Building without nails: Enabling flexibility and structural integrity through digital prototyping

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ABSTRACT: The convergence of digital tools, materials, and production processes has offered designers the opportunity to respond to diverse forms of users' demands for design variations, in an efficient and precise model. Different methodologies have been proposed with the aim of efficiently accommodating flexibility in the building realm, based on technological applications. This paper demonstrates recent developments in combining advanced structural design with computational modeling, towards realizing a construction system that allows for significant flexibility and adaptability in housing design within the Canadian context. Based on advanced Digital Prototyping strategies, the system enables high accuracy in the design phase leading to subsequent precision in production and assembly. Such an application allows delivering high levels of detailing in production of structural components, thus supporting the intention of pre-defined assembly on jobsites and reducing waste. The paper represents a phase from an ongoing research endeavor that aims at enabling customization in housing realm, based on digitization of the design and production processes.

KEYWORDS: Flexibility, Adaptability, Customization, Prefabrication, Digital Prototyping.

INTRODUCTION

Recent developments in digital design tools and techniques have offered the Architecture, Engineering, and Construction (AEC) industry the means to allow for higher control over the design, manufacturing, and construction processes. Through the use of advanced design and modeling software, designers and engineers are developing abilities to simulate structural performance, components production and assembly, towards a more efficient, and precise model for construction. While these technologies allow for cost and time control throughout various processes, one the key factors is supporting the notion of flexibility. The term flexibility comprises multiple principles within the domain of architecture, including modularity, adaptability, and renovation (Till and Schneider 2005, 287). These concepts have been an interesting area of research and exploration, with the aim of developing strategies to design building components that would adapt or modify itself to changes. Commonly, buildings are aimed to change in response to social, economic, or environmental aspects. However, one of the main limitation of implementing flexibility is high cost, and complexity associated with linking design to construction components.

Pertaining to housing, Till and Schneider (2005) defined flexible housing as buildings that can adapt to the changing needs of occupants, comprising different possibilities of pre-construction layout selection, as well as the ability to change one's housing over time. Additionally, it includes the capability of integrating technology throughout occupation in response to change in demographics, or adaptive re-use. As a result of wide modes of applicability, there are numerous approaches for achieving flexibility.

Within the context of this research, flexibility is explored on two levels. The first level examines flexibility at initial design stages, with the notion of enabling participatory design in the form of pre-construction choices to homebuyers. The second level is denoted with post-occupancy adaptability, with the aim of responding to prospective changes in socio-demographic characteristics of occupants. The framework for this approach stems from the structural system and its design model, coupled with Digital Prototyping strategies. On the one hand, the physical characteristics of the system's components and their configuration establish the basis to analyze the capacity of housing designs to accommodate variations requested by homebuyers. On the other hand, Digital Prototyping empowers high precision in visualization, fabrication, and assembly of building components, thus enabling implementation of design variations efficiently. The aim of such a framework is to respond more effectively to wider sector of customers and market demands, given the variation in socio- demographic patterns, thus expand market shares.

1.0 DESIGN FOR FLEXIBILITY

Design for flexibility involves a certain logic of technological applications with regard to the provision of services that allow for various configuration of components. Such a logic is based on a clear differentiation between elements that are fixed, and others that are open to change and variation. Perhaps one of the leading constructional principles to facilitate flexibility in housing is “supports”, developed by Habraken in the 1960s, for the Dutch housing sector. This theory presented a vision of housing wherein a dwelling would utilize a process that supports and adapts to user decisions within a larger framework of communal services and infrastructure. The theory distinguished between two fundamental components: “supports” and ‘in-fills”. While “supports” are regarded as the physical entity, or the rigid part of the building, “in-fills” represent the flexible part that could be adjusted on different levels: social, industrial, economic and organizational. The system was designed to facilitate variations of floor layouts over time, while also accommodating the design of dwellings to meet the diverse standards of normally accepted housing in any particular society (Habraken 1972). This foundation further developed and promoted Habraken’s open building method, and thus marked the first attempt towards personalization on a mass scale in the Netherlands (Habraken et al. 1976, 81).

