim colour, exterior colour, wheels and more. These options are accounted for in the construction, or in this case, the build process, but do not affect the final completion date at the end of the production line. These options allow for customisation of a mass produced product, the question being, it should be possible to affect the same modus operandi in the construction industry producing affordable housing.

## Origin of Study: The Mass Production Concept

This study has its origin in the concept of mass production for the affordable housing market. The concept on mass production has been discussed earlier in this paper, with the concept of the production line from Henry Ford in 1910. During the 1970s the new wave of production began with Toyota using the concept of so called lean production. This concept took the original production line methodology and removed the waste from the process. This so-called waste was a combination of time and cost in the processes that serially followed on to each next stage. The solution in the main was to develop just in time delivery procedure. These procedures minimised storage and the need to collect materials and deliver them to the production line. Instead, the materials or components would be delivered directly to the factory and taken straight to the location needed to build the final product. This process was developed further to optimise the time and cost, via the removal of element of the production process as a pure linear process.

The product was now delivered using smaller teams gather around the product to complete smaller combined tasks. The repetition and variation of tasks created higher productivity amongst the workers. What has been termed 'the third wave' of lean production began to emerge from these, the idea that along with mass production, the need from the end users for personalization or customisation could be achieved. Alvin Toffler first predicted the concept of mass-customisation in 1970 and again in 1980 in his book 'Future Shock'. However, Stanley Davis in 'Future Perfect', (1987), coined the term 'mass-customisation'.

## The Study and Methodology

Purpose and Scope of this research was to capture how the use of BIM in the mass customisation of affordable housing. The justification behind this research originates from the need for architectural industry to face the current challenges that BIM adoption creates. BIM adoption is seen as a panacea to lean productivity and efficiency in the studio and has many advantages that should be embraced in order to achieve advantages in building design and the processes that are needed to create those designs. From such an approach and embracing BIM, the aim of creating more affordable housing typologies is exponentially achievable. This paper aims to detail and explain the systematic evaluation of the 'Chameleon House Project'. Allowing for the assessment and demonstration of BIM adoption in the design of affordable housing typologies in the UK.

The systems proposed by this paper are limited but provide a platform from which future mass customisation could be used to realise the desires and expectations of homebuyers or prospective self-builders. The current delivery system of affordable housing does not involve the end user at an early enough stage. Therefore, to capture potential market share, mass custom approach to design and build should be introduced. The use of greater standardisation will allow the end user to directly assess and select each element of the home. This creates a true mass custom model, in a market that currently dictates a set design with very little option for modification other than fixtures and fittings. The research was undertaken via a external link with architectural practice and Northumbria University. The aim of the research project was to develop a very low cost housing system that would achieve both Code for Sustainable Homes (CSH) and Lifetime Homes (LTH) compliance. The approach was to use BIM to implement the project as the adoption methodology within both the SME external architectural practice and the research team within Northumbria University.

The originality and value of this paper stems from the adoption of BIM in the design process and the systematic approach that is possible based on the study and its findings. Developed originally as the response to a research project brief for an affordable housing system that would allow the prospective self-builder the opportunity to become the master builder, utilising BIM and related software. Allowing them to accomplish all of the design stages from initial layouts, elevations, to costing and then towards completion on site. This brief asked for an affordable housing design that could be created from a simple kit of parts. These parts, once used to create a completed design, were required to be both Code for Sustainable Homes (CSH) and Lifetime Homes compliant.


*Image 04: Chameleon House, Architect: David Morton. (Image: D.Morton)*

Due to limitations of time and budget for the research, it was not feasible to design a complete set of new panels for the timber frame system. This also would have created high initial set up costs for the client once the system was piloted on the proposed development site. It was therefore decided to complete a desktop study of the existing systems available to the timber frame market and select a panel system that would be readily aligned to the parameters of the Chameleon House project. This allowed for the proposed design to be completed and demonstrate a proposed business model to the client. This created a different paradigm for the project, the adoption of a semi-open system. Upon commercialisation of the system, this would allow prospective self-builders to retain the goal of customisation of a mass produced system.


*Image 05: Chameleon House, Architect: David Morton. (Image: D.Morton)*

In addition to this, the use of a semi-open system reduces the concern over dependence on one supplier or manufacturer of parts in the future. The drawback of this flexibility was the high levels of co-ordination to integrate all of the possible elements seamlessly. The extra overall costs of this flexibility was countered in the final design by the use of service walls and shared service routes throughout the dwelling, that could be shared and utilised with all variations of internal layout and external form. Such design framework follows the work of Alvaro Siza, who in 1977 foresaw the need for mass-produced customisable housing. Siza developed the SAAL system, which followed an intuitive set of design rules. The rules allow the house design to be extended and modified within a set of rules, similar to a design code.

