Sapienza
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Digitally Fabricated
Low Cost Housing

Material, Joint and Prototype

Doctoral Dissertation

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SAPIENZA
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Doctoral Dissertation

Digitally Fabricated
LOW-COST HOUSING
Material, Joint and Prototype

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SAPIENZA
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Fabbricazione Digitale nella produzione di ALLOGGI A BASSO COSTO
Materiale, giunto e prototipo

Da:

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To my son, Nour
The future is all yours. I hope that I would be the kind of father you look up to

"...Architecture depends upon its time. It is the crystallization of its inner structure, the slow unfolding of its form. That is the reason why technology and architecture are so closely related. Our real hope is that they will grow together, that someday the one will be the expression of the other. Only then will we have architecture worthy of its name: architecture as a true symbol of our time"

Mies van der Rohe, 1950

"An architect must be a craftsman. Of course, any tools will do; these days, the tools may include a computer, an experimental model, and mathematics. However, it is still craftsmanship – the work of someone who does not separate the work of the mind from the work of the hand. It involves a circular process that takes you from the idea to a drawing, from a drawing to a construction, and from construction back to idea."

Renzo Piano, 2003

Abstract

Motivated by the global housing deficit and limited natural resources, this study aims to utilize digital fabrication technologies coupled with local sustainable materials in the quest for alternative, adequate low-cost housing solutions for the less fortunate population, mainly in developing countries.

The thesis is structured into two main parts: a theoretical and an empirical study. The theoretical part identifies the research problem and lays the foundation of knowledge, as well as defines the motivating questions, aim, objectives, scope, methodology and tools used throughout the thesis. An overview of fundamental concepts of mechanisation, standardisation, prefabrication, mass housing, and mass customisation is provided. Different types of prefabricated housing are presented followed by a discussion of select architect-led and industry-led early precedents in prefabrication. The theoretical part also includes an analysis of state-of-the-art built projects or prototypes of digitally fabricated houses. Through this analysis, how these prototypes respond to housing problems is addressed and an observation is made of how these built projects can be categorised into main streams or different trends. After defining the potentials and limitations of these precedents, a number of design criteria or design guidelines are proposed forming the basis for the proposition of a housing system that addresses these drawbacks under the name "*Housing System 01*".

The second part of the thesis is a *Design-Build-Evaluate* empirical study in which the proposed housing system combining concepts of complete off-site prefabrication with modular parametric localised digital fabrication is outlined. Given the necessity of cost reductions, an integral joining system (snap-fit) using an agricultural residue panel material is tested as the principal method for the construction of wall assemblies. The study proves that by using integral joints, it is possible to involve the end-user of the housing unit in the construction activities promoting the concept of "*Self-Build*", as the simplicity of the system allows for the participation of end-users with no previous construction expertise thereby decreasing cost.

A set of mechanical tests are performed to characterise wheat straw panels and then snap-fit joints are dimensioned within the elastic limits of this specific material. Three partial wall assembly prototypes are built. One axial compression test is performed on one of the prototypes. The tests show that the material and the joint system promise to provide a viable construction system as an alternative low-cost housing solution. Further optimisation and more physical structural testing are needed to address more complex forces and loading scenarios.

CHAPTER 1 | Introduction

1.1 Problem definition

With diminishing earth resources, concepts of sustainable design are becoming a usual background to the practice of contemporary architecture. The quest for being efficient and economical is crucial more than ever before. There is an incremental increase in the demand for housing units with the unprecedented growth of population especially in poor and developing countries (UN, 2005). Demographic expansion is continuing regardless of ever-growing shortfalls of housing, services and livelihood opportunities (UN-Habitat, 2011). It is very difficult to get a credible figure of the actual deficit in housing around the globe due to insufficient data, and the rapid increase. The rate of increase is even faster than published data that becomes quickly out-dated.

Moreover, according to United Nations Higher Commission for Refugees global trend report (UNHCR, 2015) an estimated 13.9 million individuals were newly displaced due to conflict or persecution in 2014. This includes 11 million persons newly displaced within the borders of their own country, the highest figure on record. The other 2.9 million individuals were new refugees.

It's undoubtedly a global crisis that is formulating with almost 60 million persons living in camps or currently homeless. Putting these factors into account, a rapid low-cost housing methodology needs to respond to these pressing demands because the practice of construction industry in these countries lacks efficiency and is one of the economic sectors with the lowest productivity and industrialisation rates (Alvarado & Turkienicz, 2010).

Egypt as an example of a developing country has received around 120.000 Syrian refugees from 2011 till 2017 according to the latest report by the UN refugee agency (UNHCR, 2017). The country already faces high risk with the spreading of informal housing settlements around large cities. According to the Egyptian central agency for public mobilization and statistics (CAPMAS), Egypt has around 1221 informal housing areas, out of which 81 around Cairo, 32 around Giza, 41 around Alexandria and 109 around Dakahleya. In order to understand the gravity of the problem; around 8 million inhabitants out of the 15 million living in and around Cairo are living in these areas, which cover approximately 45% of the Capital's area.

Egypt's housing shortage is estimated to be 3.5 million units; but with a population of 92 million and growing, around 175,000 to 200,000 additional housing units are required each year (Global property guide, 2015). While there are approximately 5.6 million vacant units nationwide, most of these are beyond the means of the low and middle-income classes. About 44.4% of Egypt's housing stock is occupied by owners, while about 35.7% of the housing stock is rented. Other tenure types are gifts, and in–kind privileges (14.1%), and public housing (5.5%) (Global property guide, 2015).

Investments in the lower segments of the market remain weak. The country's major developers tend to cater exclusively to the upper middle and upper classes due to the absence of an efficient mortgage law. Approximately 50% of the population is classified as lower income and around 37% of urban space in Egypt consists of informal settlements, while "unsafe slums" are roughly 1% of urban areas, according to Sherif El-Gohary, of the Ministry of Urban Renewal and Informal Settlements (Global property guide, 2015).

This housing deficit is largely responded to by the informal sector making it one of the largest producers of housing in many developing countries. The following map (Figure 1-1) for example shows Cairo city with the red zones representing informal settlements and green zones representing formal ones.

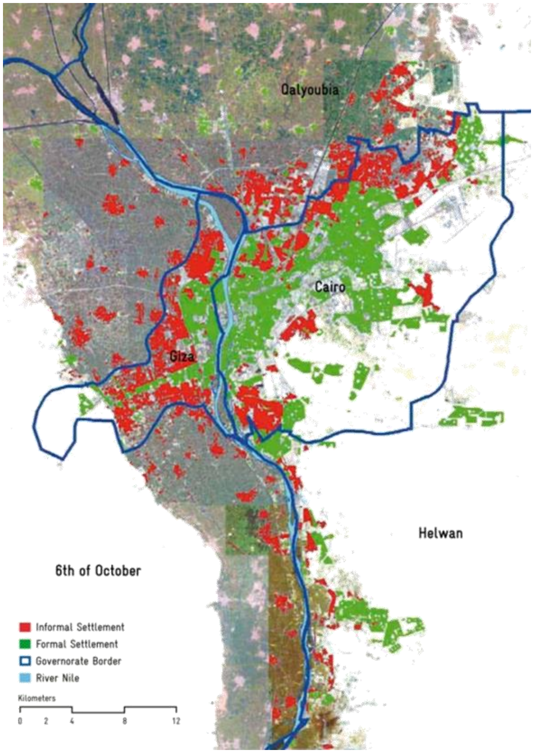

Figure 1-1: Informal housing settlements in and around Cairo. **Source:** (GTZ Egypt, 2009)

Informal settlements may contain a few dwellings or thousands of them, and are generally characterized by inadequate infrastructure, poor access to basic services, unsuitable environments, uncontrolled and unhealthy population densities, inadequate dwellings, poor access to health and education facilities and lack of effective administration by the municipality. Informal settlements are not peculiar to Egypt – they are increasingly the norm in Africa and in many other developing countries where the need for urban housing for the poor cannot be matched with delivery of any kind of formal housing.

Definition of a squatter/informal settlement varies widely from country to country and depends on a variety of parameters. In general, it is considered as a residential area in an urban locality inhabited by the very poor who have no access to tenured land on their own, and hence "squat" on vacant land, either private or public.

Priorities of urban migrants change over time, depending on various conditions that they find themselves in. But one of the first dilemmas they face which persists for a long period is the question of an *"adequate house"*. With little resources, financial or otherwise, skills or access to them, the drastic option of illegally occupying a vacant piece of land to build a rudimentary shelter is the only one available to them.

The problem is further enlarged by the lack of interest, enthusiasm or concern and maybe even the aggressive position that government agencies assume towards the "invasion" of the urban areas by the masses. Squatter settlements are seen as a social evil that has to be eliminated. Such a confusing reaction and attitude towards squatter settlements has not helped the more basic question of "adequate housing for all".

1.2 Research questions

Living in the digital and information age, with the tools of digital design and fabrication at our disposal: Are these tools able to provide an *alternative rapid method* for creating *functionally efficient*, *structurally stable and low-cost* constructions for the poor people in developing countries? Do they provide means for customizing housing units on a mass scale?

At a first glance, the question appears to be simple and straight-forward, nevertheless on a deeper examination; the complexity lying beneath can be easily seen. Attempting to answer this question involves various factors of different weights according to location, cultural factors and market dynamics among many others. N.J. Hebraken (1999) stresses in his book *Supports: an alternative to mass housing* that it is necessary to consider housing as a totality of events which cannot be looked at meaningfully in isolation from each other. In his own words, "*we shall be dealing with mutually related forces arising from all sides of society and which, if all goes well, act in equilibrium. The action of these forces is the concept we call housing and the tangible results we call towns and dwellings*".

The research takes the position that, thoughtful designers and architects need to see beyond the short-lived seduction by the new and surprising technological capability of parametric design and digital fabrication. If the capacity and the competence of using the fabrication tools efficiently exist, why aren't they widely used to fabricate shelters and houses for the less fortunate?

It's not only a question into the digital means but also a question into morals of digital fabrication, into the driving forces that orient the development of the field. There is a critical need to move from just "*being able*" to "*being driven by responsibility*", if it's all about "*making*" the world a better place.

A sceptical argument was repeatedly faced by this research concerning the motivation for the use of digital means of design and fabrication in a context that has other housing solutions like traditional/vernacular local construction methods. In other words, why use digital fabrication while the problem can be addressed using locally adapted solutions/materials/methods? The answer to this argument will be addressed in more detail in section 3.4 of this thesis. But in general terms, although digital tools may require more initial time to build interrelations and fabricate a working prototype compared to traditional hand-crafted methods, long-term productivity can be dramatically superior due to the ease of iterative design improvements and repeatability.

In the words of James Stevens and Ralph Nelson in their book Digital Vernacular (2015), the digital era is seen as the new vernacular. For them, "All vernacular is digital" because throughout history the human hands and fingers -the digits- have shaped mud and logs, worked metal and stone, mixed water and sand. They show a concern in this book -and the author shares the same concern- that too much of the digital architecture produced around the world today with its smooth, fluid forms and shapes often lack any vernacular dimension or reference. Local materials and production circumstances are typically neglected. They argue for a thoughtful adoption of digital technologies by local communities of designers and builders that embrace the legacy and lessons of building practices intrinsic to the cultures and societies in which they operate (Stevens & Nelson, 2015). This specific aspect is aligned with the research work presented in this thesis. The research goes to the extent of scanning the construction market looking for alternative sustainable materials that are suited for low-cost housing with minimal environmental impact while being easily machine-able using digital fabrication tools.

1.3 Aims and objectives

When we refer to low-cost or low-income housing we almost always imply: minimum variation, large quantity and limited quality. This research aims at reversing these notions. The research aims at creating a modular flexible parametrically designed, digitally fabricated system for the construction of a rural low-cost single-family house. The design system shall address various aspects of mass-customisation, economy, material selection, material efficiency and suitability to the context. Such a prototype must respect the specific conditions found in developing countries and defined in the research as socio-economic, environmental and technical design criteria. It must also guarantee acceptable conditions of habitability and sustainability.

The research will attempt to use the available fabrication tools in a sustainable manner to create flexible low-income residential units having the following characteristics:

Low cost:

The researcher holds the argument that digital fabrication can be cheap. Once a person has access to fabrication machines, he can create a car, a mobile phone, agricultural equipment, etc. at the cost of "raw materials". The standard industrial supply-chain greatly inflates the price of manufactured goods. If a person buys a commercially-manufactured product, the price he pays has to cover the costs of mining the material, shipping the material to the manufacturing plant, running the machines, labour, marketing, more shipping, and mark-ups by several retailers. Digital fabrication instead, by empowering people to manufacture their own wealth in their backyard, cuts out all those extra costs and reduces the cost to (Energy + Information + Raw materials). Energy can potentially come from the sun and information can be shared freely on the Internet, so the only eventual cost is raw materials. If the main raw material at this point comes from local surroundings (e.g. agricultural residues) that have no/little value then another cost saving can be foreseen.

During the development of the thesis and for the sake of fabricating prototypes, the author found a local fabricator who built his own Computer Numerical Control Milling machine through the use open source online information and forums. Working with local entrepreneurs who are willing to create their own machines and fabrication facilities validates the possibility of creating shadow economies and profoundly change the dynamics of the existing housing market.

Parametrically modified:

Besides being a growing trend within the practice for formal, expressive and decorative reasons; parametric design is an appealing approach for designers, because it facilitates flexibility within design and construction domains. To an extent, every object is parametric. The geometry gains shape by assigning specific values to its parameters. On the other hand, since Digital fabrication is flexible, one machine can fulfil many roles and reduces space and resources. Industrial mass-production required a different factory for every type of product, but flexible, digital manufacturing allows the same set of tools to be used in making almost any physical object. Flexibility makes it worthwhile to invest in fabrication tools; only industrialists would invest in a tool that makes the same thing repetitively, but a tool that can respond to changing and growing needs is a tool worth having.

Environmentally responsible:

Attention will be given to the contextual aspects of the housing unit due to the fact that it is situated within a zone with a long history of agricultural activities. This aspect is particularly important for the success of a low-cost housing unit built within the region. The material selection plays a key role in defining how responsible towards the environment the design can be. It is understandable that tens of materials can be used for secondary structural elements and finishes. But by material selection, the author intends the material used for the main structure of the housing unit.

Besides the general aim of the study; the research also has the following partial objectives:

- Understanding the different trends of digitally fabricated housing and why they did not qualify as a widespread solution to the housing deficit despite offering progressive solutions to the housing sector.
- Developing hands-on experience with digital fabrication tools in order to formulate a better understanding of the potentials and limitations of each available tool.
- Assessing the mechanical and structural performance of the selected material and the proposed housing construction system.
- Exploring the interrelations and dependencies that occur between tool, material and process through-out the design and construction phases.

1.4 Scope

The use of parametric design systems can extend across different levels and stages of architect-building relationship. Table 1-1 describes a generic vision in terms of breaking down the complexity of the housing project into four main levels: Multiple unit configurations, Macro scale configuration, Micro scale configuration, and Machining scale. In other words, we can use parametric design tools in an early stage design phase for multiple unit configurations, or later on in a closer look into space planning within the same unit, or even closer to building component scale and further into machining and production aspects of construction components.

This break down has a great potential in alignment with parametric design as a proposed approach because parametric design can accommodate for change within the boundaries of a designed logical system. This means that not every single user preference can be accounted for unless it was incorporated from the beginning as a changeable parameter. In the meantime, with careful planning and thorough analysis, defining the key parameters can give a great deal of flexibility and account for a wide range of user preferences.

This research places a main focus on level three (building component scale), i.e. the stage that is mainly involved with or influenced by digital fabrication. The scope of work for the proposed prototype will definitely affect and be affected by level 2 and 4. As for the factors from level 1 which are concerned with the urban scale, they do not lie at the core of this investigation and will not be addressed in this thesis. Normally, the scope of the research has been continuously refined and oriented along the progression of time based on findings, observations and accessibility to different data.

Table 1-1: The levels of possible parametric design intervention within the design process.

Level 1	**Multiple unit Overall Configuration**	**Example Aspects**	**User Involvement**
	Environmental impact	Max floor Areas	Intermediate between user preferences and planning guidelines
	Group Cultural norms	Orientation	
		Privacy Control	
Level 2	**Macro Scale Configuration**		Maximum as it involves user preferences
	Room layout	Spatial relationships	
	Functional relationships	Fenestration, Etc.	
Level 3	**Micro Scale Configuration**		Minimal as technical knowledge is required
	Fabrication detailing	Component scale	
	Assembly logic planning	Joints	
	Structural concerns	Material selection	
Level 4	**Machining Scale**	Work Piece Handling	Minimal as technical knowledge is required
		Tooling - Finishing	

1.5 Methodology

The thesis is structured into two main parts, a theoretical part and an empirical design-testing based part. This research has design and experimentation at its core, in which design is intertwined with analysis and testing. It is not always easy to draw a precise deterministic line between qualitative and quantitative methods for the study of Architectural problems, due to the very nature of the discipline itself being a blend of Science and Art. Nevertheless, the author attempts to outline in this section a number of research methods followed through different phases of the research. Given the nature of the problem that is multi-dimensional, flexibility was needed in order to stretch out across several disciplines (geometry, environment, structure and manufacturing/fabrication aspects), each of them requiring a different methodology, e.g.

qualitative methods for assessment of complexity, mathematical and quantitative methods for geometrical descriptions and structural analysis, etc.