Following these efforts, Kendell and Teicher (2000) have subsequently explored various trends towards open buildings. They have also proposed flexible and economical methods for implementing these systems in levels, based on analysis of realized projects around the globe. Both Habraken, and Open Building approach focus on the application of technology, modern construction techniques, and prefabricated components as viable strategy to enable flexibility.

The system described in this paper combines innovative structural design, with digital capabilities in order to achieve design flexibility on two levels: macro and micro. Whilst macro flexibility is denoted with volume and exterior perimeter of the building, micro flexibility describes variations that can be implemented within interior blocks, without affecting building envelope. Such an approach to flexibility bases its logic on the concept of modularity, and standardization of components, leading to multiple configuration possibilities. Modularization of design supports multiple product configuration by simultaneously taking advantage of the economies of scale and scope. This enables accommodating design variations on various levels. Additionally, the application of digital design strategies, considered as a vital technological enablers of the model, allows for high precision in fabrication and assembly through data management, as well as comprehensive documentation of building information.

1.1. Enabling customization through flexibility in design

As mentioned earlier, one of the main concepts of flexibility in design relates to allowing user participation at early design stages. Such a concept has become a viable approach in response to sharp increase in demand for personalized goods and products, thus defying standard mass production paradigm; one introduced by Ford in 1920s. Later on, in the 1960s, the integration of information technologies, and digitization of design and production processes lead to a new paradigm. Toffler’s 1970 book “Future Shock” anticipated these changes as technological capacities, and he further described them as a “third wave” in a subsequent study (Toffler 1980, 72). Also referred to as mass customization by Stanley Davis in his 1987 book “Future Perfect”, this process was formally systematized by Joseph Pine in 1993.

Many segments of diverse and variable industries are currently moving towards greater customization in reaction to consumers and markets demand. Within the building industry, components could be mass customized, allowing for optimal variances with regards to differing contextual characteristics, therefore enabling the production of uniquely shaped and sized buildings. Ever a vital sector in the building industry, housing has witnessed a renewed surge of interest in the last two decades, especially following these new approaches to modes of design and production. Although this interest has taken many forms and constituencies, digital design and manufacturing strategies have inspired the most diverse research and pragmatic solutions to contemporary industry challenges, resulting in advanced customization solutions.

Flexibility in design can be regarded as a core component in achieving customization, whereas the level of customization relies primarily on the degree of flexibility and its relevance to the building system’s technological capabilities. In that sense, the question of this research becomes what are the dimensions of achieving flexibility. Friedman (2011) proposed a project-based decision-making model that would assist designers and builders to define the degree of flexibility in housing design with regard to project type. This is aimed at providing guidelines for the selection and implementation of resilient design strategies, so as to fit their users’ needs and maintain their market approach. Accordingly, the type of flexibility selected is based on the definition of the socio-economic backgrounds of users, in addition to cost, regulations, and execution time.

The focus of this research goes beyond traditional flexibility models, to one that stems solely from a progressive technological approach, leading to efficiently enabling customization in the housing realm. The proposed integrates the structural logic, with Digital Prototyping strategies as a vital element within the flexibility model. Nevertheless, the criteria to identify levels of flexibility and design alternatives to be offered, includes the notion of establishing a comprehensive process for making choices from a range of flexible alternatives.

2.0 THE STRUCTURAL SYSTEM: BONE Structure®

The BONE Structure® is a proprietary construction system that combines cold-formed steel components and insulating materials in an integrated manner. The steel components are all designed to be assembled using solely screws and bolts, eliminating the need for cutting, piercing and welding on jobsite. As a consequence, the amount of residual matter resulting from the construction process is reduced significantly. The system differentiates itself from traditional steel construction system by combining the advantages of a post-and-beam structure; larger spans, size of openings, the integration of the structural system with the thermal envelope, and the precision of assembly provided by pre-manufactured components.