The research project involved three main stages; first the deduction of base house design and system of rules for the linking of these internal spaces to each other within the confines of the external panel system. The second stage of the project was to codify the relationships of the internal spaces to ensure compliance with Code for Sustainable Home and Lifetime Homes. These relationships in turn required further codification to relate to the external fabric, which became stage three.


HIEF PROJECT SUMMARY FOR CHAMELEON HOUSE - DEC 2012

CHAMELEON HOUSE

FLEXIBLE PANELISED HOUSING SYSTEM

| COMPATABILITY OF SYSTEM : ORIGINAL AIMS | AUTO CAD (AutoCAD) | sketchUP (Free) (SketchUp) | sketchUP (PRO Version) (Google) | Autodesk REVIT | 3D Vega | 4projects | BIMx |
|---|---|---|---|---|---|---|---|
| The proposed system should be readily usable by non architects. What can the design be created in? | ☑ | ☑ | ☑ | ☑ | | | |
| Which files can the model be exported/ transferred from? | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ |
| Which files can the model be exported/ transferred to? | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ |
| Which software will allow cost take off? | | | | | | ☑ | |
| Which software will allow for ECO Analysis from the model? | NOTE: The file types used and their interoperability will allow any ECO BIM software such as gbXML to be used for analysis of completed 'Chameleon' model. gbXML | | | | | ☑ | |

INTEROPERABILITY OF DEVELOPED HOUSING SYSTEM

*Image 06: Chameleon House Component Compatibility Matrix, (Image: D.Morton)*

## What is affordable housing archetype?

The housing market in the UK today delivers very little choice at the lower price ranges. This occurs from a number of factors. Many house builders wishing to construct a development of 25 or more dwellings would employ the standard convention of utilising a small number of house types that would be repeated around the development. Such an approach is commonplace and allows for cost efficiencies at all stages of the design process. From the initial design stage, the convention of designing a small number of dwellings that can be repeated throughout the site reduces the potential of large amounts of information for the individual dwellings. Focusing on a small series of dwellings allows for this information to be vastly reduced. This reduction brings with it efficiencies in both time and cost. The construction phases also benefit from this reduction in variation, as the purchasing of components, fixtures, fittings and general materials are often replicated throughout the small series of dwelling designs to optimise cost efficiencies. The repetition of both design elements and material choices allow for lower overall construction costs and therefore more affordable housing for the market. However, all of these efficiencies stem from the reduction of choice and the repetition that remove the individuality and customisation of the final product. The result is housing that is mass-produced and therefore deficient in the required levels of individuality frequently sought from potential buyers in this market.

The aim of this paper is to surmount the accepted norm that mass production in housing cannot also achieve levels of customisation that limited today's affordable housing market. Secondly, it aims to explore how Building Information Modelling (BIM) can be used to increase levels of customisation that are directly controlled by the end user.

As the market segment for low cost housing increases, the clients of these housing types are becoming more accustomed to dealing with an increasing number of the tasks once deemed the role of the professional. Although this trend stems from the reoccurring, need to retain a low initial costs ceiling in relation to the need to retain overall control on the smaller budgets such projects are constructed within.

## The need to reduce numbers: A design methodology that allow customisation with the minimum of component options.

Noguchi and Friedman developed the methodology that allows customisation with the minimum number of components in 2002. This formula denoted that mass customisation *'MC'* was a function of the products that could be mass produced *'P'* and the user interaction in the form of services, which allow the these end users to customise the product to their own particular needs. Therefore, mass customisation is a function of services and products.

ORIGINAL 'MASS CUSTOMISATION FORMULA *(Noguchi and Friedman, 2002)*

$$MC = f\,(PS)$$

*Image 07: Mass Customisation Formula, Noguchi and Friedman, 2002.*

Each of these elements (product and service) is created from a sub-system that stem from a complete systemisation of the mass custom process. The conceptual model for the services and user interaction is a merger of *'l'* location, *'p'* personnel and 't' for tools. The location factor is included in the services sub-system as it forms the input of the location for user interaction when customising the house design. This interaction may be held in the office of the home supplying or designing company. However, the increasing trend for interactions is remote, often via internet-based websites. The personnel factor *'P'* allows for the inclusion of the role and impact the sales team have on the level of customisation chosen by the end user. This factor will be significant when the sales personnel carry out their role effectively and explain the variations and options available to the end user. This factor includes some element of 'tools' however these are limited to the role they are providing as these tools would include brochures, web sites and allow the levels of customisation to be fully understood by the end user. The tools *'t'* factor may include the catalogue and web pages of the personnel factor.