In an article in the Journal of Architectural Education, David Salomon stresses on a concept of architectural research that is more pluralistic. The author shares the same view towards the relationship between design and research. Salomon sees the research enterprise as encompassing both qualitative and quantitative methods, yielding both "objective truths" and "personal fictions". In other words, both design and research are, he claims, "well-fabricated hybrids." (Saloman cited in Groat & Wang, 2013)

Adapting the nomenclature used by Groat and Wang in their book "Architectural Research Methods", chapter three of this thesis analyses a group of "case-studies" in digitally fabricated housing using multiple sources of information in order to draw a clearer image on the reasons for the lack of diffusion of these solutions as long term solutions for housing deficit. A focus was made on multiple cases, studied in their real-life contexts. The selection of the case studies was based on the need to define a representative sample of projects upon which a qualitative discussion was made. The author attempted to generalize and extract visible trends between different groups of case studies.

The final section of the thesis tries to validate the assumptions and propositions made by the author about the applicability and constructability of the proposed housing system. This phase of the research necessitated the construction of a partial full-scale prototype that was tested structurally using experimental testing methods that will be thoroughly discussed in their relevant chapter(s).

1.6 Tools

1.6.1 (Digital) Physical Tools

Every few generations, the fundamental means of production are transformed: Steam, electricity, standardization, assembly line, lean manufacturing and now robotics. Sometimes this comes from management techniques, but the actual powerful changes come from new tools (Anderson 2012 cited in Stoutjesdijk, 2014).

As young architects educated in the certainties of traditional practice, we are faced by an evolutionary stage initiated by information technology and digital realms. There is a growing interest between large populations of architects in the physical making of architecture. Architects face an urgent need to revolutionize their tools and understandings of the practice of architecture.

This need or urge is rooted in the diminishing natural resources and growing global human demands. The Digital media in design and fabrication promise to address these demands through more efficient processes of design and construction. It is safe to say that these tools are becoming prominent and an essential part of most cutting-edge architecture firms.

Frank Ghery's firm, Ghery Partners, has been a pioneer in integrating digital technologies into design development and construction administration stages of architectural design, and in demonstrating that digital fabrication technologies can be used on large-scale, large-budget buildings. Most of Ghery's designs would have either been economically unbuildable without the integration of digital modelling tools and the ability to directly fabricate components of the building with various digital fabrication technologies.

Many of the digital fabrication practitioners claim it provides an economy of means related to the very nature of the machines that require accurate and precise data extracted directly from design data. This direct translation eliminates the need for the interpretation of 2D drawings into translating them into constructible elements. It can be argued that the correspondence between design information and fabrication information is relatively high. Hence, it becomes logic to consider the economy of means of digital fabrication tools for the construction of low-cost residential units. With the large diffusion of digital tools, they are becoming more affordable.

1.6.2 (Digital) Virtual Tools

On the other hand, parametric design is a compelling and flexible approach to accommodate for the possible variations in the design and fabrication of the proposed prototypes. It can be noted that the process of geometry creation in a conventional setting would take less time but on the other hand modifying it would be time consuming as it necessitates recreating the static geometries. Meanwhile, in a parametric setting, the process of geometry creation takes longer time as it involves creating interrelations and dependencies between geometrical entities but in return consumes less time to modify. It cannot be decisively said that both time intervals are equal, as the two processes of creation and modification rely considerably on the agility and speed of the designer.

Parametric design depends on defining relationships and the willingness (and ability) of the designer to consider the relationship-definition phase as an integral part of the broader design process. It initially requires the designer to take one step back from the direct activity of design and focus on the logic that binds the design together. The relationship creation process necessarily requires a formal notation and introduces additional concepts that have not previously been considered as part of "design thinking" (Woodbury, 2010).

Nonetheless, if the parametric setup does not contain a parameter that aligns directly with the modification needed for the model, the setup needs to be changed in a way that Woodburry refers to as "erase, edit, relate, and repair" (Davis, Burry, & Burry, 2011). This can be difficult and time consuming with large parametric models, particularly if the consequences of this modification need to be traced back through a complex network of relationships. Research by Davis, Burry, & Burry (2011) covers that specific point, suggesting the replacement of dataflow programming - which is predominant in parametric models- by logic programming in which the user can focus on describing relationships between objects and leave the logical inferences (the way data flows in these relationships) for the computer to deduce.

Parametric design reaches its high potential when combined with material behaviour. It is very common now to see architecture merely as an expression of fascination with the capabilities that parametric tools bring to the disposal of the designer. When parametric definitions address not only inert geometries but also, or perhaps primarily, material properties and physical behaviour, architecture responds to actual design drives and acquires broader relevance (Zarzycki, 2012). That's why physical models, assemblies and mock-ups are extensively used during this thesis. Access to fabrication facilities, tools and workshops is of central importance to this line of research.

1.7 Thesis structure

The thesis is structured into two main parts. A theoretical part which comprises the first three chapters and then followed by an empirical design-testing based part which comprises chapter from four to six. The first chapter starts by defining the research problem and laying the foundation of knowledge required to fully comprehend the approach proposed throughout the thesis. The chapter defines motivating questions, aims and objectives, scope, methodology and tools used throughout the thesis.

Chapter two presents an overview of some basic concepts of mechanisation, standardisation, prefabrication, mass housing and mass customisation. The chapter also explains different types of prefabricated housing followed by some architect-led and industry-led early precedents in prefabrication.

Chapter three presents an analysis of state-of-the-art built projects or prototypes of digitally fabricated houses. Through the analysis, an understanding is developed on how these prototypes responded to housing problems. An observation was made on how these built projects can be categorized into main streams or different trends.

Chapter four defines the potentials and limitations of these precedents, and thus proposes a number of design criteria or design guidelines, which form the basis for the preposition of a housing system that addresses these drawbacks under the name "*Housing System 01*".

The second part of the thesis is a design-based empirical study in which a housing system is proposed combining concepts of traditional prefabrication with more progressive digital fabrication methods in search for an efficient housing system that can respond to economic and environmental drives. Given the necessity of cost reductions, an integral jointing system is tested as the principal method for the construction of wall assemblies. By integral joints, it is possible to involve the end-user of the housing unit in the construction activities promoting the concept of Self-Build, as the simplicity if the system allows for the participation of end-users with no previous construction expertise.

The core material is tested for mechanical performance as a sheet, and also in the assembly that represents one of the components of the design proposition. This construction system is tested through a proof-of-concept, full-scale partial mock-up using agricultural residue panels and CNC-milling machines in order to test assembly logics and verify design intents. One structural test is performed on the designed wall assembly in order to better understand its behaviour and therefore inform the design system for further modifications.

The thesis started by a very ambitious plan to build and test all the designed housing system components but due to the steep timeline of the doctoral research it was not possible to perform all the testing activities initially planned. Therefore, the author would like to put some emphasis on the interpretation of the testing results as a trend that needs more verification through full-scale mock-ups.

THESIS STRUCTURE

THEORETICAL BACKGROUND

PROBLEM DEFINITION
Informal settelments - Refugee problems
Lack of customization & user involvement
Mass production failure

MOTIVATION
Provide an affordable mass-customized housing solution

RESEARCH QUESTION
Digital Fabrication technologies can provide a feasible solution?
What is the structure of the process/method that ensures an economic solution?

METHODOLOGY
Research by Design and Experimentation
Multidisciplinary approach
Comparison to traditional construction practices
Design-Build-Evaluate

Chapter 01

STATE OF THE ART
How did others approach the problem?
Precedent built examples
Lessons learned

ACTION PLAN
Formulate program based on a given context
Choose material + Scale + Scope + Tools + Budget

Chapter 02
Chapter 03

THEORATICAL FRAMEWORK
How the proposal intends on avoiding precedent problems
Pre-fabricating wetspaces VS Digitally fabricating naked spaces
Technical Complexity VS Formal - Spatial Freedom

DESIGN CRITERIA

Economic Criteria	Social Criteria	Environmental Criteria	Technical Criteria
- Minimum budget	- House planning	- Context Definition	- Kit of parts + Chunks
- High Density	- Extended Families	- Local sustainable material	- Minimizing material waste
- Maximum Efficiency	- User Involvement	- Dense Clustering	- Optimizing the process
	- Acceptable space for long term living		- Joining systems

Chapter 04

EXPERIMENTATION DESIGN

PROPOSITIONS | HOUSING SYSTEM 01
Modular Parametric Assemblies
+
Off-site mass produced core (Wet spaces: Kitchen+bathroom)
+
Design Interface

BOTTOM-UP STUDY
Mehcanical Material Tests
Detailed Joint Design
Simple Structural Calculations

PROOF OF CONCEPT
Design feedback
Full-scale joint testing - Full scale Prototypes
Strucutral Evaluation

Chapter 05
Chapter 06

EVALUATION AND FEEDBACK

Chapter 07

CHAPTER 2 | Background

2.1 Where we come from?

Art and construction are enormous fields. Colin Davies (2005) argues that one of the curious characteristics of the architecture field is that it is more likely allied with art than with construction. In the introduction of his book *Outline of European Architecture*, first published in 1942, the great modernist architectural historian Nikolas Pevsner defines architecture in purely artistic terms. Painters, he says, deal with line and colour, sculptors deal with form, and architects deal with space. We can definitely object to that abstract view assuming the architect is not different from a painter or sculptor. One objection would be the fact that buildings are usable objects, more like bridges or boats than paintings or statues. Davies goes on to debate that architecture and construction, which one might assume to be very close, actually have very little in common. Architects and builders may be able to work together on a professional level but culturally they are worlds apart. They speak different languages, they have different aims and different tastes, they are educated differently and they have different histories.

As shocking as this might sound, in the developed world the great majority of buildings, perhaps 80 percent by value, are not designed by architects and fall outside the architecture field. Yet inside the architecture field, in schools of architecture for example, it is normal to speak and act as if all buildings were designed by architects (Davies, 2005). It is a fiction tacitly maintained to preserve the illusion that architecture is a real force for change in the world. Ironically, this self-delusion is one of the reasons why architecture is at present not a real force for change in the world. Most of the non-architectural 80 percent of buildings are houses. Very few ordinary houses count as architecture. This is another of architecture's guilty secrets: that it fails to have any effect on most people's most intimate experience of buildings (Davies, 2005).

In support of this argument, and in a public lecture personally attended by the author in Rome in 2015, the British architect Cameron Sinclair –founder of architecture for humanity and later SMALL WORKS- claimed that architects are commissioned to design buildings for almost only 3% of the world population, while 97% still crave for architecture but unable to afford it. An argument to support this was also discussed by Davies in (Stoutjesdijk, 2014) claiming that the richest 1% of the population owned 40% of the global assets in 2000 and that the richest 10% accounted for 85% of the global assets. According to Sinclair, the economic model adapted by architects searching for traditional commissions from wealthy clients will come to an end, or at best will be even more challenging to find with the rising competition on a global scale. Instead, alternative models of architect/client relationship shall be found in order to deliver architecture to communities that are in desperate need for almost all building typologies. Housing is probably number one priority for growing populations in developing countries, thus represents a logic target for the application of these alternative methods.

The changes in the dynamics of the production markets are already visible. We can see tens of start-ups that help you customize services to your own needs starting from personal gadgets to clothes to electronic equipment. The information tools through internet and web-based platforms provide free access to information. Local fabrication labs provide access to digital tools for manufacturing. With this combination, production starts to move away from corporate authority into an open landscape of potentials and opportunities.

Architecture as seen by the author is not far from this kind of change. Examples of projects such as e.g. *Wikihouse* open access house design, which can be downloaded by anyone with an internet connection and manufactured by having accessibility to relatively cheap fabrication equipment. Another initiative is the *Open Building Institute (OBI)* which has put the mission of making affordable, ecological housing widely available as their main target. They also aim at diffusing and sharing knowledge that concerns different aspects of housing construction. They have designed and modelled a library of modular components that is downloadable via their online platform from a catalogue of virtual parts using open source software to build custom designs. Some of the modules were physically prototyped and tested but others were not.

It is important at this point to lay the knowledge foundation of fundamental concepts upon which the housing field operates. The origins of concepts such as prefabrication, mass production and mass customisation are critical to understanding, analysing and potentially advising on new directions for low-cost housing construction that fits current social, environmental, economic needs and limitations.

2.2 Fundamental concepts

2.2.1 Mechanisation, Standardisation and Mass Production

Mechanisation by definition, is the process of starting to use machines to do something that was previously done by hand (Cambridge Online Dictionary). This activity can be tracked to almost all ancient civilizations such as Egypt, Iraq and China, where there was always an urge to go beyond the human capability in search for more efficiency in performing daily tasks. Simple machines such as levers and water wheels are considered among the oldest inventions.

While following the records and traditions which relate to the steam-engine, Robert Thurston proposes to call attention to the fact that its history illustrates the very important truth: *Great inventions are never, and great discoveries are seldom, the work of any one mind. Every great invention is really either an aggregation of minor inventions, or the final step of a progression.* It is not a creation, but a growth. Hence, the same invention is frequently brought out in several countries, and by several individuals, simultaneously (Thurston, 2011). Although the English inventor Newcomen was the first to design a practical device to harness steam to produce mechanical work in 1712 in England, James Watt is today better known than Newcomen in relation to the origin of the steam engine.

Mechanisation in one of its eminent forms for the production of goods in the United States first emerged in the textile industry at the end of the eighteenth century and spread to other industries throughout the nineteenth century.

With the industry embracing mechanisation two major changes occurred: the replacement of skilled craftsmen by unskilled labour and standardisation. Derived by economic urges, factory owners worked towards eliminating artisans and craftsmen as they were paid much higher wages than unskilled workers. There was a large investment of time and money from the employer in training the craftsmen through apprenticeships. "*Early successes with machines encouraged the owners of textile mills to mechanize: they quickly learned that, in addition to increasing productivity and 'saving labour,' textile machines also 'cheapened labour' by reducing the skill required of workers*" (Biggs cited in Hayes J. , 2005).

The industrial economy of the early nineteenth century depended on skilled artisanal labour, and its shortage led to high wages nearly double those paid in some parts of Britain" (Biggs cited in Hayes J. , 2005). After investing in training, an employer found it very costly to replace skilled craftsmen, and it was difficult to replace a craftsman outright because of a skilled labour shortage. With mechanisation came the division of labour. Craftsmen could be replaced by unskilled labourers because jobs were divided to such an extent that an individual worker performed one particular task repetitively, and these unskilled workers could be easily replaced. The larger effect this produced was the ability of factory owners to hire from a larger portion of the population, which in turn lowered the pay of workers. Ultimately, mechanisation reduced the overall skill level of the workforce at large. "By the end of the nineteenth century, industrialists understood that success of manufacturing lay in mechanisation. Special-purpose machines were already helping to build guns, sewing machines, bicycles, and other goods" (Hayes J. , 2005).

Although mechanised factories emerged in England before the United States, standardisation was a French ideal, which then developed in the United States. In his book "*From the American system to mass production"* David Hounshell (1985) traces the beginnings of mass production in American factories back to the French Enlightenment period. Rather than the economic motivations that spurred the development of mechanisation in the textile industry, standardisation was born out of the "Enlightened military mind" of General Jean-Baptiste de Gribeauval. "Beginning in 1765 Gribeauval sought to rationalise French armaments by introducing standardised weapons with standardised parts" (Hounshell, 1985). "[…] *Gribeauval envisioned a rationalised world of standardised, interchangeable parts*". The intellectual influence of the Enlightenment on Thomas Jefferson and the influence of the French military on the United States War Department during the Revolutionary War spurred American arms manufacturers to develop systems of standardised interchangeable parts which became known later as the American System of Manufactures.

The American system evolved through the nineteenth century spreading to more publicly available goods. The ultimate representation was manifested by Henry Ford (Figure 2-1) and his engineers at Ford's Highland Park factory and River Rouge industrial complex in Detroit, where mechanisation in the production and assembly of standardised parts became known as "mass production".