Pertaining to form, The BONE Structure is an orthogonal system that has been designed using a 5 feet incremental module in the X-Y plane and 6 inches module in the Z direction, leading high level of standardization of components. Given that the system is always undergoing research and development, the latest version of the system (10.0) includes the half-grid feature, providing more flexibility to the architectural design.

The various structural components are fabricated using typical sheet metal processes and equipment, including Computer Numerical Control (CNC) punch presses, laser cutting, bending and stamping. Additionally, robotized welding is used for some assemblies. All components have an overall length of maximum ten feet in order to facilitate procurement. Structural columns have a composite square profile, 4 inches x 4 inches, assembled in plant employing self-tapping screws. An additional H-shaped profile can be added on the exterior side of columns to enhance their resistance to lateral loads. Stronger members are designed using a thickness of 0.1875 inch whenever required. Figure 1 represents a holistic view of the structural system components.

Figure 1: An overview of the structural system, and a close-up for the connection. Source: (Author 2014)

Floor and roof structure main components are variable lengths of a seventeen inches deep profile manufactured using eleven gauge galvanized steel, the maximum standard span being 25 feet. These profiles are characterized by large openings that are performed to remove some weight to the components and to allow for better efficiency for trades such as electricity, HVAC and plumbing. Stronger members are designed using a thickness of 0.1875 inch when required. Secondary joists are put in the transverse direction between the joists with a typical spacing of 20 inches.

Once land preparation is completed, and the foundation is poured and cured, steel components and fasteners are delivered. The prefabricated structural components are anchored to the foundation by using cast-in anchors available in three standardized dimensions. The anchors are positioned using spacing templates, eliminating the use of a measuring tape. Assembly instructions are obtained from digital models, thus capitalizing on the efficiency of building processes.

Floor structure is completed by adding a 0.75 in thick thirteen plies plywood panel over the steel components. These panels are pre-pierced and pre-cut using CNC machining centres. The assembly is performed using self-tapping screws as holes in plywood panels are aligned with holes in the steel structure underneath. The plywood panels are supported on all edges and define a structural diaphragm. On the roof, the diaphragm is achieved by a Structural Insulated Panel (SIP) fastened to the structure by screws installed from the interior side. These SIPs are composed of two layers of Oriented Strand Board (OSB) with an Expensed Polystyrene (EPS) layer in between. The typical thickness of EPS is 10.5 inches, giving an insulating rating of R-40. In some cases, additional structural components such as structural lintels above sliding doors and garage doors, overhangs, balconies, terrace structures and canopies are then added. Openings for doors and windows are pre-framed using pre-cut plywood parts with machined holes and grooves.

The subsequent steps are denoted with covering the complete wall area with 3 inches thick EPS panels. These panels are cut in three configurations to fit exactly in between the structural components. They are held in place by z shaped profiles. The whole wall is finally covered with a 2.5 inches thick layer of polyurethane sprayed foam. The depth of the z profiles is calibrated to exceed the polyurethane and receive the exterior finish. A nylon thermal break positioned between the z shaped profile and the structural columns prevents metallic continuity through the thermal shell. On the interior, wall and ceilings are covered with galvanized steel furring profiles that are clipped to the structure, making it ready for drywall installation. Exposed components such as architectural stair structure, exposed cross bracings, terrace structure and sunshades are typically installed when spray foam application is completed. The shell is then completed by installing doors and windows and sealing the perimeters of these components.

The presented structural system achieves flexibility in building design through three Dimensional modularity, in addition to specific physical characteristics of its components. This allows for numerous configuration possibilities, with the aim of responding to users' demand for internal and external design variations.

3.0. DIGITAL PROTOTYPING IN DESIGN

Within the engineering and design realm, Digital Prototyping is defined as the mean by which engineers, and designers can explore products virtually before being built. It allows for designers to validate, simulate, optimize, and visualize products data throughout the product development process within an advanced a digital environment. Such a process is structured on different levels of automation, depending on the nature of the product, and operations involved in the process (Bullinger at al. 2000, 100).