ORIGINAL 'MASS CUSTOMISATION FORMULA FOR PRODUCT SUB-SYSTEM

*(Noguchi and Friedman, 2002)*

$$S = f\,(l,p,t)$$

$f$ = FUNCTION of
l = LOCATION FACTORS
p= PERSONNEL FACTORS
t = TOOL FACTORS

UPDATED 'MASS CUSTOMISATION FORMULA FOR PRODUCT SUB-SYSTEM

*(Morton, 2014)*

$$S = \left( \frac{d_m + d_p}{T_r} \right)$$

dm = DISTANCE TRAVELLED BY MATERIALS
dp= DISTANCE TRAVELLED BY PERSONNEL
Tr = REPETITION OF TOOLING/TASK

*Image 08: Service Sub-System of Mass Customisation Formula, Noguchi and Friedman, 2002.*
*Updated Mass Customisation Formula, D.Morton 2014.*

However, it would also include signification elements to assist in the end user immerse themselves into the services available. This immersion can include full size prototypes, 3D visualisations' and augmented reality devices.

Therefore, it can be seen below that the original 'MC' formula is derived from a function of six sub-systems. This allows for complete systemisation of the mass customisation approach.

The product factor comprises of four sub-system factors that consider the interior and exterior components of the mass customised house and include the volume of the dwelling and variable options on components that would be fitted in the latter stages of the construction sequence such as kitchen and bathroom fittings. The volume of the Chameleon House has defined floor areas that comply with both the Code for Sustainable Homes and Lifetime Homes criteria. Therefore, the sub-system, in the Chameleon House has spatial limitations that were not considered in the original Noguchi and Friedman formula. However, customisation can still be achieved in the manipulation of the dimensions of these spaces to allow for custom arrangements of the floor plans to suit individual end user requirements. The exterior components have been designed and dimensioned to co-ordinate with a large number of 'options' for internal layout. These components can then be selected by the end user to enclose their desired plan in standardised structural wall panels, prior to choosing the exterior cladding options.

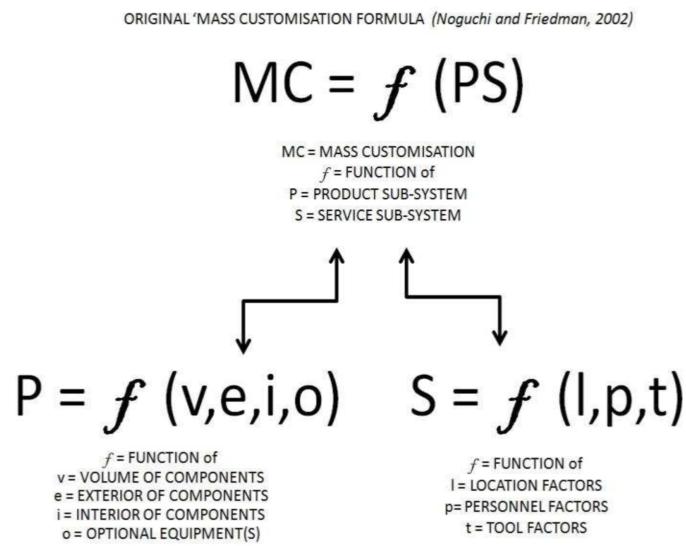


*Image 09: Sub-Systems of Mass Customisation Formula, Noguchi and Friedman,2002.*

The study has shown that a there is a potential hybrid of Noguchi and Friedman's formula when BIM is utilised in the formation of a mass customised home. The product sub-system is now influenced by the potential of sharing components within larger areas of the design, without affecting the levels of customisation. The repetition of elements and details for services is also possible when BIM is used to consider higher levels of design investigation.

ORIGINAL 'MASS CUSTOMISATION FORMULA FOR PRODUCT SUB-SYSTEM
*(Noguchi and Friedman, 2002)*

$$P = f\,(v,e,i,o)$$

$f$ = FUNCTION of
v = VOLUME OF COMPONENTS
e = EXTERIOR OF COMPONENTS
i = INTERIOR OF COMPONENTS
o = OPTIONAL EQUIPMENT(S)

UPDATED 'MASS CUSTOMISATION FORMULA FOR PRODUCT SUB-SYSTEM
*(Morton, 2014)*

$$P = \left(\frac{S}{C_S} + Re\right)^{Sh}$$

S = SERVICES (TYPES & COSTS)
$C_S$= SIZE OF COMPONENTS
Re = REPETITION OF COMPONENTS
Sh = SHARING OF COMPONENTS

*Image 10: Product Sub-System of Mass Customisation Formula, Noguchi and Friedman, 2002.*
*Updated Product Sub-System of Mass Customisation Formula, D.Morton 2014.*

Therefore, this study has shown that Noguchi and Friedman's formula, published in 2002, had considered and established a comprehensive systemisation for the mass customisation approach. Updating this formula using BIM to create a enhanced level of systemisation.