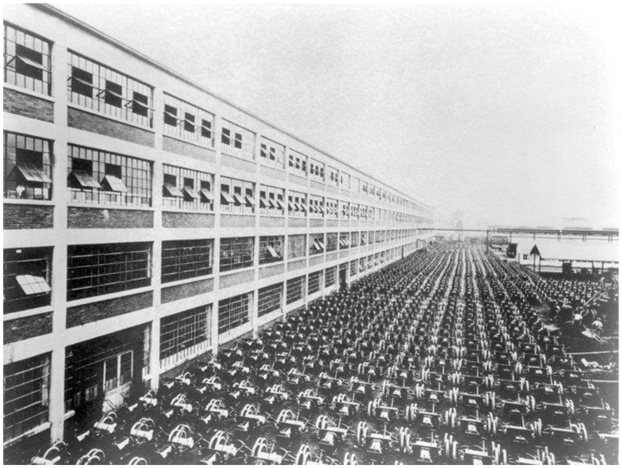

Figure 2-1: One day worth of Ford T model production, Highland Park Factory. **Source:** https://www.jalopyjournal.com/?p=16390

Mass production was more than just standardising parts as every movement by man or machine had been streamlined, and the entire process required to build a Model T automobile from start to finish had been thoroughly analysed and removed of all inefficiencies. Highly specialised, single-task machines produced standard parts that were assembled on a moving assembly line, which became synonymous with mass production. Ford revolutionised automobile manufacture, making cars available to the public for the first time. Production of the Model T jumped from 6000 units per year to 200.000 in 1913 to 800.000 in 1919, and peaked at 2.000.000 in 1923. The utterly staggering production of the Model T seemed to demonstrate the unlimited potential of mass production. The mass production can be manifested in the immortal quote that Henry Ford said: "*You can have any colour you want as long as it's black.*"

The benefits of high-quality, low-cost parts that can be used interchangeably, became common practice for virtually all manufacturing. Consumer products, like home appliances which roll off the assembly line identically, were well suited for mass production. It was felt at one point that the same principles could be applied to any and all industry, giving the same benefits in efficiency and productivity.

Within the field of construction, building materials were easily adapted to mechanised production, and standardised building materials produced in factories began changing the way buildings were constructed and the way architects practiced. Although standardisation and mechanisation made the production of buildings parts more efficient and cost effective, the appeal of mass-produced buildings transfixed architects like Le Corbusier and Walter Gropius.

Although Gropius was perhaps the pioneer with his proposal to Allgemaine Electricitäts Gesselleschaft (AEG) in 1910 and his pushing of his agenda for industrialised building through the Bauhaus to flourishing architects and designers, Le Corbusier is the one who ultimately advanced the cause. Again, the concept of growth resurfaces where no one mind was responsible for the whole but small aggregate or incremental steps in which each architect further evolved the main idea. Conceptually Le Corbusier adds little to the basic formulations of Gropius, yet in the years after it is Le Corbusier, not Gropius, who ignites the imagination of a generation of architects; it is not the reasoned arguments of Gropius but the stimulating force of Le Corbusier's visual images, and the suggestive power of his style, that leads the modern movement in its drive for industrialisation and standardization.

When Le Corbusier praised grain silos and factories because their pure form had been shaped by the economic rules of production, he came down in favour of engineers. They are the unselfconscious makers, he said, the vernacular architects and producers of modern form. For Le Corbusier, engineers, unlike architects, are not guided by preconception about appearance. Instead, they possess a single-minded focus on purpose and economy. Poetic mass, surface, and plan result from the filters of economics and process through which their projects must pass (Kieran & Timberlake, 2004).

Le Corbusier saw great promise in the production of architecture by machines, particularly in housing where it offered a way to fulfil a social housing agenda. Economic and social agendas were merged with construction and architecture in his vision of a vernacular.

These modernist architects saw the potential of a social and economic reform through the adoption of standardisation and mass production into building construction. They saw it as a way to rationalise housing construction and have better control over quality while minimising time and cost.

2.2.2 Mass Housing

One of the most common approaches/strategies that are largely adopted by government agencies to solve the deficit of housing units is to build large amount of monotonous, repetitious houses or apartment buildings (Figure 2-2). Although houses are not serially produced like automobiles in the sense of moving assembly lines, highly specialised single-task machines, repetitive tasks by workers; a tremendous cost saving can be achieved by limited variation in a large housing development. Realised projects in Mexico, Brazil, Egypt and many other African countries demonstrate clearly that no/little consideration is given to the individuality of house occupants. From one point of view, supporters of this approach think that having a decent housing unit that has the basic level of human needs is way better than having no house at all, even if it is not personalised to the specific needs of the user. Their argument also extends to the aspect of construction speed where producing large amounts of similar building components (mass production) is supposedly more economic and time-saving.

Mass Housing is seen by Hebraken as one of the methods for the supply of housing but neither the only one nor the right one (Hebraken, 1999). He argues that mass housing is not new: the idea of building several dwellings as one project is as ancient as Romans. He defines the fundamental drawback of mass housing in the fear of interference of the user in the decision-making and the chaos that this might bring to the process, so at this point the involvement of the individual is deemed undesirable. He claims that our current ideas about housing reduce the individual to a mere statistic. However, he acknowledges that genuine improvements have been achieved in housing in the last 50 years through the application of Mass Housing. Mass housing -he argues- takes away man’s act and presents him with a form; it seeks to provide a comfortable form to be used by people who do not have to lift a finger to influence it.

Figure 2-2: A mass housing project in China. **Source:** Construction Review Online, 2015

By definition, to "standardise" a product means to reduce to or bring into conformity with a standard. An entity produced in series that has been standardised is identical or nearly identical to the standard and all the other entities produced as well. If there is no difference between entities, then it could be said that to standardise means to eliminate variation among entities in a series. Therefore, an entity that is standard exhibits little or no variation from the next. The concept is therefore not connected to form. If a series of objects are all radically complex geometrically, yet all have the identical complex geometry then, they would be considered standard. If another series of objects have simple formal qualities, yet each entity of the series is different, then they would not be considered standard, but rather non-standard. This concept of standard and standardise is related to mass production in a manufacturing setting where the production of a series is connected to a mould or die from which all entities have been created.

If the goal is to reduce costs and the price of construction materials is fixed, the design that requires the least labour will be the least expensive. Walls with the least amount of variation are orthogonal, with a few openings as possible, preferably none. Roofs and Floors follow the same logic. Since affordable housing by nature should be inexpensive to build, the same ruthless logic is applied in excess (Hayes J. , 2005). There is no one standard that generates the building, but less variation means lower cost. Therefore, in the construction of a building the concept of standardisation is not completely restricted to the production of a series.

The transformation of the construction industry into a highly industrialised corporate endeavour left the architect in a position of lesser power. The current practice model is a system that theoretically allows for infinite variability but often becomes practice of merely choosing products and systems for economy. In many instances design is inevitably reduced to the specification of components and systems originally conceived without reference to the uniqueness of the project, either as a technological or social construct. The level of uniqueness inherent to any individual building project necessitates a high level of innovation, which often 'appears' incompatible with present client demands for reliability and economy.

On the contrary, the end-user currently demands individuality and self-expression which dictates that a balance should be found between reliability, economy and speed on one hand; innovation, personalisation and uniqueness on the other.

2.2.3 Prefabrication in Housing

Prefabricated housing is a general term that indicates building components are pre-made in the factory, and then transported to the building site to be assembled and installed on a permanent foundation (Huang, Krawczyk, & Schipporeit, 2006).

The history of prefab housing began nearly four hundred years ago, when a panelised wood house was shipped from England to Cape Ann, Massachusetts in 1624 to provide housing for a fishing fleet (Arieff cited in Huang, Krawczyk, & Schipporeit, 2006). Parts of buildings have been made in factories for at least 200 years. Machine-made bricks, ceramic tiles, sawn timber, sheet glass, sash windows, cast-iron columns and beams – all were familiar factory-made products in nineteenth-century Europe and America. Whole buildings - houses, hospitals, churches, factories, barracks - were made in kit form and shipped to colonies and war zones all over the world. Twentieth century examples include the mobile home, the post-war British 'prefab' and container cabins for offshore oil workers.

Many architects attempted to develop design systems that were modular and pre-fabricated using off-site standard building techniques, but the relationship between architecture and prefabrication has always been problematic. Many architects have found it hard to accept the idea that the products of their art might be made in a factory. This is not surprising, perhaps. When the industrial revolution started, architecture was already an ancient craft. Some have seen and still see that architecture as a barrier of resistance against industrial culture, maintaining eternal values in a world driven largely by financial power and mere economics.

In the nineteenth century architecture remained someway distant from industry, concerning itself with churches, art galleries and town halls while ignoring factories, railway sheds and urban housing for the poor. But then in the early years of the twentieth century it seemed that architecture and industry might be reconciled. Progressive architects in France, Germany and USA tried to create a new architecture that would use the products of industry while teaching industry about art. Stripped of all traditional ornament, the new modernist architecture would be the very embodiment of a reformed industrial world.

In his book "the prefabricated home", Professor Colin Davies (2005) describes the architecture field as "broader and vaguer" than just "the design of buildings", but narrow in its reliance on star personalities, professional jargon, excessive publicity, and the creation of myths of its own history. Davies argues that adherence to this position has left the profession unable to assimilate popular notions about architecture and types such as the single-family house; most which, he reminds the readers, are now designed by non-architects in styles that architects find unappealing. He proposes that the "key to the reform" is an understanding and appreciation of the "non-architectural history of the prefabricated house". This book represents Davies's attempt to provide this history and to begin bridging the gap between architecture and the consumer-driven home building market.

He explains that modernist architects have put the prefabricated house at the centre of their programme of reform.

> "*Architectural history may pretend otherwise, but the fact is that their prefabricated house projects all failed. Some architects interpret this as a failure of the prefabricated house per se, a proof that buildings do not lend themselves to factory production. But this is not true. Millions of successful prefabricated houses have been built all over the world, but architectural history ignores them because they are beyond the pale of the architectural field. While architecture has been struggling to find the true artistic expression of industrial production, construction has been quietly industrializing itself behind architecture's back*"

(Davies, 2005)

Davies suggests that it was the inflated egos of architects themselves that caused most prefabrication experiments to fail. He traces this in part to the academic establishment that teaches students that most buildings are designed by architects and that as professionals they will have control over all aspects of the design process. To remedy these problems, Davies hopes that architects will give up the desire for sole authorship; stop rejecting popular taste as vulgar; and find ways to embrace lean production in order to balance a desire for individuality with the economics and methods of the building industry.

Gilbert Herbert highlights one of the main problems of pre-fabricated housing in his book "*The Dream of the Factory-Made House*":

> *[....] hoping to produce a factory-built product competitive in quality with the traditionally built houses of the tract developer, at a significantly lower price; this was the goal of General Panel*[1]*, as it was of most other prefab firms. In this formidable task, where the high costs of research, development and tooling could only be offset by large-scale production, the advocates of the factory-built house turned again and again to the paradigm of the automobile for encouragement and for justification. But this analogy was a false one. Car prices initially were high, to cover high tooling costs and disproportionate overheads, while production slowly increased. But as a generic product the car was unique, and its manufacturers had a complete monopoly; one either paid the high price or did not acquire a car. Eventually, of course, production rose to levels where prices could significantly be reduced, generating even larger demand. In more recent times one could see a parallel in the manufacture and marketing of computers. But industrialised housing did not produce a unique product, the competition of the traditionally built house was an ever-present factor, and the industry was denied that sheltered growth period it needed to reach the critical level of mass production."*

The following points are seen by the author as the most common disadvantages of prefabricated housing that most of literature collectively agree to:

- Continuous tendency for standardisation of parts largely pushed by economy, limit the potential flexibility for adapting the housing needs of the users.
- Relatively high cost due to the utilisation of cranes, experienced set crews, specialised workers, material and element transport to and from mass production plants.
- Home owners do not develop a sense of belonging as they are not allowed to be involved in the design/construction processes. Usually the involvement is limited to a small number of design parameters like choosing out of a catalog of predefined solutions.

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[1] General Panel is a company started by Gropius with his fellow German architect Konrad Wachsmans after arriving to the United States after WW2. The company sought to emulate the factory-based production of the automobile for the production of pre-fabricated houses.

On the potentials side, improvements of quality and efficiency are accomplished because factories can offer controlled working conditions, automation of some tasks, fewer scheduling and weather-related problems, and simplified inspection processes.

Therefore, it is very important to guarantee quality housing in terms of adequate process of design and construction which includes the participation of the community. These two aspects imply that the housing unit, as a finished product, must include tangible aspects related with the quality of materials, finishes, processes, resources, environment, habitability and stability as well as intangible aspects related to social, cultural and economic issues (Arango, 2003 cited in Rayo, 2015).

2.3 Types of prefabricated housing

The categorisation adapted here follows (Huang, Krawczyk, & Schipporeit, 2006), where they defined six different types of prefabricated housing systems from a component-scale point of view: fully modular, sectional, panelised, pre-cut, components/kit of parts, and chassis and infill. They based their categorisation on the scale of individual components. Other categorisations are often simpler with only four categories: Manufactured homes (which is another term for mobile homes), Modular homes, Panelised homes and Pre-cut homes. The following section provides definitions and examples of prefabricated housing based on the broader categorisation which is more comprehensive at this point.

2.3.1 Fully Modular

All the components of a single housing unit are entirely made, assembled and finished at the manufacturing plant; as three-dimensional modules requiring only simple connections to the foundations and main service conduits once at the site. The size of the modular unit is restricted by highway law or shipping constraints. Prefabricated modular and capsule architecture on a large scale was explored in the 1960s and 1970s (Figure 2-3), most famously by Moshe Safdie in the Habitat ’67 project in Montreal; contemporarily by the Spanish architect Ricardo Bofill for the Kafka castle project in Barcelona and later by Kisho Kurokawa for the Nakagin Capsule Tower in Tokyo.

Figure 2-3: (a) Habitat 67 by Moshe Safdie, Montreal, (b): Kafka Castle by Ricardo Bofill in Barcelona, (c) Nakagin Capsule Tower in Tokyo. **Source:** a - Wikipedia, b and c – Archdaily

2.3.2 Sectional

Small and easy to transport sectional modules but incomplete, as they need complementary components or processing once they reach the site. An approach largely used in ship and plane building. A sectional module housing based on the same techniques used for concrete sewage pipes was a project introduced recently in the Venice Biennale of Architecture 2016 by the Portuguese architect Samuel Gonçalves. The concrete modules match the shapes and dimensions of standard concrete sewer pipes, which means they can be produced by modifying existing production lines.

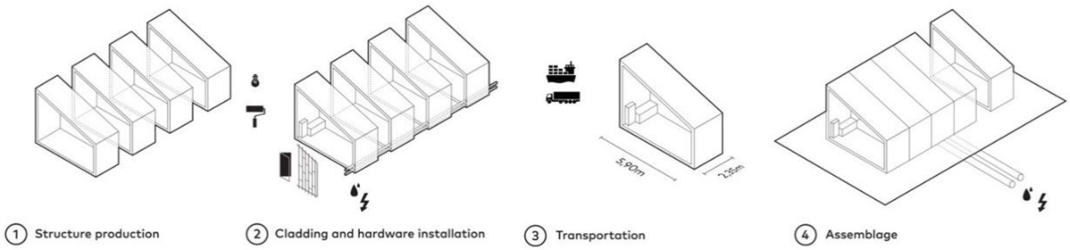


Figure 2-4: Concept Diagram of Sectional Housing System "Gomos". **Source:** Dezeen, 2016

2.3.3 Panelised

Flat component assemblies such as completed wall panels, roof trusses, partitions, and floor assemblies are built in the factory and then shipped out to the site where they are assembled thereby saving on-site framing labour. Components like wall panels will often be nearly finished with windows, doors, wiring, and exterior siding. Panelised homes are built to be site permanent and are therefore built to local, state, or regional building codes. Panelised homes are generally easier and cheaper to ship as they can be compactly bundled and moved on fewer and smaller vehicles. In most cases, the panelised components are load-bearing walls to replace post and beam framing system.

Figure 2-5: (Left): Panel preparation in Factory with openings already cut and prepared, (Right): Erection in site using cranes and trained workers. Source: Left - https://www.oremonte.org/enchanting-panelized-homes-texas/, Rigth: prefabaus.org.au

2.3.4 Pre-cut

Many names are used to describe this type of prefabricated houses such as: Kit houses, Mill-cut houses, Pre-cut houses, Ready-cut houses, Mail order homes or Catalogue homes. Unlike modular homes, which are built in sections at a factory, in a kit house every separate piece of lumber is shipped already numbered and cut to fit its particular place in the house, thus eliminating the need for measuring and cutting, and likewise the waste of time. These pre-cut materials are the basic elements of the house and are not yet assembled into more detailed components and assemblies like in the panelised house.

Pre-cut wood framing systems have been developed in Japan. It is possible in Japan today to e-mail, fax or otherwise send a plan to a housing system provider, receive an estimate the same day, place an order for your custom house, and have it delivered the same week. The materials you would receive include the entire framing and enclosure package including roof framing and decking and exterior insulted panels. Using numbered pieces of lumber and unique metal connectors, frames can be assembled quickly and accurately with low-skilled labour. Pre-cut, numbered wall panels are also placed and secured easily (Brew, 2005).

2.3.5 Components/Kit of Parts

A kit-of-parts is a collection of discrete building components that are pre-engineered and designed to be assembled in a variety of ways. Components are sized for convenient handing or according to shipping constraints. LV Series developed by Rocio Romero is an example of a modernist house by kit-of parts system. All LV models have a standard width of 26’-0”, but vary in length. The architect offers customisation and unique solutions based on client requirements.