Digital Prototyping combines Computer Aided Design (CAD) technologies with Virtual Reality (VR) to allow producing prototypes more efficiently, thus optimizing the product development process. One of the strategic advantages of Digital Prototyping is real-time decision making at early stages of product development. This enhances the process and makes it more efficient, leading to allowing for earlier modifications, and optimization of the prototype. Furthermore, virtual prototypes enable qualitative evaluation of product qualities, thus eliminating errors that might occur within the fabrication process.

Bullinger, Warschat, & Fischer (2000) defined a crucial component of Digital Prototyping that is the Digital Mock-Up (DMU); a purely digital test model of a technical product. Such a model enables for a current and consistent availability of multiple view of the product shape, function, and technological coherences. This constitutes the basis on which modeling and simulation performed and communicated for an improved configuration of the product. Commonly, virtual products are employed as a reference for testing the design regarding its feasibility, functionality, and efficiency prior to production of physical prototypes. This is done by building a comprehensive model that brings 3D data into a single 3D model. This is done either for exclusive products, or ones integrated within a system. In such a virtual environment, possible defects can be detected and corrected in design before building physical products. The model also enables unprecedented precision in establishing the link between design and manufacturing, thus improving productivity.

Digital Prototyping as an approach has been successfully implemented in various domains, such as aircraft construction, shipbuilding, and the automotive industry. Also, various software platforms have been employed, including for instance, *Autodesk Inventor*, *Solidworks*, and *CATIA* by *Dessault*. Nevertheless, the selection criteria of the platform relates to the capability of devising a workflow that is compatible with the nature of the product, level of technology involved, and users participating in the product development process. We present in this research a workflow model that complements the nature of the structural system, as well as the targeted flexibility model.

3.1. Achieving structural integrity through Digital Prototyping

The application of Digital Prototyping throughout BONE Structure system design process aims at implementing effective data sharing and management platform, to allow for collaboration between different team members. There is a series of operations that take place prior to aggregating information on the employed platform, *Autodesk Inventor*. These operations function either simultaneously, or consecutively, depending on the nature of data input/output.

The process is initiated on a Building Information Modeling (BIM) platform, *Autodesk Revit,* allowing for visualization, and validation of data at the conceptual design stage, as well as effective communication between design team members. The model is used also for referencing purposes, in relation to contextual data. The following step is denoted with integrated structural modelling and analysis, using a conventional structural analysis software, with focus on verifying, and optimizing structural members, connections, and assembly. This step is fed from a database of families comprising various structural system components; columns, beams, bracing, anchors, bolts, in addition to other connections, organized in a hierarchical manner.

Once realized, the BIM file is then imported to *Autodesk Inventor* for precise allocation and assembly of structural members within the design. Taking advantage of computational design capabilities of the design team, a special algorithm was designed and coded to automate this operation. Basically, the algorithm acts as placement agent that assigns structural components following a specific pattern, then generate connections. In that sense, the process is optimized with regard to time, and precision. Additionally, the algorithm performs, and simulates a number of the assembly tasks, in real-time, thus overcoming possible complexities associated with the building process. The implementation of this algorithm takes the 3D BIM model into a level of 4-Dimentionnal, and 5-Dimensional operations, whereas accurate quantities can be extracted from the model. Figure 2 demonstrates a completed model on Inventor and the level of detail obtained.