UPDATED 'MASS CUSTOMISATION FORMULA *(Morton, 2014)*

$$MC = \left(\frac{S}{C_s} + R_e\right)^{S_h} + \left(\frac{d_m + d_p}{T_r}\right)$$

S = SERVICES (TYPES & COSTS)
$C_s$= SIZE OF COMPONENTS
$R_e$ = REPETITION OF COMPONENTS
Sh = SHARING OF COMPONENTS

dm = DISTANCE TRAVELLED BY MATERIALS
dp= DISTANCE TRAVELLED BY PERSONNEL
Tr = REPETITION OF TOOLING/TASK

*Image 11: Mass Customisation Formula, Noguchi and Friedman,2002. (Image: D.Morton)*

The current trend for a potential home owners to opt for a design build and construct route that sees them take a key role from inception to completion started in the UK in the 1970s with early pioneers such as Walter Segal. The first Segal scheme was constructed in Lewisham. Three small sites, which were not deemed applicable for mainstream housing, were offered to Segal to allow for the construction of houses using Segal's self-build approach. The success of these initial dwellings proved a preparatory step towards many further schemes around the UK. Segal is now regarded as a pioneer of affordable housing. After his death in 1985, the Walter Segal Trust was created and the design and construction approach has gained an increasing following to the present day.

The paradox of mass customising has considerable potential impact on the affordable housing market. Customisation with only minimum component options is somewhat of an architectural panacea but also a paradigm. The level of customisation adds to the richness of possibilities for the homeowner, whilst the increasing levels of customisation require increased levels of complexity. These are common constraints of a mass custom approach. The system takes its name 'Chameleon House' from its ability to be changeable and react to changing needs. It is a system that allows for a complete structural envelope for dwellings to be created from a timber panel system that can be constructed in either open or closed format. Timber panel systems on the market today are of these two derivatives 'open' or 'closed'. As the names suggest, they differ in the fact that one of the panel systems is manufacturer without an internal closing element (usually plasterboard or similar). This allows the dwelling to be constructed from the panels whilst retaining the flexibility of changes being made during this programmed construction period. Such changes may be altering plug socket positions, heating pipes or other services. Whereas the closed panel, as the name suggests is fully completed in the factory, with all socket and switches located in position on the internal board of each wall panel. The latter system creates a faster mode of construction, whilst the former creates maximum customisation.

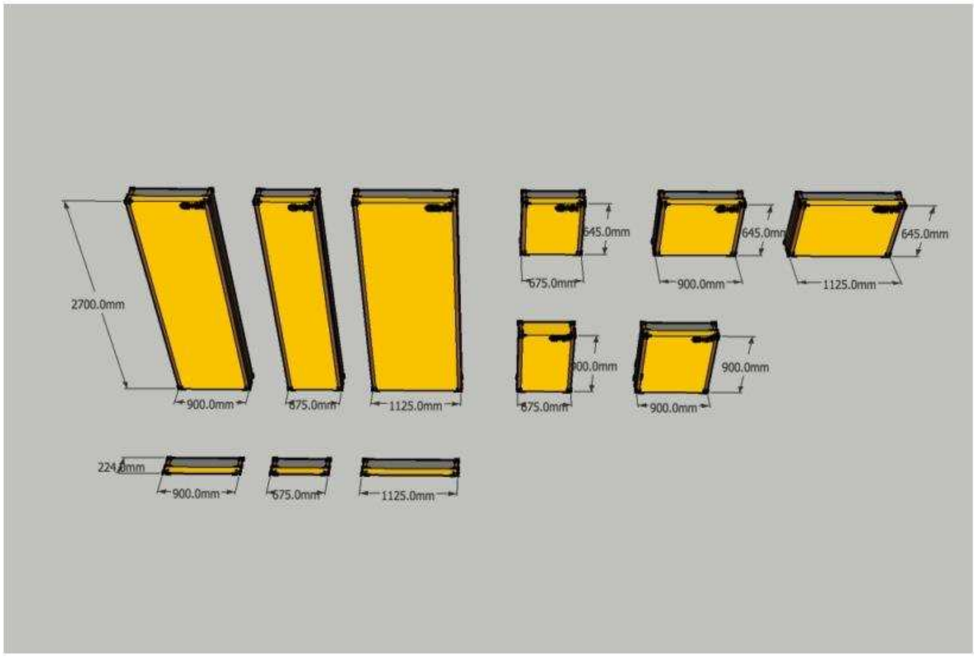


*Image 12: Chameleon House, Architect: David Morton. (Image: D.Morton)*

Most timber panel systems have a large variety of panel widths, and a small number of panel height variants. This number of options is controlled in the Chameleon House system; never the less the system is very versatile and can accommodate a large variety of dimensional tolerance in variations from the mass customisation approach. The overall buildup of each panel has been design to allow for the need to adapt to a variety of external cladding options. This has been achieved by coordinating all of the panel widths to brick sizes as a base dimensional size. This allows the system to co-ordinate with a large array of external materials, from brickwork, rendered block, timber cladding and rain screen systems. The system allows for eight external panel types. Three of these are full height wall panels, the remaining five are variations of infill panels the accommodate options for window positions and arrangements within the façade.