Figure 2-6: An example of kits and parts available for the end-user to choose from. Each element has its pricing and the client can ask for different combinations. **Source:** LV Series Homes Brochure downloadable from: www. http://www.rocioromero.com/LVSeries.html

2.3.6 Chassis and Infill

This is a hybrid system that includes prefabricated posts and beams to form a framing system as the primary structure, and using the automobile industry’s term – chassis. This is made possible by dividing the house into two notional elements: the chassis, the standardised, mass produced part of the system, provides the structure and services for the building, and the infill, which consists of interchangeable wall and floor components, provides for customisation and adaptability. This system was proposed through a master thesis in the department of mechanical engineering in MIT in 2003, but its roots can be traced back to “supports” by Hebraken as will be discussed in 2.5.6.

Although the concept is different and the houses are not prefabricated, Chassis and infill recalls to the mind the recent housing efforts made by Pritzker winner architect Alejandro Aravena in his “incremental” approach. The government in this approach provides each family in the housing development with a half-finished house and the rest is left for them to complete and expand based on their available resources. While initiated by different motivations, both approaches share the general idea of the residents having strong input to the design and construction of their own residences by deciding on many variations of the infills within a framework of an existing chassis.

Figure 2-7: The Scheepstimmermanstraat project in Amsterdam is an example of user participation in housing. **Source:** Wikipedia.

2.4 Mass customisation

“We shape our dwellings and afterwards our dwellings shape us”

Mr. Winston S. Churchill in the House of Commons, 1944

In this century we desire choice, expression, individuality and the ability to change our minds at the last minute. The term “mass customisation” started to gain popularity in the early-nineties; it was coined by Stan Davis in his book *Future Perfect* but the term was popularized by Joseph Pine in his book *Mass Customisation: The New Frontier in Business Competition* in 1993 (Schodek, Bechthold, Griggs, Kao, & Steinberg, 2004)

Virtually all executives today recognize the need to provide outstanding service to customers. Focusing on the customer, however, is both an imperative and a potential challenge. In their desire to become customer driven, many companies have resorted to inventing new programs and procedures to meet every customer's request. But as customers and their needs grow increasingly diverse, such an approach has become a sure way to add unnecessary cost and complexity to operations (Gilmore & B. Joseph Pine II, 1997).

Companies throughout the world have embraced mass customisation in an attempt to avoid those pitfalls and provide unique value to their customers in an efficient manner. Readily available information technology and flexible work processes permit them to customise goods or services for individual customers in high volumes and at a relatively low cost. But many managers at these companies have discovered that mass customisation, too, can produce unnecessary cost and complexity. They are realizing that they did not examine thoroughly enough what kind of customisation their customers would value before they plunged ahead with this new strategy. That is understandable. Until now, no framework has existed to help managers determine the type of customisation they should pursue.

In car industry for example and for years, insignificant choices like power windows and upholstery colour have been possible, but the major aspects of the car have been fixed (Lawrence, 2003). Consumers are only able to choose which of a few models is closest to what they desire, without the opportunity for a real personalised solution. General Motors (GM) has suggested a new model for car production that may change all that. The Hy-wire or AUTOnomy fuel cell concept relies on a generic mass-produced chassis, but allows the body of the car to be customised. The easily replaceable body could be exchanged for different occasions or as new styles became popular (Lawrence, 2003). A concept that recalls to the mind the idea of chassis and infill discussed earlier.

In an article called "The four faces of customisation" published by Harvard business review in 1997, four distinct approaches to customisation were identified, which they called *collaborative*, *adaptive*, *cosmetic*, and *transparent*. When designing or redesigning a product, process, or business unit, managers should examine each of the approaches for possible insights into how best to serve their customers. In some cases, a single approach will dominate the design. More often, however, managers will discover that they need a mix of some or all of the four approaches to serve their own particular set of customers.

Collaborative customizers conduct a dialogue with individual customers to help them articulate their needs, to identify the precise offering that fulfils those needs, and to make customised products for them. The approach most often associated with the term mass customisation, collaborative customisation is appropriate for businesses whose customers cannot easily articulate what they want and grow frustrated when forced to select from a plethora of options.

Adaptive customizers offer one standard, but customisable, product that is designed so that users can alter it themselves. The adaptive approach is appropriate for businesses whose customers want the product to perform in different ways on different occasions, and available technology makes it possible for them to customize the product easily on their own. (A programmed lighting unit is an example in which the customer is able to experiment different lighting moods and combinations and save them into pre-sets)

Cosmetic customizers present a standard product differently to different customers. The cosmetic approach is appropriate when customers use a product the same way and differ only in how they want it presented. Rather than being customised or customisable, the standard offering is *packaged* specially for each customer. For example, the product is displayed differently, its attributes and benefits are advertised in different ways, the customer's name is placed on each item, or promotional programs are designed and communicated differently. Although personalising a product in this way is, frankly, cosmetic, it is still of real value to many customers. (Billions of dollars spent each year on such products as embellished T-shirts and sweatshirts.)

Transparent customizers provide individual customers with unique goods or services without letting them know explicitly that those products and services have been customised for them. The transparent approach to customisation is appropriate when customers' specific needs are predictable or can easily be deduced, and especially when customers do not want to state their needs repeatedly. Transparent customizers observe customers' behaviour without direct interaction and then inconspicuously customize their offerings within a standard package.

This new practice is already being provided by companies working in the industrial production. Examples like Nike shoes, Swatch and Automobile manufacturers. They provide real time choice for lower price and higher quality. Through supply chain management achieved by electronic software they can tailor to your need the exact product of your choice (Kieran & Timberlake, 2004).

Gropius outlines the extent of the standardisation required in housing from his point of view:

> "*Before this is practicable, however, every part of the house-floor-beams, wall, slabs, windows, doors, staircases and fittings – will have to be normed. The repetition of standardised parts, and the use of identical materials in different buildings, will have the same sort of coordinating and sobering effect on the aspect of our towns as uniformity of type in modern attire has in social life. But that will in no sense restrict the architect's freedom of design. For although every house and block of flats will bear the*

unmistakable impress of our age, there will always remain, as in the clothes we wear, sufficient scope for the individual to find expression for his own personality".

(Barnes & Feldman, 1982)

2.5 Early precedents of architect-led prefabricated housing

This part gives a brief historical overview of some of the housing prototypes built with notions of "*Pre-fabrication*" in the twentieth century. By no means shall this be considered a detailed full review of all attempts in pre-fabricated housing construction in the twentieth century. The number of trials is overwhelmingly large that it makes it almost impossible to include all. Instead, the showcased projects represent what the author thinks is relative from a scale, approach and historical significance point of view.

2.5.1 Maison Dom-ino (1914-1915) by Le Corbusier

It was a very basic minimalistic structure comprising a group of horizontal slabs supported by a group of thin concrete columns around the edges with a stair case providing access to different levels on one side of the floor plan. The name is a wordplay that combines an allusion to domus (Latin for house) and the pieces of the game of dominoes, because the floor plan resembled the game and because the units could be aligned in a series like dominoes, to make row houses of different patterns.

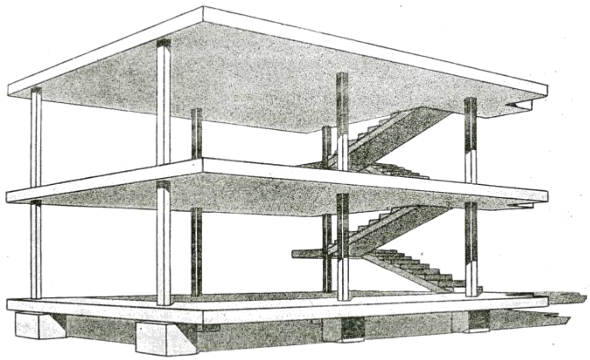


Figure 2-8: Maison Dom-ino designed by Le Corbusier. **Source:** Wikipedia

Celebrating the 100th anniversary of "Dom-ino House", German architect Valentin Bontjes Van Beek and students from the Architectural Association in London built a full-size model of Le Corbusier's seminal Maison Dom-ino in the gardens of the Venice Biennale in 2014. The structure was conceived originally in steel and concrete. The newly built prototype that was manufactured from engineered timber will be on display in London and Tokyo later as a part of "Happy Birthday Dom-ino program".

The frame was to be completely independent of the floor plans of the house thus giving freedom and flexibility to the design of the interior configuration. The model eliminated load-bearing walls and the supporting beams for the ceiling. This concept is quite close to the “supports” approach developed by the Dutch architect N. John Habraken in the 1960s (Section 2.5.6).

2.5.2 American System-Built Houses (1911-1916) by Frank Lloyd Wright

They represent another attempt lead by Frank Lloyd Wright addressing modest affordable housing through pre-fabrication and standardisation. The Wright firm produced seven standardised designs for houses from which the costumer could select. Because of this standardisation process, the lumber could be pre-cut off site and shipped for construction cutting down on waste and skilled labour. They cannot be regarded as entirely pre-fabricated houses as most construction activities were performed on-site, while only lumber for main structure was prepared off-site.

The project came to end due to the beginning of the first World War in April 1917, where building materials were diverted to the war effort, delaying new home construction. It is believed that about 25 System-Built Homes were constructed, but only about 15 survive. They can be found in Wisconsin, Illinois, Indiana, and Iowa in the US.

Figure 2-9: Three of the six American System-built homes in the Burnham Street Historic District, Milwaukee, Wisconsin. **Source:** Wikipedia

2.5.3 Dymaxion House (1927) by Buckminster Fuller

A revolutionary vision was created by the American architect, theorist, designer and inventor Buckminster Fuller. It represented his futuristic vision and solution to the need for a mass-produced, affordable, easily transportable and environmentally efficient house. The word "Dymaxion" was devised by combining parts of three of Fuller's favourite words: DY (dynamic), MAX (maximum), and ION (tension). The house used tension suspension from a central column or mast, sold for the price of a Cadillac, and could be shipped worldwide in its own metal tube. Toward the end of WW II, Fuller attempted to create a new industry for mass-producing Dymaxion Houses.

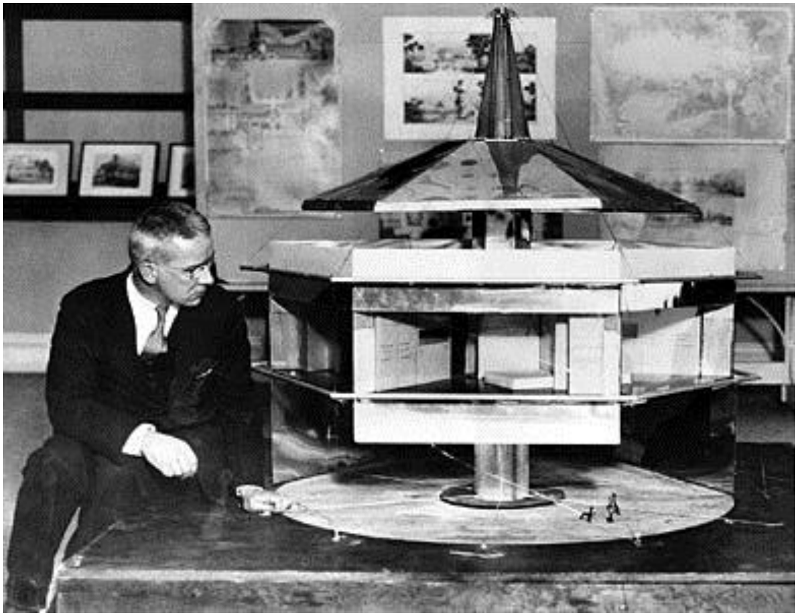


Figure 2-10: Fuller with a scaled model of the original design of the Dymaxion House. **Source:** Archdaily

Fuller designed a house that was heated and cooled by natural means, which made its own power, was earthquake and storm-proof, and made of permanent, engineered materials that required no periodic painting, reroofing, or other maintenance. He later had a two-year research initiative with Beech Aircraft Industries, who held an abundance of Aluminium in the aftermath of WWII. In 1946 he completed two prototypes, the Barwise prototype and the Danbury prototype, though neither was assembled nor mass-produced, mainly due to the unwillingness of Fuller to compromise his designs.

In 1948 William Graham, a former investor in the project, purchased and combined both prototypes and created the "*Wichita House*," which carried a refined vision of the original Dymaxion: the hexagon was transformed into a smooth circle, and the building was set only a few inches above the ground (rather than fully suspended, as the Dymaxion would have been). Aside from the patented Dymaxion bathroom, none of the original housing elements were included in the Wichita House.

Although never built, the Dymaxion's design displayed forward-thinking and influential innovations in prefabrication and sustainability. Not only would the house have been exemplary in its self-sufficiency, but it also could have been mass-produced, flat-packaged and shipped throughout the world.

2.5.4 Packaged House (1941) by Konrad Wachsmann & Walter Gropius

Following WWII, Wachsmann who was trained as a cabinetmaker, and studied at the Art-and Crafts school of Berlin and Dresden and at the Berlin Academy of Arts, received a visa to visit the US. He used to work for the timber building company Christof and Unmäck, where he was a designer for wood prefabricated houses. He arrived in New York and lived with his friend Walter Gropius with whom he collaborated on a number of projects prior to the Pearl Harbour attack on December 7, 1941 (Imperiale, 2012). In his autobiography, Wachsmann explains that he was very optimistic and saw a great opportunity and a new beginning in the events unfolding with WW2 while Walter Gropius was very frustrated. He said he believed people would come back to their senses and would be forced to think rationally about the future. This is how they started to collaborate on an industrialised modular housing system, "The packaged House."

Figure 2-11: Packaged House/General Panel System simple floor plans. **Source:** http://modul-ar.blogspot.it/2016/02/modulacion-precedentes-sobre-sistemas.html

The housing system is quite simple, and architecturally modest. It is conceived as a single-story, rectangular plan with a shallow pitched roof and inset porch. What is interesting about the house is that the entire house is not conceived as a single repetitive unit, but that using the modular bay of 3’-4”, infinite configurations could be made of the system, adapting to various climatic and site conditions, and to the taste of the architect and requirements of the owner. Wachsmann’s “universal Joint” was a discrete fastener that connects modular panels from any primary axis; without nails or screws. It would give great structural stability to the joining of prefabricated panels. The jointing system was based on 2-, 3-, and 4-way connections between panels. All the building surfaces were to be created from the same panels: exterior walls, interior partitions, floors, ceilings and the roof.

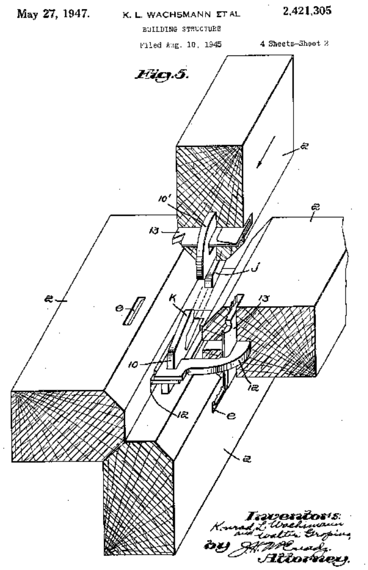


Figure 2-12: The universal joint developed by Wachsmann for the general panel system. **Source:** Google Patents

Wachsmann spent years developing the project and slowed down the design development and fabrication phases as he sought to perfect the system. His main concern was always the universality of the system which was continuously hindered by some fabrication necessities. The title of the book, *The Dream of the Factory-Made House* by Gilbert Herbert reveals that the “Packaged House” remained a dream in that it never did in fact go into production to satisfy housing needs (Imperiale, 2012). It was a conceptually rich project, but was never fully executed nor a commercial success. This is a shame, as the system was a leap forward that deserves attention even compared to available systems of our current times.

2.5.5 Le Maisons Tropicales (1949-1951) by Jean Prouvé

After the Second World War, there was a renewed interest for pre-fabricated construction in order to tackle the destruction that was caused by these devastating events. Between 1949 and 1951, Jean Prouvé was commissioned to produce three prototype prefabricated tropical houses to address the shortage of housing and civic buildings in the French colonies of West Africa. "Les Maisons Tropicales" can be seen as the most elegant expression of Prouvé's love of mobility. The ability to construct and dismantle was fundamental to Prouvé's work and is evident in his designs for chairs, tables, tents and buildings.

Figure 2-13: The original Prouve house prototype erected in Congo was dismantled, returned to France and restored. **Source:** http://bare-minimums.blogspot.it/

Les Maisons Tropicales are the culmination of twenty years of experimentation by Prouvé into the prefabrication and industrial production of buildings. Two were erected in Brazzaville, in the Republic of Congo, in 1951. Built side by side and connected by a bridge, the smaller Brazzaville house was an information office for the company "Aluminium Francais" while the larger 18 x 10m house, was the home of the company's commercial director, Jacques Piget.