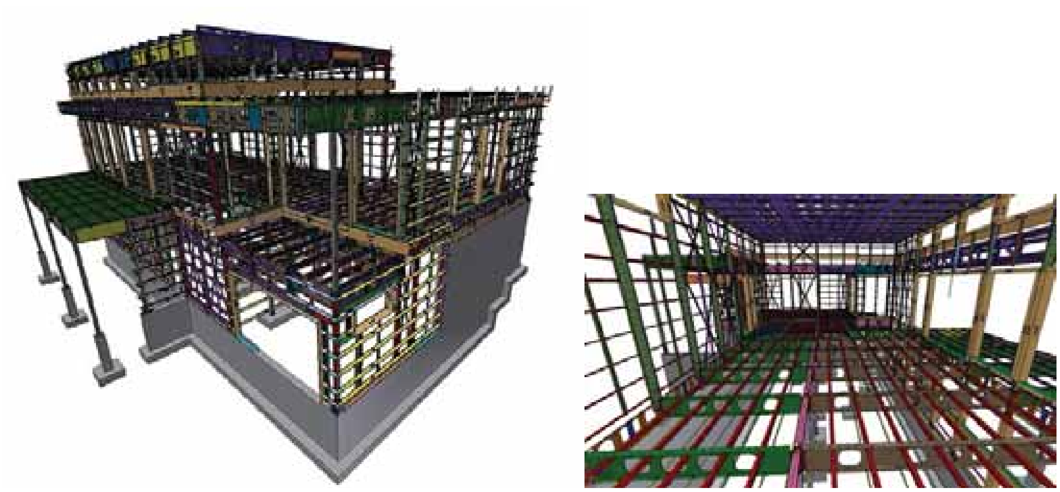

Figure 2: A screen-shot from *Autodesk Inventor* of a 3D model demonstrating levels of details in components and connections in project employing fully standardized parts. Source: (Author 2014)

In addition to just-in-time virtual tracking of components during design, the application of Digital Prototyping informs the fabrication of parts. Data extracted from the 3D model is used to feed different CNC machinery with precise fabrication instruction. Since many of the projects involves design and production of special parts, Digital Prototypes becomes a vital player in this situation. Special parts are designed, tested, optimized, simulated, and fabricated in relationship with the standardized parts. This would also lead to simplifying workflow from design to manufacturing, as collaboration occurs dynamically, thus maintaining information accuracy.

4.0. DIGITAL PROTOTYPING TOWARDS DESIGN FLEXIBILITY

The BONE Structure system is designed to enable the previously mentioned flexibility approach: macro and micro level. The key factor behind achieving these levels relies on technological enablers. While micro flexibility is intended to enable user participation in the design phase, macro flexibility explores the notion of variation in volume, and post-occupancy adaptability. Other than the innovation in the design of the structural system, Digital Prototyping is considered as a significant sub-system within the comprehensive flexibility approach. Its implementation strategy relies on two procedures: data management, and product documentation, supporting micro and macro flexibility consecutively.

Pertaining to micro flexibility, Digital Prototyping is implemented through an integrated workflow that supports editing and changing parts and components without the need to change parametric data. It allows for real-time modification in building spatial layout, while preserving the use of standard structural components. Additionally, employed to surpass conventional capabilities of the software platform, the placement algorithm and supplementary plugins operate to enhance the level of flexibility to accommodate potential design variation. In other words, flexibility in design is enabled through flexibility in the data workflow strategy. Figure 3 demonstrates possibilities for micro flexibility to support user participation.

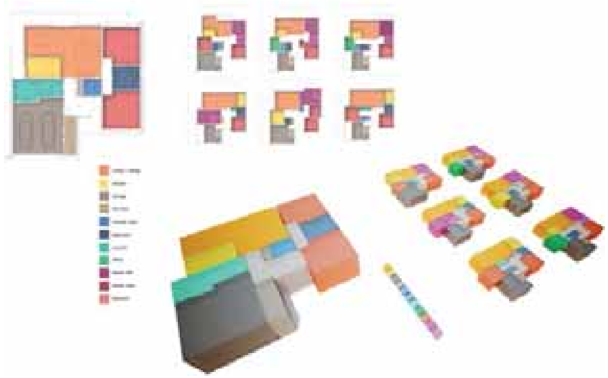

Figure 3: Micro flexibility achieved through various configuration of spatial layout functions, within a predefined volume. Source: (Author 2014)