The WRAP approach: An envelope design methodology that is established via interior spatial conditions. the concept of the WRAP approach to the Chameleon House focused on the cost effective balance between the external surfaces of the interior spaces to yield the most flexible spatial core with the minimum exterior surface area.

The affordable housing market has a number of key drivers that dictate size, layout proportion and types of materials used in the delivery of housing in this sector. The methodology for Chameleon House Project was to create systems for internal layout and exterior construction that achieved both Code for Sustainable Homes and Life Time Homes accreditation. The design approach for the Chameleon House Project does not align itself with the recognised approaches of panels system in general, that of production, semi-custom and custom. The concept of the panel's interconnectivity and flexibility affording the system alignment with the mass-customisation approach or mass custom design. This is the result of three basic design elements for housing; the overall volume, exterior and interior as stated by Noguchi (2001).

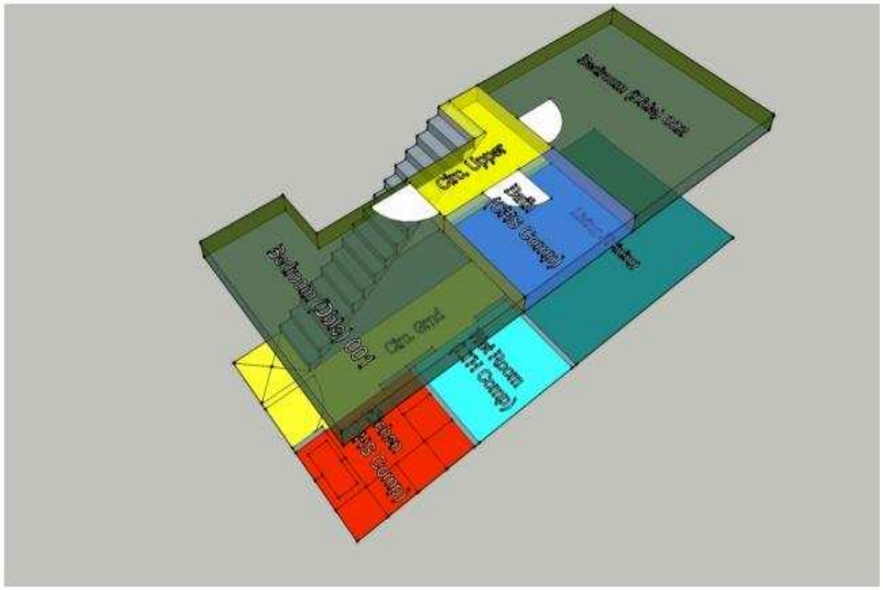

*Image 13: CSH and LTH Compliant floor plates for Chameleon House. (Image: D.Morton)*

The utilisation of daylight was a important consideration for the design. The concept originated from the Scandinavian housing market, where the internal spaces are design to maximise the extent that daylight penetrates the internal volume of each room. The term 'leading to light', which also originates from Scandinavian home design, is given when the architect positions the internal doors and fenestration on the external envelope to align directly. This alignment affords the end user the view of external spaces surrounding the home and emotional connection with the surroundings whilst still remaining inside the home as they open the door and enter a room. This direct visual reference with external space is further enhanced by utilising higher ceiling heights for all internal spaces. In the UK the standard ceiling, height is 2400mm, whereas the ceiling height in many Scandinavian homes is 2700mm (+/- 50mm).