Set on concrete stills because of the sloping site, La Maison Tropicale consisted of a folded, sheet steel portal frame with fixed and sliding aluminium wall panels. In response to the hot climate an adjustable aluminium sunscreen surrounded the veranda and acted as an outer reflective skin. Blue glass portholes protected against UV rays and the double roof structure provided natural ventilation. The design of the component parts was crucial. Flat, they could be tightly packed into a cargo plane for ease of transport. Light, they could be carried by just two men for ease of construction and not wider than 4m, the width of the rolling machine at Prouvé's factory, for economy of manufacture. Although designed for mass production, no further tropical houses were ordered. The prototypes proved no less expensive than locally built structures and with their industrial aesthetic did not appeal to the conservative colonial French bureaucrats. The three Prouvé tropical houses, still in situ in the Republic of Congo in 2000 in a dilapidated state and riddled with bullet holes, were then dismantled, returned to France and restored.

2.5.6 Supports, an alternative to mass housing (1961) by Habraken

N. John Habraken is a Dutch architect, educator, and theorist and chair of the MIT Department of Architecture from 1975-1981, conceived a much more sophisticated approach to provide manufactured homes. His theoretical contributions are in the field of user participation in mass housing, the integration of users and residents into the design process. The visual result of his theory is the architecture of lively variety. Habraken is the initiator of the international "Participation movement" in architecture. His book "Supports: An Alternative to Mass Housing", first published in 1961, was his manifesto for housing user participation.

Habraken 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's influential book, "The Systematic Design of Supports" led to what is now called Open Building. It also laid the foundation for participatory design or co-design which is becoming a rising trend in many fields such as software, product, landscape, urban and architectural design as a way of creating environments that are more responsive and appropriate to their inhabitants' cultural, emotional, spiritual and practical needs.

2.6 Early precedents of industry-led prefabricated housing

2.6.1 Sears Catalog Houses (1908) by Sears, Roebuck and Co.

They were catalog and kit houses sold primarily through mail order by Sears, Roebuck and Company, an American retailer. Sears reported that more than 70,000 of these homes were sold in North America between 1908 and 1940. More than 370 different home designs in a wide range of architectural styles and sizes were offered over the program's 33-year history (Sears, 2012).

Sears Modern Homes offered the latest technology available to house buyers in the early part of the twentieth century. Central heating, indoor plumbing, and electricity were all new developments in house design that "Modern Homes" incorporated, although not all of the houses were designed with these conveniences. Primarily shipped via railroad boxcars, these kits included most of the materials needed to build a house. Once delivered, many of these houses were assembled by the new homeowner, relatives, friends and neighbors, in a fashion similar to the traditional barn-raisings of farming families. Other homeowners relied on local carpenters or contractors to assemble the houses. In some cases, Sears provided construction services to assemble the homes. Some builders and companies purchased homes directly from Sears to build as model homes, speculative homes or homes for customers or employees.

Sears was not an innovator in home design or construction techniques; however, Modern Home designs did offer distinct advantages over other construction methods. The ability to mass-produce the materials used in Sears homes lessened manufacturing costs, which lowered purchase costs for customers. Not only did precut and fitted materials shrink construction time up to 40% but Sears's use of "balloon style" framing, drywall, and asphalt shingles greatly eased construction for homebuyers (Sears, 2012).

Figure 2-14: House Model 52 by Sears developed between 1908 and 1914. **Source:** Sears Archives

2.6.2 Loustron Houses (1948) by Loustron Corporation

The "Loustron Houses" were manufactured in the U.S to accommodate for the large number of returning soldiers after the Second World War. It is well-known that prefabricated housing had existed before the Lustron home came on the market. However, it was Lustron's promises of assembly-line efficiency and modular construction that set it apart from its competitors.

In January 1947, the newly formed Lustron Corporation announced that it had received a $12.5-million Reconstruction Finance Corporation loan to manufacture mass-produced prefabricated homes that featured enamel-coated steel panels led by Chicago industrialist and inventor Carl Strandlund, who had worked with constructing prefabricated gas stations. Lustron offered a home that would "defy weather, wear, and time." The low maintenance, extremely durable, baked on porcelain enamel finish was expected to attract modern families who might not have the time or interest in repairing and painting conventional wood and plaster houses.

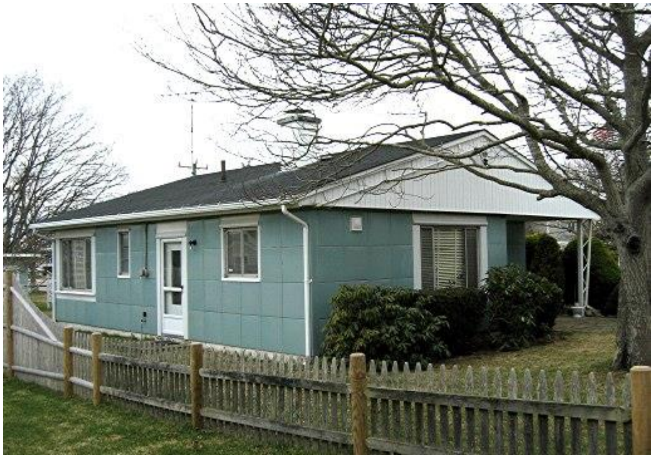


Figure 2-15: About 2000 Lustron Houses still exist in 36 states in the US. **Source:** https://connecticuthistory.org/metal-homes-for-the-atomic-age/

The range of flexibility offered by the Loustron Company involved mainly four house models each with 2 variations (2 and 3-bedroom models) ranging from 63 to 106 square meters. Lustron homes were usually built on concrete slab foundations with no basement. However, about 40 Lustron homes have been reported to have basements. Their sturdy steel frame was constructed on-site by a team of local workers who assembled the house piece-by-piece from a special delivery truck. The assembly team, who worked for the local Lustron builder-dealer followed a special manual from Lustron, and were supposed to complete a house in 360 man-hours.

Despite being an extremely well-funded, well-publicized, government-supported enterprise manufacturing a desperately needed product, the Lustron Corporation declared bankruptcy in 1950. Production delays, lack of viable distribution strategies, and the escalating prices for the finished product all contributed to the failure. Additionally, local zoning codes also played a part. In some municipalities, for example, an ordinance prohibited homes with steel chimneys.

2.7 From prefabrication to digital fabrication

It is important here to differentiate between “Pre-fabrication” and “Digital Fabrication” in the context of housing construction. Prefabrication does not necessarily include modern or revolutionary manufacturing/construction techniques. As demonstrated through the historical precedents, prefabrication can largely involve traditional methods for construction and assembly of materials. A handful of projects involved machinery in a manufacturing plant to perform repetitive tasks. More recently, it can occasionally include parts or assemblies that were constructed using digital fabrication tools in controlled environments. On the contrary digital fabrication works seamlessly between CAD software and Computer Numerical Control (CNC) machines, enabling low-cost production of customised artefacts. Examples of fabrication projects developed in cutting edge research show that actual fabrication can even take place on-site such as D-shape printing (Figure 2-16), Contour Crafting (Figure 2-17), 3D printed canal house or in close proximity to the construction site through nodes/labs of digital fabrication that do not have to be necessarily close to where the design takes place as will be demonstrated later through showcased projects.

Figure 2-16: D Shape 3D printing Technology developed by Enrico Dini. **Source:** https://d-shape.com/

On that front, Professor Larry Sass (2013) used the expression of "two flavors" to describe two distinct approaches to the use of digital production in the field of architecture. The first being "Project based digital design and digital manufacturing" which is defined by architects who create one-of-a-kind building as sculptural artefacts. Design commissions completed by architects like Frank Ghery, Greg Lynn, Bernhard Cache, Lisa Iwamoto and Nader Tehrani among many others, postulate ideas about fabrication through prototyping. Their projects prove that a lot of creative possibilities exist behind these new technologies. These architects represent their designs with advanced curved surfaces as well as solid and parametric modelling software, and then physically produce complex designs by CAD/CAM manufacturing. They employ a combination of sophisticated technologies such as curved surface CAD modeling tools to simplify areas of design complexity.

The second approach of digitally fabricated architecture is a "Production system" where multiple iterations of a design are generated and manufactured. The first example Contour Crafting is one example of rapid digital fabrication of houses by using layered concrete dispensed from a computer-controlled machine. The greatest potential of Contour Crafting relates to housing in developing countries in need of original and replacement concrete structures (Koshnevis, 2004). Although highly theoretical till present day with problems of scalability, cost and technicalities but it still represents a strong conceptual framework for the use of additive manufacturing technologies in housing construction.

Figure 2-17: Contour Crafting, a system developed by Professor Behrokh Khoshnevis.
Source: http://www.contourcrafting.org/

A second example of a production system is defined as "materialization". It is a systematic method of subdividing geometry into constructible components ready for digital fabrication. The second approach was demonstrated through a pilot study performed by Larry Sass in the summer of 2005. The project was a small cabin built completely of interlocking plywood components manufactured from CAD/CAM machines as will be demonstrated in section 3.1.1. A second example of a materialized design was built using interlocking plywood components. This version was constructed as part of a museum exhibition and was assembled with a few tools and assemblies that were sustained by friction. In the next chapter, a more detailed, in-depth analysis of these two prototypes is made. From these two examples of digitally fabricated structures it is possible to mass produce many of these buildings from the same data. It also means manufacturing is possible anywhere using similar machines controlled by computers.

With the spread of parametric design tools and robust digital fabrication technologies, a new paradigm has started in which these technologies promise to address the design and construction of housing units with more flexibility and variation, hence a more customisable approach.

Many research initiatives and published work approach housing from a completely industrial, mechanical point of view. Attempting to completely alter how buildings are conceived by applying mass production/mass customisation technologies which are already used widely in vehicles, aviation and other well-established manufacturing industries. On the other side of the spectrum lies a completely different approach which considers fabrication as a tool to empower people to think, build, experiment and realize their own ideas away from the control of big scale corporate gurus, hence it takes more of a social decentralised standpoint. This thesis takes a position in between both standpoints. It tries to foresee the potentials of synergies between offsite prefabrication as a means to reach a higher level of quality and efficiency; and the freedom offered by the involvement of digital fabrication labs and hackerspaces and open source digital information which enables the close association of end users in stages of design and direct involvement in the phase of assembly and construction.

2.7.1 Complete off-site prefabrication

Colin Davies presents a strongly stated argument in his book: *The prefabricated home* (2005) in which he says:

> *The strength of the prefabricated house lies in its popularity, its relative cheapness and the industrial base from which it operates. These are precisely the areas in which modern architecture is weakest. Modern architecture is unpopular, expensive and sometimes divorced from industrial production. This is why whenever it has tried to extend its field to include the territory of the prefabricated house it has failed and been forced to retreat.*

Two of the strongest advocates of complete off-site fabrication are Stephan Kieran and James Timberlake. In their book titled "*Refabricating architecture: How manufacturing methodologies are poised to transform Building Construction*", they skilfully demonstrate that contemporary building construction is a linear process, in both design and construction, where segregation of intelligence and information is the norm (Kieran & Timberlake, 2004). Parties involved in the construction industry are motivated and derived by different objectives which represent a process that is not as efficient as it should be.

A primary research focus for Kieran and Timberlake, through their architectural design firm based in Philadelphia, USA, has been to align design and fabrication technology into a seamless process. They argue that looking at automobile, shipbuilding and aerospace industries would teach architects how to incorporate collective intelligence and non-hierarchical production structures. Those industries have proven to be progressively economic, efficient, and they yield a higher quality product while the production of buildings falls behind using methods and practices of the nineteenth century.

Hundreds of years ago, architecture could have been held in the intelligence of one maker, the master builder, who is partially an architect, builder, product and building engineer, and material scientist. In current practice, the disjunction of these elements of master building has been part of the educational system, the licensing procedures, the insurance requirements and separate professional organizations. The industrialisation of production of almost every commodity has removed product engineering from the scope of the architect. The environmental control systems in buildings are also no longer simple as buildings are becoming more complex.

In order to regain the position of the master maker or the team maestro, the architect is asked to master a vast range of sciences and technologies, which happens to be almost impossible given the tremendous complexity involved in building construction in the present time. In the meantime, excluding architects from participation in the "means and methods" of making turns them into plain stylists. Kieran and Timberlake build-up a strong argument that architects are even giving up their remaining stronghold by giving up the control on the means and methods of realizing their ideas. In their own words:

> *“The architect makes architecture in equal measure with ideas and materials. Architecture is conceived out of ideas about site and use, ideas that are shaped and reshaped into form to suit purpose and place. Materials, the stuff we build with, give physical substance to this shape and to the idea that animates it. By allowing architecture to become reduced to the current degree and by relinquishing responsibility for assembly, product development, and materials science to specialists, the architect has allowed the means and methods of building to move outside the sphere of architecture.”*

They envision the complete integration of design with the craft of assembly supported by the materials scientist, the product engineer, and the process engineer, all using tools of present information science as the central enabler.

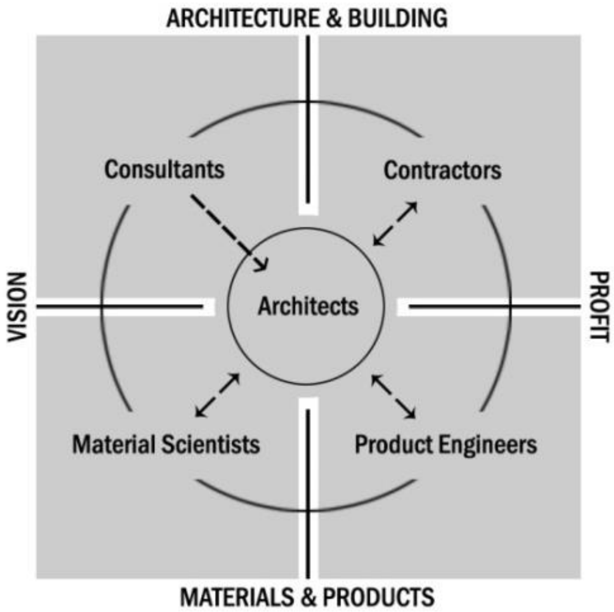


Figure 2-18: Integrated practice and information flow in the proposed model of practice.
Source: Keiran and Timberlake, 2004

They also see today's master architect as an amalgam of material scientist, product engineer, process engineer, user, and client who creates architecture informed by commodity and art.

In classic process engineering terms and equally for architects, the rule of thumb that was taken for granted in the past is that:

Quality x Scope = Cost x Time

Quality and scope are generally desirable aspects of every commodity. Every person admires things that are well-made and in other words “crafted”. Every consumer also wishes for more rather than less. On the other hand, cost and time are not desirable aspects. They represent the limit at which quality and scope are brought to a stop. Kieran and Timberlake argue that this equation does not apply anymore to any of the developed industries in the present time, as the process engineers along with product engineers are always working towards pushing up the limits of quality and detail for less time and less money. This is quite evident in car manufacturing as consumers are always demanding more variation, more flexibility and more features thus more scope and more quality for less time and cost. This simply reformulates the equation to:

Quality x Scope > Cost x Time

It can be said that revisiting the old rule of thumb was inevitable in a time of dramatic shortage of resources. Furthermore, looking towards the aerospace and car industries, it is safe to say that they have a set of processes that are more efficient, fast and economical. Architecture needs to learn from these sister industries, not about shape and form but more about processes and materials.

Another argument that is skillfully presented in this book is the dramatically different approach to building construction from the old tradition of bottom-up construction involving foundation/frame/skin/systems/finish/equipment to a more progressive quilt-like approach. The building is built in a series of grand blocks that are built off-site in a controlled environment and then assembled on-site. This concept is strongly visible in other industries like cars, airplanes and ships in which the role of the brand name owner (Original Equipment Manufacturer – OEM) is more of an assembler of chunks coming from other suppliers who in turn receive smaller chunks from others and so on.