On the other hand, macro flexibility explores variations in building volume and envelope, either at early design stages, or in the form of potential post-occupancy adaptability in response to future changes in socio-demographic characteristics of occupants. Both ideas are made possible by the structural system framework, in addition to product documentation of the Digital Prototyping strategy. Given that parts and components of the structure are assembled using bolts and fasteners, and all of these connections are documented digitally, variation in building envelope can be achieved effectually. In the case of pre-construction design, the placement algorithm tolerates configuration of special parts and components, by replacing standard ones. Yet, in other case of post-occupancy adaptability, components can be disassembled easily, then reassembled following other configuration in response to building occupants requirements. Figure 4 demonstrates a project that dictated the design and fabrication of specific parts to suite the custom design, while keeping the principles; materials, process, and standardized connection details of the BONE Structure system. Such flexibility in design, and optimization in production were only made possible through the application of Digital Prototyping, including particularly coded algorithms.

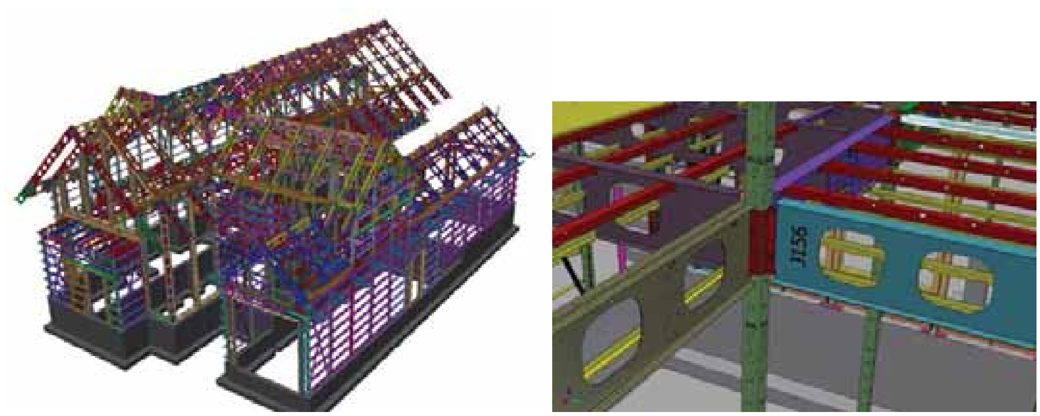

Figure 4: Screen-shot from *Autodesk Inventor* of a 3D model for a special design project. The images demonstrate level of details attained while using special components. Source: (Author 2014)

CONCLUSION

Advancements in design and fabrication technologies have changed the way buildings are being designed and conceived. Various approaches have been proposed in order to devise methodologies to model data throughout the design and production of buildings. Many of these approaches explored flexibility enabled through digital processes, referring to other engineering disciplines. The aim has been always to develop models that can consequently respond to either pre-construction variations, or adaptability denoted with changing needs over the time. These approaches have taken different forms and constituencies, with special focus on the notion of digitization of data workflows, and management.

This paper represents a technological approach to enable flexibility in the design and production of buildings, specifically housing, through combining a state-of-the-art structural system, and a digital modeling strategy; Digital Prototyping. Whereas Digital Prototyping has been applied in many engineering and design domains, yet in architecture, such an approach is still in an exploratory phase. The described Digital Prototyping platform in this paper tends to complement the tactility of the structural system, towards greater flexibility in design. This relates directly to the concept of data management and collaborative qualities, leading to effective communication between design team members, as well as fabricators, through establishing a coherent workflow to handle design flexibility. Furthermore, to surpass conventional capabilities of the platform, a computational design logic in the form of a placement algorithm has been coded, and implemented specifically to enhance digital processes. These computational tactics capitalize on the structural integrity of the design system, through automating a set of instruction within the modeling process, thus advancing the flexibility approach.

The work described in this paper represents a phase from an ongoing endeavor towards implementing a comprehensive system for mass customization in architecture. The proposed flexibility approach, in the form of combining a structural system, and a technological strategy, is seen as a crucial element to realize the paradigm of mass customization, specifically in the housing realm. Future exploration will focus on the concept of interoperability, a more advanced form of data management.

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