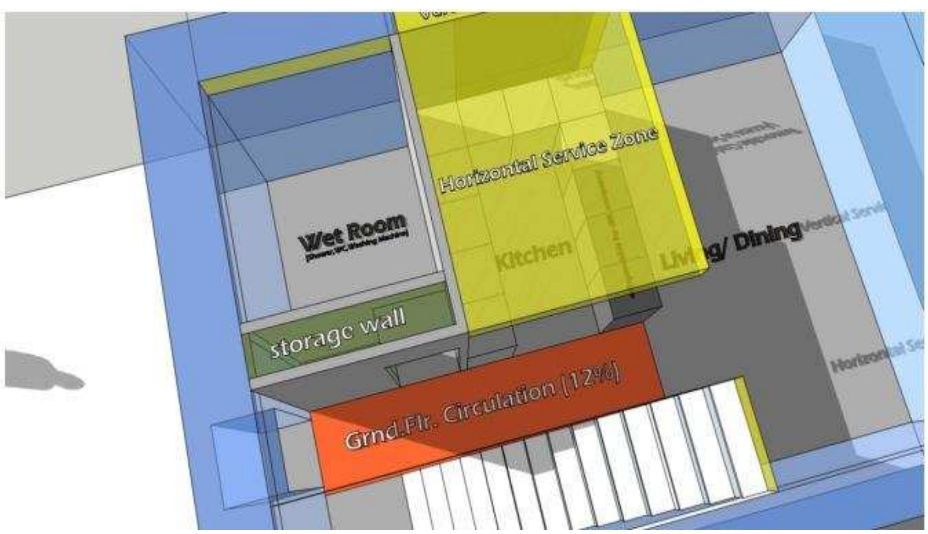


*Image 14: 'Service Wall Cores' within Chameleon House. (Image: D.Morton)*

The use of prefabrication was exploited to minimise onsite waste and improve overall quality of the final product. When logistics, planning and design drawings have been completed and agreed prior to commencement, then construction times can be reduced by 20-30%. The research project is to be commercialised in 2014 and once the construction team have become more familiar with the processes of the Chameleon House system is is envisaged that the team will complete the timber frame shell of 2.5 houses per day, with completion of the roof elements within 8 days. Standardisation of the building components (notably the windows and doors) have been exploited to minimise overall cost per dwelling. Research carried out within the Chameleon House Project suggests that development of over 100 homes, using this off site manufacturing method, can achieve cost savings in excess of 8.5%, and reduce the overall construction programme for traditional UK building techniques from 21 months down to nearer 12 months, whilst also increasing the useable area of the site by 33%.

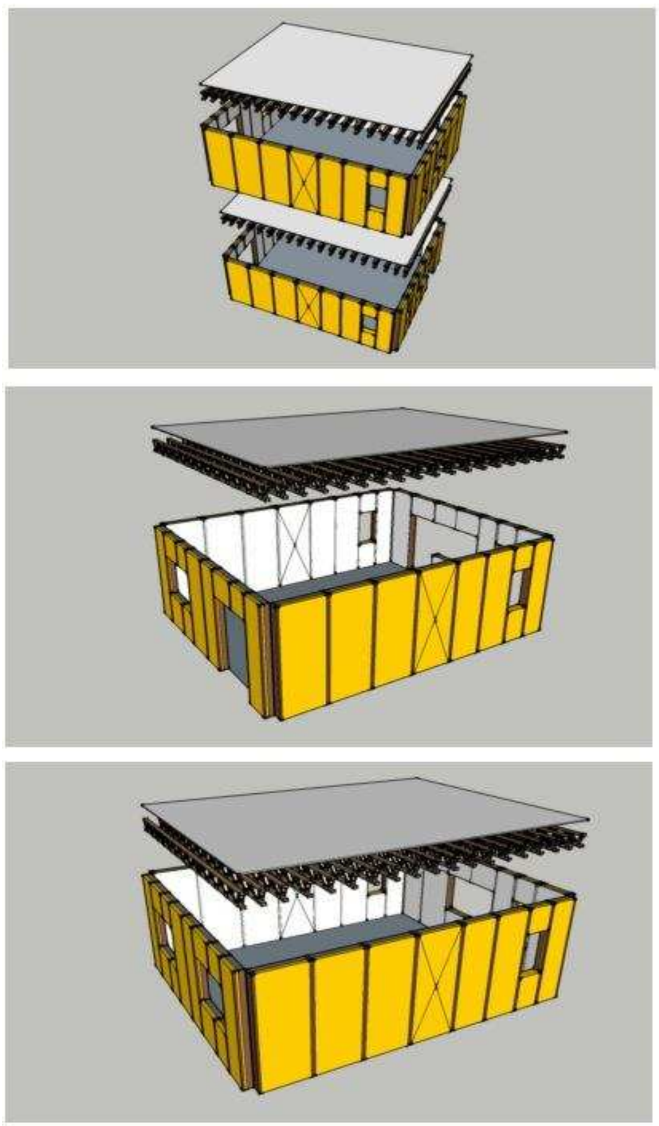

*Image 15: 'Panelised Wall System', Chameleon House. (Image: D.Morton)*

The system, if used for a typical site of 100 dwellings, the first home may be ready within 100 days, after which point the hand over rate would be 4 to 6 dwellings per week. Therefore allowing the homeowner to choose from this standard library of components to assemble their own grand design. These components are in turn mass-produced, whilst the choice and final combination of these is completed by the homeowner/ self-builder. The combinations of these choices from the standard components of the Chameleon House system make each home customised. This concept therefore follows the design methodology and concept termed 'mass custom house' developed by Noguchi in 2002.