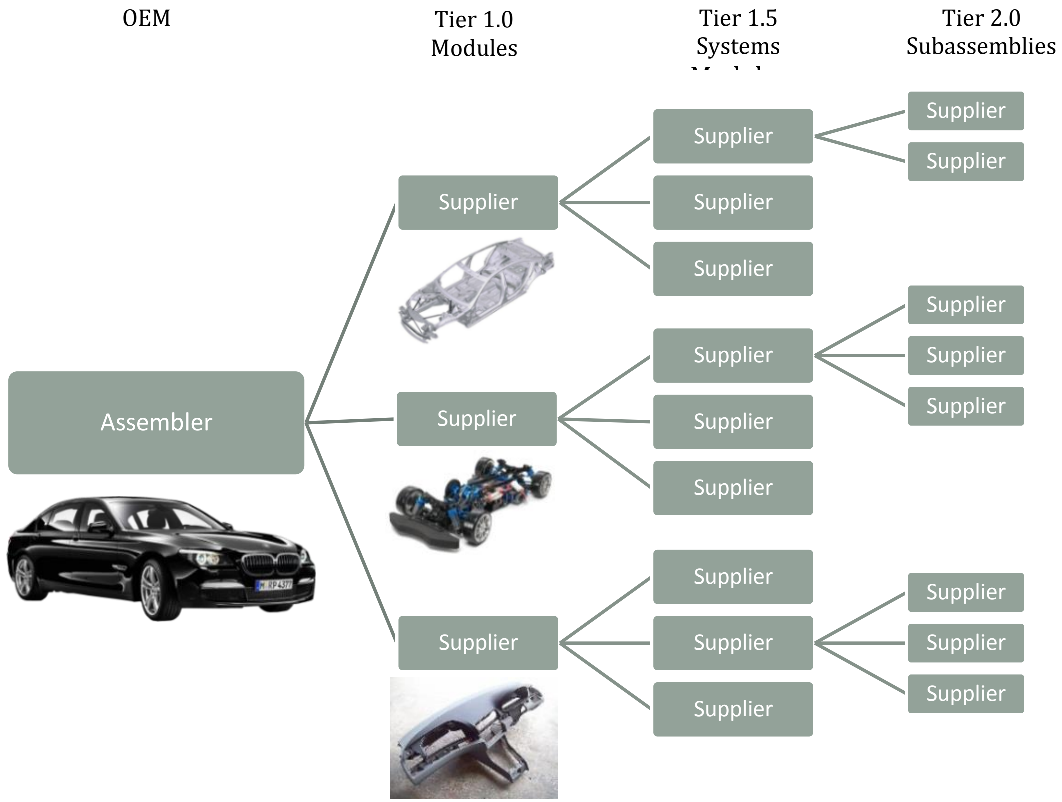


Figure 2-19: Modular Production Hierarchy. **Source:** based on Kieran & Timberlake 2004

This kind of hierarchal structure plays an important role in reaching a higher overall quality where each supplier is responsible for the quality of his sub-assembly minimising the time needed for the OEM to revise and control all parts involved in a single sub-assembly.

On the same side of the spectrum, Harry Gilles (2008) from the University of Michigan, USA, supports the same trend through his past and ongoing research work on housing and fabrication. In his paper "Prefabricated Construction using Digitally Integrated Industrial Manufacturing", he describes research being carried out in relation to prefabricated high density affordable housing. He argues that even the well-established industry of pre-fabricated houses in USA is not able to achieve the same bench marks that are reached by other industries such as Automobile industry in terms of cost efficiency and final quality of product (Giles, 2008).

He aims at demonstrating how a new paradigm for the conceptualisation and construction of buildings can be conceived as an entirely factory based process that creates advantages for construction through industrial systems technology transfer. The research tries to transform design methodology through demonstrating how alternative construction concepts, using entirely pre-manufactured volumetric units, can be adopted. He also aims at disseminating knowledge on this process showing how through integrated transfer of automotive technologies, an industrialised fabrication process for mass housing can be implemented.

A key focus of the evolving research and development is to enable *mass customisation* or *delayed differentiation* through virtual prototyping that becomes the central organizing element for design. Giles compares the capability of a car manufacturing company like BMW which has around 70000 employees in 23 locations to produce 10^17 unique variations of the BMW 7 series alone, to the building industry that falls far behind on that aspect of flexibility.

The paper goes to the extent of proposing the structure and hierarchies of a housing production line based on a designed prototype as a setting in a factory. The production line had to be both reconfigurable and able to accommodate design variations through automated digitally driven robotics that facilitate high volume outputs for minimal cost. He also acknowledges the fact that this initial setting requires significant capital investment based on projected and dependable production volume output. According to his proposal when affordable housing becomes a commodity or a 'consumer product' that is driven on the same basis as other industrially designed products, only then the capital investment would be worthwhile.

2.7.2 Digital fabrication as a social transformation tool

On the other side of the spectrum lies a completely different approach which considers fabrication as a tool to empower people to think, build, experiment and realize their own ideas away from the control of corporate gurus, hence it takes more of a social decentralised standpoint. Motivated by the growing urban population in African nations with an expectation of tripling within the period of 30 years, some research initiatives are trying to disseminate technology transfer and education through Fablabs and Hacker spaces which have at heart the issue of public enabling and democratisation of the means of production.

Ella Peinovich and John Fernández (2012) from MIT elaborated through their work with locals in Kenya, that modern fabrication technologies can be of great potential to resolve problems not only for housing. In the summer of 2010, a team of engineers and designers from the Massachusetts Institute of Technology (MIT) partnered with an engineer and technician from the Science and Technology Park at the University of Nairobi (Nairobi-FabLab) to manufacture a low-cost sanitation centre using digital design and fabrication tools available at the University of Nairobi. The principals of Localised Design-Manufacture were utilised throughout the process of CAD/CAM fabrication to surface sculpt a precision mould plug for a fibreglass mould used to pre-cast ferrocement components. The team addressed the lack of sanitation in slums with a low-cost solution that could be pre-manufactured and easily assembled on-site, employing local labour throughout the design and manufacturing processes from skilled fabrication technicians to on-site assemblers.

They proposed a localised design-manufacture loop that involves a local engineer along with a local assembler or craftsman. Localised Design-Manufacture promotes working within the community, recognising the skill of the local informal workers while augmenting that capacity through the introduction of new, global technologies.

They emphasise that working within developing countries, meeting the formal necessity is not a comprehensive solution; for maximum impact and uptake, one must consider the cultural implications of the process in which it is achieved. The novelty of the Localised Design-Manufacture methodology is that it necessitates a design process that incorporates craft and democratises the CAD/CAM process, while maintaining cultural sensitivity. Achieving these goals is what transforms the methodological proposal into a design exercise in which design sensibility is deployed to achieve cultural sensitivity. It is the combination of appropriate technology and local context that can facilitate development in a culturally sustainable manner.

CAD/CAM processes are well positioned for widespread adoption by providing benefits to the craftsman, including repeatability, precision, replicability and scalability, without compromising customisation. Though digital tools may require more time to produce a first working prototype compared to traditional hand-crafted methods, long-term productivity is dramatically enhanced due to ease of iterative design improvements and repeatability.

The trials led by Botha and Sass on the fabrication of a cabin merely from plywood components through bi-lateral assembly represent another exploration towards the use of fabrication tools for low-cost housing. Although being reasonably feasible, the major difference from the work of Ella Peinovich and John Fernández in Kenya is that the design decisions are always taken by the designer in the virtual environment which leaves the builder/craftsperson/assembler or even user without much input to the process. It transforms him into a receiver of assembly instructions that have already been designed virtually. As a result, there is limited capacity growth within the local craftsmen to maintain the production methodology without external assistance.

Between these two approaches to the integration of digital fabrication in the construction process lies a great pool of opportunities and spaces to explore the potential synergies between local craftsman knowledge and expertise and sophisticated new technological solutions. This thesis takes the position that local involvement and social acceptance is crucial to the success of any proposed housing solution. Furthermore, the attempt to just build housing units with no attention given to the community uptake would probably lead to a complete failure. Nonetheless, it is important to state that the scope of this study is more concerned with the efficiency, constructability and technicalities of the building process. Further analysis about social acceptability and community take-up can be performed within the disciplines of urban design or social sciences.

CHAPTER 3 | Digitally Fabricated Housing Trends

In this chapter, an analysis is performed through the course of the last two decades (1995-2015) tracking the evolution of digitally fabricated housing. The aim here is to deepen the understanding of these experimental precedents, built prototypes and realised projects in order to assess the points of strength and weakness and define the appropriate direction to follow through the development of the applied study. It provides a time line tracking with milestones of the usage of digital fabrication tools in housing construction. The analysis includes but not limited to: Design/construction time – overall cost – materials for primary/secondary structure – tools for virtual design/actual fabrication – special design methods/considerations (when applicable). The case studies are organised in a comprehensive chronological table. The chapter suggests there are three main trends for digital fabrication in housing. Organisationally, the chapter will showcase the case studies under each trend and then comment, discuss and reflect upon the trend in general stating some potentials and drawbacks that are seen by the author.

The selection of the case studies in this chapter aims at displaying a representative sample that covers the spectrum of digitally manufactured housing not only from a time-progression point of view but also highlighting the trends and milestones in the development of new housing construction methods. The table at the end of this chapter provides a timeline of the selected projects and their analysed aspects. It is challenging to draw a precise line between "prefabricated" and "digitally fabricated" housing, as prefabrication occasionally includes parts or assemblies that were constructed using digital fabrication tools. However, the case studies in this chapter represent prototypes that used digital manufacturing technologies for the major part of the construction, e.g. primary/secondary structure.

Due to the novelty of some of the case studies and the difficulty of finding reliable published information, the author established direct communication -when possible- with parties involved in design and construction to guarantee the accuracy of the information provided. The data gathering techniques included but were not limited to emails and inquiries through official websites.

3.1 Trend 1: Socially driven

A common trend that is community enabling and socially oriented can be deducted from the following case studies. It can also be noted that these prototypes were defined as post disaster interventions and almost always reliant on the end-user as an active contributor not in the design process but more in the construction phase. Since the community is at the heart of the process; open source digital information, Hackerspaces (Hackerspaces, 2015) and Fablabs (Fabfoundation, 2015) become the core of this trend for housing development. The highlighted examples used a puzzle like, do-it-yourself approach as a means to reach an efficient, rapid and affordable construction. The degree of success in reaching these goals is yet to be evaluated.

3.1.1 The instant House, Massachusetts, USA

This prototype was a research initiative by Professor Larry Sass in the department of Architecture at MIT in 2005. The aim was developing a novel design and fabrication process for mass customised emergency, transitional and developing contexts (Botha & Sass, 2006). The Instant house process produces a customised, habitable mono-material plywood structure, assembled manually with rubber mallets and crowbars. The materials are connected with a limited number of joint types that sustain their assembly through friction, such that nails, screws or glue are not needed during assembly. This aspect is interesting to the line of research that this thesis is following as will be demonstrated later in chapter four and five.

The Instant Cabin was manually modelled in CAD. One hundred sheets of plywood were used to fabricate one thousand interlocking elements with a single CNC machine. The cabin was designed, fabricated and assembled as a four-step process. Once the initial 3D model (design) was created in the computer, a collection of smaller interlocking planar elements was generated guided by a set of fabrication rules (Step 1). Composition of the elements, location in space, integral assembly geometry, size limits and element shapes were constrained to the limits of average plywood sheet stock (48" x 96" [122cm x 244cm])(Step 2). Each element was modelled as a 3D shape inclusive of friction-based assembly features and a number that was used later to guide manual assembly onsite (Step 3). Last, a worker assembled the manufactured elements using only a rubber mallet. Assembly was sustained by friction only (Step 4).

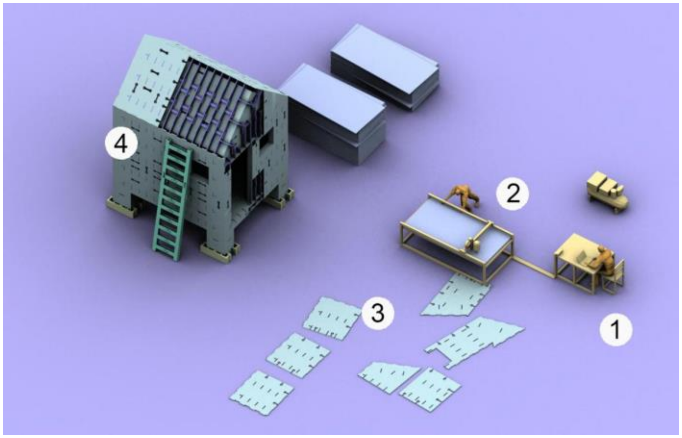


Figure 3-1: Four Stage concept of the Instant Cabin.
Source: https://ddf.mit.edu/news/2014/project-summary

The project was then formalised into a bigger theoretical framework in which automation is envisioned to replace manual modelling. They propose the development of an automated generative system, first for shape design and secondly for fabrication through a generative subdivision based on the Wood Frame Grammar (Sass, 2005). Sass proposed a framework for the design and fabrication process associated with the instant house which is basically divided into 5 different stages: shape design, design development, evaluation, fabrication and construction.

According to Sass (2006) the parameters for the initial shape design are defined based on regional criteria with a set number of variations assigned to each parameter. Parameters include climate, location, spatial constraints, vernacular influence and stylistic variations. Afterwards, the selected iteration goes through a preliminary evaluation process. The design development phase involves the subdivision of the initial surface model in CAD using Wood Frame Grammar (Sass, 2005). After the design development process produces parts for fabrication, a scaled laser cut model is produced using the same geometry for full-scale house. This scaled model is used for the confirmation of construction sequence and subjective design evaluation in real space. The fourth stage "Fabrication" is the stage in which machine G-Code generation, nesting, cutting, post processing and packing are performed. The fifth and final stage is "Construction" in which two people construct the one-room cabin in three days eliminating the need for cranes and scaffolding due to small component sizes that can be easily handled.

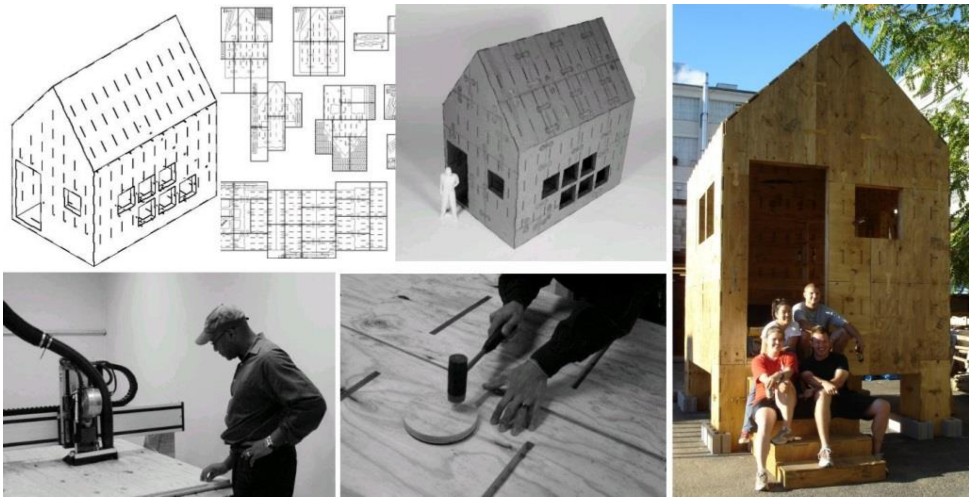


Figure 3-2: Shape grammars used to design vocabulary of Instant cabin.
Source: Sass, 2005

3.1.2 The Shotgun House, New Orleans, USA

As a progression based on the previous work by professor Larry Sass in MIT on the instant house, the digital design and fabrication unit lead by Sass developed another prototype for the New York MoMA exhibition: "Home delivery, fabricating the modern dwelling" in 2008. The design was based on a classical style New Orleans house known as the "shotgun house". The intent was to show diverse potentials for using digital fabrication technologies for building a fully ornamental legacy house in a post disaster area like New Orleans that was hit by Hurricane Katrina in 2005. The house was assembled of 5000 plywood components all held together by friction, with no nails or glue. This structure used the same system of wood joining used to construct the instant house out of plywood (Sass, 2005). Secondary components (ornamentation, doors and windows) were also sustained by friction.

The detailed analysis of the jointing system used in the construction of this house shows some interesting treatments of corner edges and sheathing fixation. The corners are always treated as rigid joints which helps maintain a good structural integrity. As seen in the following image, an external (+) shaped key insert is responsible for holding the sheathing sheets in place other than the friction tabs. The fixation depends merely upon friction for sustaining the structure. Publications dealing with the design and construction of this house almost always focus on the process of generative creation of 2D geometries or the process of direct translation into buildable components using digital fabrication.