## A Sum of the Parts: Leveraging BIM to achieve effective delivery of mass customised housing.

The system of perimeter external wall panels were designed to allow for dimensional alignment with the possible variations in internal arrangements of rooms.

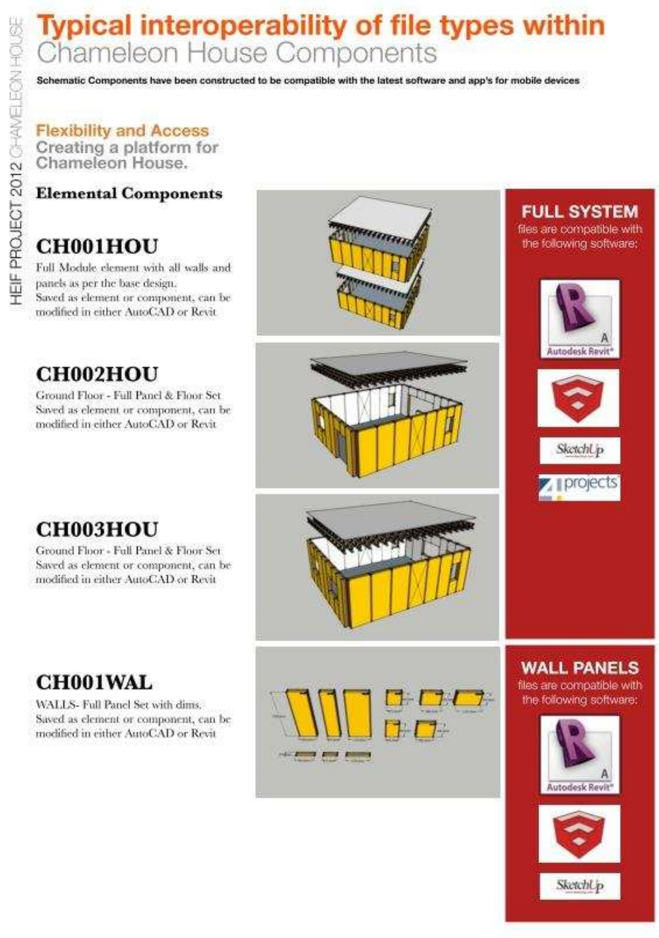


*Image 16: Chameleon House, Architect: David Morton. (Image: D.Morton)*

The internal systems of room parameters and circulation zones were assessed in terms of geometries and potential characteristics of layout.

Against the external modularisation of panels to allow for adaptation of location and sizes of the external wall panels. The system uses a standard kerto beam to the perimeter of the floor zone to receive the floor cassette. A kerto beam is a laminated veneer beam that can be formed into structural components such as beams, frames, roof and floor elements within a timber-framed building. This detail was chosen for its simplicity and cost effectiveness. This use of a cassette floor also allows for maximum flexibility in terms of locations of ground and first floor internal partitions, as the floor cassette spans from external wall to external wall with no physical loading taken by internal walls. As a result, the system allows for complete open plan living as an option if required by the homeowner. The rules of the system for both the internal spatial options and associated components were aligned with the rules for the external envelope panels. Each was identified calibrated and encoded into the overall housing system. Each panel of the external walls were then constructed in sketchUP and Revit to ensure a BIM compatible component. Each external wall component was coded and then used in varying combinations to assess flexibility of wall runs against the criteria of internal special options and external cladding choices. It was envisaged that the number of wall panels could be made smaller, but after trialing various combinations of internal layout, it was found that a minimum of five external panel widths were required. The components of the Chameleon House System were created using SketchUP and Revit software. Each component was initially created in sketchUP and saved as a .skp file. These files were then separately loaded into Revit as a 'Conceptual Mass Model Family'. This route was use as it allowed the components to be manipulated and reviewed on freely available sketchUP software, which was one of the key requirements of the client. When using Revit the imported components can be used once the 'ass' visibility is selected within the software package. Alternatively, all components once loaded into Revit can be loaded into a single 'project'. The sketchUP model will then appear in your new Revit project and the user can manipulate the components as desired. Once the project is complete, the model can be interrogated for data, in terms of numbers of components, elements which can then be used to develop simple costs analysis.

Utilising the potential of the BIM software the components were imported into Revit to trial build a basic two-bedroom dwelling. From this model, 3D representations could be readily extracted and rendered. The components could also be counted and listed in terms of a basic schedule, from which basic costs could be applied. These stages used BIM to enhance the ability for the homeowner to assess affordability and then redesign or customise the dwelling further. Such an approach could also be used on a much larger scale and allow for developments of large numbers of dwellings that could achieve levels of customisation.

## The study's findings and future considerations

'Quantitative advances of this magnitude create qualitative shifts', Davis (1987). These shifts are currently being used to engage with problems of leaner and more cost effective segmentation of the design components, in order to deliver better results. However, such advances have and will lead to better constructional detailing, increased quality at a level of affordability not previously achieved.