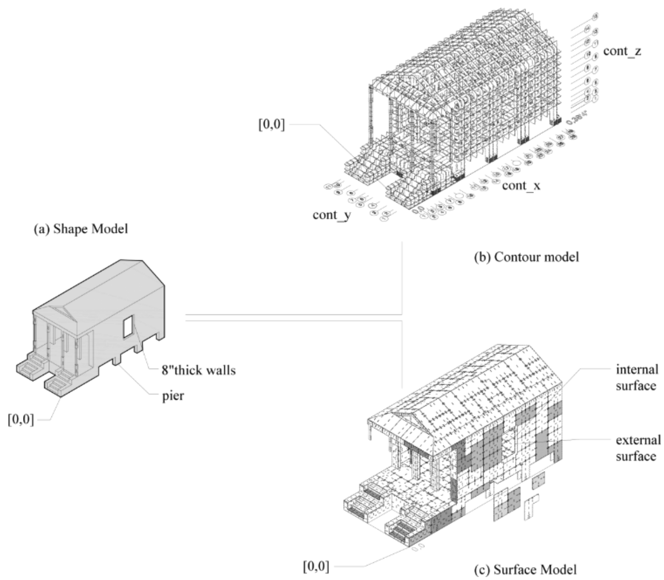


Figure 3-3: Starting model, Interior contours and exterior sheathing. **Source:** https://ddf.mit.edu/news/2014/project-summary

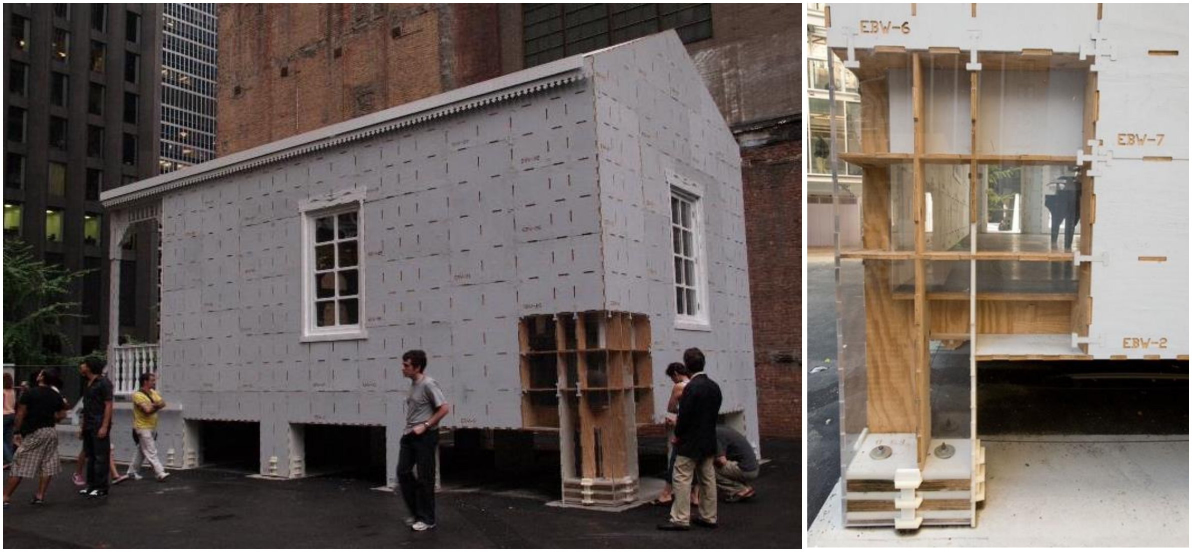


Figure 3-4: (Left) Same logic used in instant cabin was applied to New Orleans prototype. (Right) Jointing system with no external sheathing to showcase how the structure is conceived. **Source:** https://ddf.mit.edu/milestones/03

Although a full-scale house was built using this technique, little information is available concerning the verification of the structural behaviour of these joints under different loads. In a video published by (The Museum of Modern Art, 2008) Prof Sass mentions (min 1:16) using a glue gun and a crow bar for eventual alignments. It is not clear where this glue is used. If it is used for fixing the external key inserts in place, this might raise some concern on the long term structural behaviour in exposed weather. It is however understandable that this house was intended as a showcase for the potentials and possible future applications of this design and fabrication method.

3.1.3 ECOnnect, Delft, Netherlands

Pieter Stoutjesdijk and Hugo Nagtzaam, two Dutch architects based in Delft, initiated a small company called "ECOnnect" with the main aim of developing an open source platform for exchanging design and fabrication information related to building digitally fabricated houses. They partnered with ECOboard, a company that produces bio-based panels from agricultural residues such as straw and reeds (Stoutjesdijk, 2014). Their motivation was to provide an adequate housing solution for the exponentially increasing population through democratisation of the manufacturing process. Stoutjesdijk (2013) argues that the direct connection between atoms and bits offered by digital fabrication enables the creation of buildings in the same way software is created. Digital, customisable blueprints of physical building parts could be shared and developed globally like pieces of source code for a script, before directly being constructed locally with digital fabrication devices.

One of the first applications was a post-disaster shelter designed for Villa Rosa; an informal settlement in Haiti. In February 2014, ECOnnect started producing the first full scale house in the Netherlands. The estimated budget for the construction of the house is 10,000 US dollars in developing countries and twice as much in the United States and Europe. They claim to have reached a concept that perfectly fits its climatic, cultural, technological and historical context. The final results of these efforts are yet to be seen and evaluated with the final constructed house (To the extent of the author's knowledge following the official website, no further data is available regarding the constructed prototype).

There is also no evidence in their published work that structural verifications were performed. This prototype specifically opened up new questions and possibilities for the author to pursue as it deals with a sustainable eco-friendly material that might have big potentials in the context of African developing countries. The second motive for which this material is further analysed and studied is the fact that it exists in panels that can be machined using relatively cheap digital fabrication tools such as milling machines.

Figure 3-5: ECOnnect scaled model for emergency housing in Haiti. **Source:** (Stoutjesdijk, 2014)

3.1.4 Observations and Reflections

Since these prototypes were basically designed for post-disaster situations, they primarily offer minimal shelter and do no offer large spaces with flexible layouts. The surface area is a demanding requirement when it comes to long term living (excluding New Orleans shot gun house which offered a reasonable living surface area of 55 sqm).

When it comes to cost, the three case studies did not include wet and technical spaces which significantly reduces the complexity of the design and construction and thus the cost. However, it can be easily understood that in a refugee or post disaster camp using private amenities attached to or integrated in each unit is considered a luxury. The use of a monolithic material such as Plywood or ECOboards[2] in addition to end user involvement for assembly on-site contributes to cost savings.

When it comes to environmental performance, there were no environmental analyses performed through the design of the above-mentioned prototypes, at least in published work. Claims made by their authors for reducing carbon print and being environmentally driven was not substantiated by early design analyses or ecological foot print calculations. However, their main focus was more oriented towards speed, cost and ease of construction in hazardous situations.

This work opens up an interesting line of research but it remains unclear how it can be applied to larger housing types. It might be difficult to maintain a straight correspondence between design and building components beyond a certain scale.

3.2 Trend 2: Efficiency driven

In the middle of the spectrum lies another group of case studies that attempts to combine an economy and efficiency stand point with technological automated tendency in search for efficient, allegedly affordable long-term housing. The core value here is not “affordability for all”; in contrast, it is more related to the exploration of potential savings in materials, resources and construction time.

3.2.1 System 3, New York, USA

Two Austrian architects: Oskar Leo Kaufmann and Albert Rüf designed a prototype for the Museum of Modern Art exhibition in New York held in 2008. The exhibition “Home Delivery:

[2] ECOboard is an agricultural residue fibre board introduced to the European market as an alternative to other timber based panels for different applications. It will be further defined, analysed and characterized later on in this thesis.

Fabricating the modern dwelling" aimed at showcasing diverse procedural, formal and technological innovations in prefabricated architecture. Kaufmann had previously designed System 1 and System 2 with a kit-of-parts approach instead of modules or blocks in 1997 and 2001 respectively. However, System 3 used a different approach to the design and construction by dividing the house into two basic zones: "Serving Space" and "Naked Space". The serving space comprises wet spaces, vertical circulation element and technical spaces for electricity and heating and was completely manufactured and assembled off-site while maintaining its size within a standard container for ease of transport. The naked space is the rest of free space that can be configured based on personal needs and preferences of end-user. It is also digitally fabricated off-site and flat-packed into a container.

The prototype presented in MoMA exhibition (MoMA Home Delivery, 2008) was considered by Kaufmann and Rüf to be the nucleus of the system and the simplest form of what could be achieved through its use. The aim was developing a system that is expandable, movable, affordable and for lifelong use. The elementary material used for the whole building was timber which gives the building a monolithic feel extending from inside to outside. Through the official website of the architect, there was no additional information or publications concerning the prototype.

The author contacted Arch. Leo Kaufmann directly via email to have some insights into the design and fabrication of the house. The architect mentioned using a 3 axes CNC milling machine for the fabrication of all wooden parts while the rest of the house was constructed using traditional craft. 12-centimetre-thick timber panels with an external paint coat (weather proofing) were used for all wall partitions. Concerning the time frame for the design and construction of the prototype, he mentioned 12 weeks for design, 3 weeks for fabrication and 1 week for assembly. Demanding to know the overall cost of the prototype, Mr. Kaufmann responded that it was difficult to track a precise cost due to the involvement of various sponsors. The sponsors included PHILLIPS[3] who wanted to put the house for sale through auction but was faced by the financial crisis of 2008 in the US.

[3] PHILLIPS is an auction house with headquarters in London and New York interested in collections of contemporary art, photographs, editions, design, watches and jewellery.

Figure 3-6: Conceived to be a unit in a cluster or part of a larger system**. Source:** MoMA Home Delivery, 2008

3.2.2 Wikihouses

Wikihouse is an open source collaborative research and development initiative towards open systems in the design and construction of houses. The website allows anyone to register and download Creative Commons-licensed building plans. The files are prepared in Sketchup and ready for fabrication using a CNC router. The user is also free to adapt or change the files according to his specific needs. In the terms used by Wikihouse, this process is called creating your own "chapter" of Wikihouse. The initiative that started in 2011, aims at simplifying and democratising the construction of houses. Different prototypes were built in the last few years, the latest of which is the Micro house V01 (Figure 3-7).

The constructive approach used in developing the design of almost all prototypes of Wikihouses is a series of evenly spaced identical structural frames built using CNC cut plywood profiles assembled using screws and glue (Fig. 3-8 (1)). The structural frames are held together using spacers that are held in place using friction fit joints (Fig. 3-8 (2, 3)). Adding the internal and external walls that are glued and screwed to the underlying frames increases the structural resistance to lateral movements (Fig. 3-8 (4)). The positioning of the internal sheathing layer is based on the integral tabs embedded into the geometry of the structural frames and the sheathing boards (Fig. 3-8 (5)). The final external sheathing layer is installed to add more rigidity to the overall structure (Fig. 3-8 (6)). All the previous steps illustrated through Figure 3-8 represents the main structure "chassis" of the house upon which other layers of insulation and finishes must be added for thermal, moisture and weathering protection.

The approach used by Wikihouse shows the potentials of digital fabrication in the housing industry. Although the constructive logic used in the Microhouse is interesting from a technical point of view but it missed one of the most important aspects of using digital fabrication tools which is the ability to create many different parts at the same time and cost of creating many similar parts. The decision to create all similar frames recalls to the mind a mass-production approach that contradicts the very nature of digital fabrication and the ranges of flexibility it promises to offer. This might be attributed to the urge to greatly simplify the design cutting on all potential additional costs relating to design complexity.

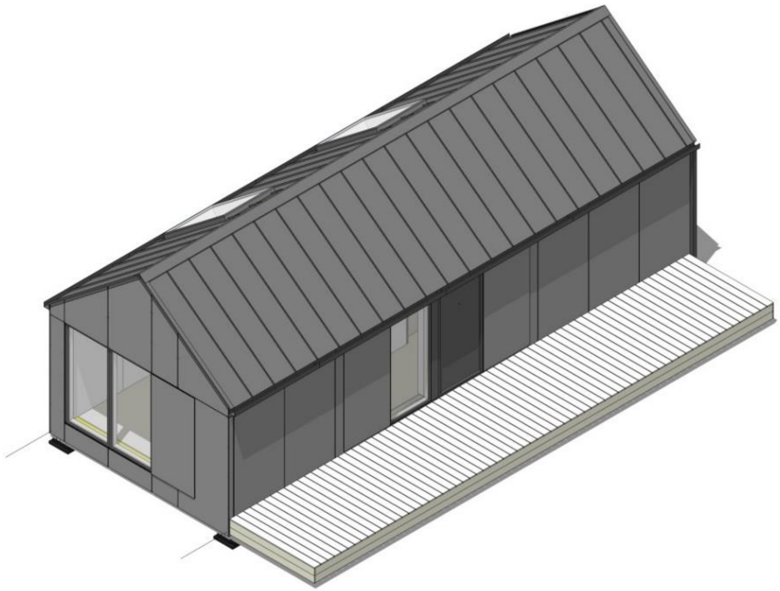


Figure 3-7: External Isometric view of Wikihouse Micro house V01 as downloaded from Wikihouse.org website

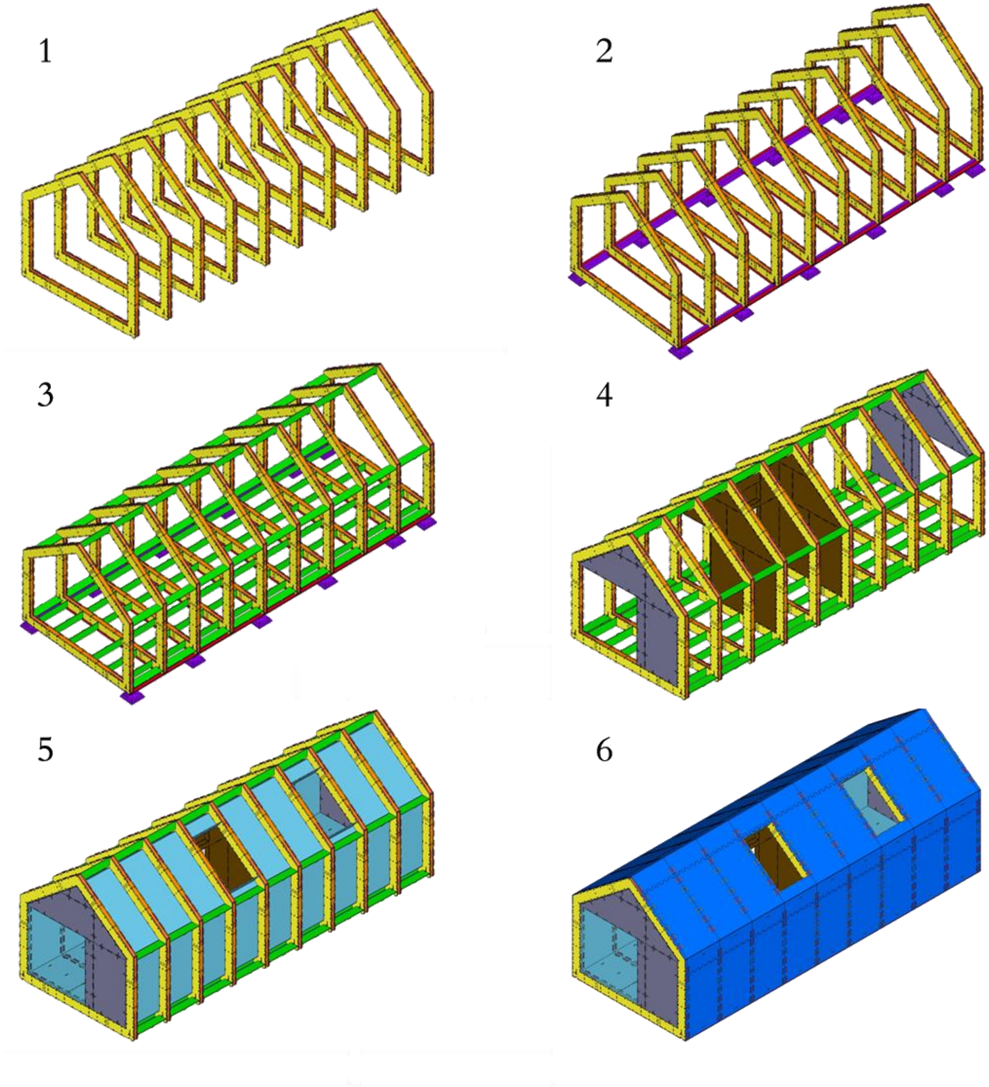


Figure 3-8: Construction sequence for the main structure named "Chassis" of Micro House. **Source:** Model downloaded from Wikihouse.org and interpreted by the author.

3.2.3 Micro Compact Home, Munich, Germany

A team of researchers and designers based in London and technical university of Munich (2001 to 2005) developed the concept of the Micro compact home in response to growing need for short term living accommodations for students, business people, leisure use and weekenders. The inspiration for the design of this micro house was basically taken from Japanese teahouses combined with efficient space planning usually deployed in aircraft, yachts and cars manufacturing (Micro Compact Home, 2015). The main structure is timber framing with Polyurethane foam for insulation covered by Anodized or Polyester powder coated Aluminium external cladding. The house is planned for basic human needs within a space of 2,4 x 2,4 x 2,4 m.

Figure 3-9: Developed for short stays, completely off-site fabrication. **Source:** http://www.microcompacthome.com/

3.2.4 Observations and Reflections

Despite the very small surface area of Micro-Compact Home (6.75 sqm) which definitely translates into cost savings for running costs of maintenance and operation, the initial cost for construction is surprisingly high. According to the official website, the price provided for a single unit and frame (excluding delivery, installation, connection to services, consultants' fees and taxes) is 43.000

USD. The inclusive guide price is from 56.000 to 100.000 USD subject to site conditions. The average price per unit meter in this case is almost 10000 USD, which is definitely high compared to average construction prices in Europe. Space efficiency and compactness is a strong feature in this house design, which might be logically tied to affordability, but on the contrast, this house provides a striking example on the higher end of the economical scale of prefabricated houses.

On one side, building a customisable system using dual zoning approach adopted in System 3 has a great potential. The flexibility offered in the use of naked space opens different configuration possibilities including vertical stacking and future extensions and more flexibility for end users. On the other hand, using timber as a monolithic material for the façade and interior finishes with perforations in the exterior skin is highly questionable from an environmental performance point of view. Although exterior timber panels were covered with insulation paint, it would surely be a concern in more extreme weather conditions. The cost for this prototype was not available as it was financed by different sponsors for MoMa exhibition. However, compared to other prototypes it can be projected that the budget is not on the higher end of the spectrum.