## Discussion Point 1:

The design systems were integrated using BIM software in order to assist the user in the formation of a dwelling that was compliant with Code for Sustainable Homes and Lifetime Homes. The systems design conventions that, along with the specification and details that accompanied the panelised system would achieve corresponding compliance. It was found that system allowed far greater levels of design freedom throughout the design and customisation process, without the need to have detailed knowledge of what the design implications were when exploring differing floor plans and Elevational options for fenestration and doors. However, it was found that the number of planning options could have been improved with further development of the rules and components on the internal spatial options. Therefore, further extrapolation of the 'p' product and its sub-systems could be a future research area in mass customisation approach to design.

### Discussion Point 2:

During the Chameleon House Project the sketchUP software being used to create the components for use in modelling and exporting to BIM software such as Revit, was purchased by Trimble. This has created a greater array of possible compatibility and ready integration of the components to be used in other BIM related software. This step change in compatibility has created a series of additions to this project that originally were not considered. The original intent to use BIM and Revit software would have required the users to purchase a 'light' version of the software in order to manipulate the components that were developed as part of the research project. The change in ownership of SketchUP has altered the markets judgment of the software. There is now an increasing diversity of compatible software such as BIMx and 3Dvega. Both of these products are available as apps to which the end user can upload the sketchUP components. They allow visualisation and appraisal of layouts and 3D walkthroughs of the proposed mass customised home.

### Discussion Point 3:

The domestic dwelling as an archetype should also consider a new element to the original Mass Customisation Formula, Noguchi and Friedman. That of internal layout and sharing of circulation space, as there is potential correlation between the optimum useable 'room'. This spatial construct to the original formula or that of the updated formula should assess the perimeters of the internal 'rooms' to that of the perimeter of the circulation space. A optimum boundary condition could then be extrapolated from this formula. It would then be possible to ascertain the distribution of doors onto corridors by assessing the resulting spatial distribution of circulation to 'other' room spaces within proposed home design.

### Discussion Point 4:

The use of visualisation in the Chameleon House Project facilitating assessment of the proposed design from the assembled components and can be undertaken to varying levels of sophistication. Using sketchUP and Revit an immediate visualisation can be explored and exported into other compatible software packages. Using Revit, this visualisation can be rendered to assess the materiality of the design. The model can be explored on both SketchUP and Revit to create a walk-through of the proposed home, allowing a virtual spatial exploration of internal and external spaces. A complete list of components can also be exported to create basic costing for a project. The project did not explore the use of stereo lithographic (stl) files. These files can be created as a direct export from both sketchUP and Revit to create an industry standard 3D modelling file. Used on a 3D printer such as a Makerbot this file can produce accurate 3D scaled models of the proposed mass customised home. Assessment of the design could also be achieved using augmented reality (AR). Plugin's are now available for sketchUP that allow a model to be view virtually using a web camera connected to a PC or laptop. When this is focused onto a trigger image, the model can be seen on the screen of the PC or laptop assisting the user deeper immersion into the proposed design. This follows the earlier studies by Sass and Botha, The Instant House (2006) which explored the use of digital fabrication of housing.

### Discussion Point 5:

The Chameleon House Project was focused around the establishment of a series of simple components in small quantities to create a viable solution to employ the services of an architect or housing design company. At the conceptual level it facilitates exploration of solutions and allows these to be readily understood.

### Discussion Point 6:

Although the current study used Revit, its capacity to explore the components parametrically was not included in this pilot. The use of parametric components, via BIM software would greatly enhance the options of customisation to the end user. However, with this greater flexibility comes the need to create sub-systems that are far more complex.

## Conclusion and future implications:

The study has also indicated that such a system could be readily implemented to create mass customisation, however the drawback being the requirement of the designer to create the system and sub-systems from which the design will evolve. These systems have many layers of sub-systems, which all require testing to ensure they yield varied solutions that are compatible. The Chameleon house has variations, but these are currently limited. Considerable investment would be required to create a greater number of rules to enlarge the framework of differentiated solutions.

The systems proposed by this paper are limited but provide a platform from which future mass customisation could be used to realise the desires and expectations of homebuyers or prospective self-builders. The current delivery system of affordable housing does not involve the end user at an early enough stage. Therefore, to capture potential market share, mass custom approach to design and build should be introduced. The use of greater standardisation will allow the end user to directly assess and select each element of the home. This creates a true mass custom model, in a market that currently dictates a set design with very little option for modification other than fixtures and fittings. The future markets may demand far greater customisation, lifestyle choices today demand far greater options for customisation, and this mindset will permeate the affordable housing market and increase the demand for mass customisation in homes.

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