On the Wikihouse website, their library of downloadable files is divided into three main categories: *Types*, which is a ready designed standard building layout combining a number of technologies into a whole building design as shown through the example of Microhouse. The second category is *Technologies*, which are open technologies and systems that can make-up sub components of an overall building. The third category is *Tools*, which is an open source library of tools that are used for manufacturing and building Wikihouses. The three different categories are open source repositories of ideas. Under the section “contribute” in their website, some challenges are placed that need active contributions towards the optimisation of the design and the construction systems. The main required contributions are structural verifications of the building system.

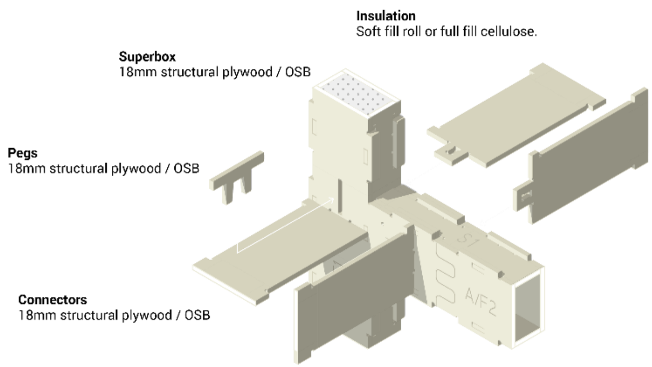


Figure 3-10: An example joint (Wren) downloaded from Wikihouse website that needs structural verification. **Source:** Wikihouse

3.3 Trend 3: Process driven

With an obvious lean towards the process, these prototypes showcase explorations and conceptual investigations towards how buildings are to be constructed. The motivation for authors of the following prototypes was always the process and know-how and the expansion of possibilities and potentials of digital fabrication tools with small or no regard to economical drives despite some of the claims made by their authors.

3.3.1 Cellophane House, New York, USA

At the higher end sits this built prototype Cellophane House designed by Kieran and Timberlake, two American architects based in Pennsylvania, USA. They took part in the New York MoMA exhibition: "Home Delivery: Fabricating the modern dwelling" held in 2008. The house is a single-family home with two bedrooms, two bathrooms, kitchen, living/dining space, roof deck, and carport with an overall area of 180 sqm.

Despite the fact that this house is not entirely digitally fabricated, digital fabrication was involved in many aspects of construction. A strong link was established between design and construction activities through extensive use of Building Information Modelling (BIM). The designers claim to have used a paperless process from conception to final assembly. The building was entirely modelled to high levels of detail, and the model was used to procure materials, plan assembly sequencing and communicate the development of the project with different manufacturers (Kierantimberlake, 2015).

Cellophane House demonstrates a holistic approach to off-site fabrication. It was a step forward in the adoption of these methods followed by Keiran and Timberlake after their other prefabricated "loblolly house." It represents a good example for holding materials together to create an inhabitable enclosure. An aluminium frame provides the structure and the means to attach factory made elements together. It is designed for rapid disassembly and recovery of all components for reassembly, helping to minimize construction and demolition debris generated.

Construction was broken down into "integrated assemblies" defined as "Chunks" and wholly manufactured and assembled off-site then delivered via trailers to the site. For this prototype, integrated assemblies (chunks) were constructed in a factory over the course of 12 weeks, and stacked together on-site in a little more than two weeks.

Cellophane House approaches mass-customisation by enabling the adaption to a range of site conditions and climates through relatively simple modifications. Since all structural loads are carried by the aluminium frame, it is simple to rearrange interior floor plans or substitute materials based on varied budgets and desires. It can be configured for both single and multiple units.

By creating a system into which pre-existing materials can be simply and cleanly inserted, the number of consultants needed to build the house is drastically reduced. Due to the nature of the joints, there are no specialised tools or facilities required, so the number of eligible fabricators is virtually limitless.

The house is enclosed with a lightweight, energy-gathering building envelope made of recyclable plastic film with photovoltaic panels adhered to its surface. PVs harvest energy from the sun and heat is captured in a cavity between layers and either held or released; minimising the energy required for heating and cooling. The south facade features glazing with integrated photovoltaic cells, promising further energy independence.

Figure 3-11: Multistory prototype built off-site completely in BIM. **Source:** KeiranTimberlake, 2015)

The house was monitored after completion to provide a more complete understanding of the insulation capacities of the building envelope, the efficacy of the thermal stack, and the dynamics between outdoor temperatures and the interior environment of the house. Sensors were placed on the west facade and roof read the envelope's surface temperatures. Data collected will be used to further refine the building envelope for optimal performance.

3.3.2 Facit Homes, London, UK

Facit Homes is a London based Studio and workshop designing and manufacturing custom designed digitally fabricated housing. They claim to be the first company in the world to use a purely digital design and production process from conception to final fabrication (Facit Homes, 2015). They registered a trade mark for the process called "D process" in which a "Mobile manufacturing unit" is delivered for the construction of the house on-site. Their design and construction process starts with preparing a full detailed 3D model in a CAD environment.

Designed parts are then nested and cut using a computer numerical control milling machine on-site. The milled parts are then assembled into bigger building blocks (cassettes) that can be handled by one or two unaided people. The cassettes are assembled like pieces of Lego with high precision tolerances. They argue that this process is more efficient and consumes less time compared to standard construction methods. Despite using digital fabrication technologies for the manufacturing of the majority of components of the building, "Facit Homes" team still relies on professional carpentry experts for manual work (Facit Homes, 2015).

Figure 3-12: On-site digital fabrication using a mobile production facility. **Source:** Facit Homes

3.3.3 Embryological House, California, USA

Within the time frame defined for the scope of this analysis, "*Embryological House*" (1997-2002) by architect Greg Lynn signals a milestone in digital design and fabrication of housing units. Although it was highly theoretical and chronologically precedent compared to other case studies, it offered a novel notion of house typology beyond the modernist "kit of parts" model to an organic, flexible, genetic and generic prototype from which an infinite number of iterations can be generated (Lynn, 1998). The project was developed with geometrical modelling and character animation software (MicroStation and Maya), as well as digitally-generated physical mock-ups (Canadian Centre for Architecture, 2007). One of the most prominent aims of Lynn's creative process is pushing the capabilities of existing automated manufacturing technologies for the production of non-standardised architectural forms.

The Canadian Centre for Architecture (CCA) houses the physical mock-ups and digital files associated with the project. And while a number of its iterations have been sufficiently developed to allow their construction potential to be tested to a certain extent, a constructed architectural version has yet to be built. *Embryological House* remains a conceptual project as originally designed - existing entirely in digital format.

3.3.4 3D Printed Canal House, Amsterdam, Netherlands

This is an ongoing three-year research activity initiated in 2014 by DUS Architects, an Amsterdam based architecture office founded in 2004 by Hans Vermeulen, Hedwig Heinsman and Martine de Wit. The aim of their research is to explore potentials of 3D printing for building industry through building an actual full-scale house on one of the canals of Amsterdam. Canal houses have a big significance and symbolism to the history of Amsterdam. They try to investigate what this traditional architype can be in a 21st century context showing how to combine traditional local values with new innovative ideas (3dprintcanalhouse, 2013). The DUS team is performing many trials and building prototypes using different materials for 3D printing with a main focus on bioplastics. They aim to print with a material that is sustainable, of biological origin, melts at a relatively low temperature, and has structural capacity. They are also researching the possibilities of printing with recycled materials like plastics, but moreover looking into using wood pallets and natural stone waste.

Figure 3-13: 3D Printed Canal House Rendering, ongoing research. **Source:** (3dprintcanalhouse, 2013)

3.3.5 Observations and Reflections

It can be seen from these case studies that cost savings were not the driving force for development of these prototype. For instance, the overall cost for Cellophane house was within one million US dollars for a house that is 168 sqm, resulting in an average of 6000 US dollars/sqm which is definitely higher than the average construction costs of 1500-2000 USD (Dol & Haffner, 2010). However, very useful lessons can be learned from this specific prototype; just to name a few:

- The use of controlled factory environment for construction provides better control on overall quality of constructed assemblies.
- Robust planning using BIM tools resulted in an ease of assembly and disassembly of a relatively large multi-storey building.
- Almost all parts can be reused in different configurations as they were disassembled with no material loss.

On the negative side, using aluminium as primary structure raises concern about embodied energy due to high energy consumed for manufacturing of profiles. The thermal bridge effect caused by high conductance of aluminium is also questionable.

On the other hand, environmental aspects of Facit Homes built prototypes were considerably better than other case studies. They include better insulation means, air tightness and overall passive design ideas. They have been designed on a case by case basis which also accounts for better fitness to context.

Although not being the only or the first investigation into 3D printing applications in construction, the canal house represents an important milestone in housing applications, due to its scale, material selection and location and the fact that it is multi-storey. Advantages of 3D printing over traditional building techniques: the possibility of using a high level of detail and ornament; variation as the process goes straight from raw material to final product, thus eliminating waste. There are no transport costs, as designs can simply be transferred digitally and printed locally. In terms of disadvantages, it is evidently a huge challenge to create a building that complies with current building regulations as there is the question of insulation, fireproofing, wind loads, foundations, etc.

3.4 Where shall we head – Outlook and vision

This chapter tracked several prototypes and built projects (Table 3-1) that highlight different approaches and stand points towards the relationship between manufacturing technologies and construction industry within the housing field.

Table 3-1: Timeline of Digitally fabricated housing from 1995 to 2015.

	Embryological House – Conceptual – Architect Greg Lynn – Trend 3 (1997)	Micro Compact Home	The instant house	Loblolly House	System 3	Cellophane House	New Orleans House	Burst *008 – Built for MoMA – Architect Jeremy Edmiston & Douglas Gauthier – Newyork, USA – Trend 2 (2008)	Contour Crafting – Research - partial prototypes – Professor Behrokh Khoshnevis – California, USA – Trend 3 (2009)	Generative House – Research – Partial prototypes – Architect Rodrigo García Alvarado & Benamy Turkienicz - Southern Brazil – Trend 1 (2010)	Digital Vernacular – Research – Scaled Prototypes – Architect Shankara Kothapuram et al. – London, UK – Trend 3 (2012)	Facit Homes	The Bunkie Co.- Company – Digitally fabricated small scale cabins – Product designer Evan bare et al. – Meaford, Canada – Trend 2 (2012)	ECOnnect	10 smart sqm - Built prototype - small scale student residence - Tengbom Architects – Virserum and Lund, Sweden - Trend 2 (2013)	3D Printed Canal House
Trend		2	1	3	2	3	1					3		1		3
Year		2001-2005	2006	2006	2008	2008	2008					2012-present		2013		2014
Architect		Richard Horden & students	MIT Research Larry Sass	Keiran Timberlake	Oskar Leo Kaufmann - Albert Rüf	Keiran Timberlake	MIT Research Larry Sass					London based firm – Bruce Bell		Pieter Stoutjesdijk & Hugo Nagtzaam		DUS Architects
Country		Munich, Germany	Massachusetts, USA	Maryland, USA	New York, USA Dornbirn, Austria	New York, USA	New York, USA					London, UK		Delft, Netherlands		Amsterdam, Netherlands
Status		Built	Built	Built	Built	Built	Built					Built		On-going		Prototype
Image																
Area in sqm		6.75	18	168	53	168	58					Variable		13		NA
Time (days)																
Design			NA	NA	84	NA	NA					120				
Fabrication		56 – 70	NA	NA	147	90	21							Ongoiing		Ongoing
Construction			3	19	1	7 assembly + 9 finishes	23					330				
Cost		43.000 to 100.000 USD	NA	NA	Planned for Auction – On hold	Estimate 1.000.000 USD	NA					116 sqm – 300.000 USD		10.000 – 20.000 USD		NA
Materials																
Primary Structure		Timber framing + Polyurethane foam insulation	Plywood	Anodized Aluminum profiles	Plywood	Bosch Aluminum Framing + Steel Connectors	Plywood					Timber Cassettes		ECOboard – agricultural residue		Bioplastics Macromelt – industrial glue
Secondary Structure		NA	NA	Equipped Wood Truss Cartridges	NA	Floors: Aluminum grate + 0.5 inch Polyethylene	NA					NA		NA		Bioplastics
Claddings		Anodized or polyster powder coated Aluminum external cladding	Plywood	Western red cedar timber - glazing	Plywood	Skin: Transparent PET recyclable Material with PV cells	Plywood – unfinished to showcase structure					Variable		ECOboard		Bioplastics
Interior finishes		Variable – unit includes appliances	Plywood	Wood Cladding / Aluminum / Glazing	Plywood – Sanitary fixtures in stainless steel	Wall panels: 8 mm polypropylene sheet	Plywood					User defined standard finishes		User defined standard finishes		Bioplastics
Process		Full CAD modeling – Partial fabrication – Off-site full assembly- One module delivery	Shape generation – Scripted part and joint generation – Puzzle Approach	Full BIM from conception to coordination-integrated assemblies	Full CAD modeling – Offsite modular fabrication – Naked element fabrication	Full BIM from conception to coordination-integrated assemblies	Shape generation – Scripted part and joint generation – Puzzle Approach					CAD detailing - Mobile fabrication facility on site-Cassette fabrication		Shape generation – Scripted part and joint generation – Puzzle Approach		Paperless process from model to printing
Tools																
Fabrication Tools		Various	CNC Milling	Various	3 Axis CNC Milling	Various	CNC Milling					CNC Milling		2.5 Axes CNC milling		3D printing
Other		Confidential	Rhino - EZCam	Revit Architecture	Rhino	Revit Architecture	Rhino - EZCam					Manual Carpentry				

As previously discussed numerous attempts were made during the last decades to design and construct houses with a notion of *"one size fits all"*; a strategy that had its motivations and justifications after WWI and II; a concept that from where the author stands contradicts the very nature of architecture as a practice relating to context, culture and environment. Specifically, in the field of housing, it has to be seen as a human need not merely a commodity for consumption.

However, synergies and adoptions from the industrial culture can and should be made in search for more efficiency in the construction process. The generally accepted advantages of prefabricated housing are: Less time, Lower cost, Less construction waste and higher construction quality.

The argument now shifts to the following question: *Does industrialised production necessarily mean that context, culture and environment are overseen? Can an industrialised design/production system of housing be context-sensitive?*

Through the possibility of choice, personalisation and expression that digital fabrication promises to offer, the real sense of mass-customisation starts to evolve (Kieran & Timberlake, 2004). The design and construction process proposed by this research tries to revive the concept of "Auto-construction" or "Self-build" in a contemporary context. The selection of a local material, available affordable machinery and end-user participation in the process of construction all represent not only potential cost savings but also promise to relate to local contexts.

The author had a first-hand experience in which he was involved in the design and construction of a vernacular resort in an Egyptian oasis. Despite having an interesting unique vernacular architectural style -from an architect's point of view- that is suited to the context, the local residents were always trying to move away from building with local stone and mud towards concrete post and beam contemporary structures. This tendency is attributed to cultural notions of "modern life" which they envision as being able to use modern means of communication, cellular phones, satellite networks, TVs, microwaves, etc. With the absence of strong planning regulations in the oasis, locals started constructing houses in reinforced concrete that had a noticeably less performance when it comes to heat gain compared to old vernacular means of construction using mud and salt stones. Not surprisingly, they started building rooms in mud and stone attached to their concrete buildings as summer retreats in which they live during hot summer days.

Moreover, Hassan Fathy was an Egyptian architect and a pioneer of "cultural sustainability". His design philosophy was built upon the foundations of end-user involvement, usage of low-cost local design methods and materials. The village of Kurna in the south of Egypt that he built between 1946 and 1952 was abandoned by the inhabitants for socio-economic motives. In 2010, the UNESCO launched a project to safeguard the village. In an interview with "Worlds Monuments Fund" one inhabitant said:

"We want to build with the spirit of Hassan Fathy, not the mud of Hassan Fathy".

The challenge here becomes re-interpreting the tools, methods and intended design outcomes of Fathy in a local contemporary context. From where the author stands, the digital tools that mark this era facilitate the reformulation of a "context-sensitive architecture"; in which the intended design outcomes are reached through applying contemporary advanced solutions instead of just trying to apply traditional construction methods that are increasingly met with scepticism and usually refused by locals. The social resistance towards adopting new technologies and housing solutions must be met with caution, attention and more involvement of the end-users.

The next chapter of the thesis will focus on how the proposed design system can address these issues in search for a flexible, efficient housing solution. The question here is what makes a new housing system different compared to Wikihouse or other previous digitally fabricated attempts? What is the practice model/argument/process that would make this design/fabrication housing system successful?

Within numerous aspects relating to digitally fabricated housing and its limited success in developing countries, the author thinks that one of the most important limitations is the almost exclusive use of timber panels over any other material as the core construction material. Because of the ease of the cutting processes involved and its wide accessibility, timber ranks amongst the oldest building materials and was indeed the most economic throughout the pre-Industrial era. Architects and researchers using timber argue that it is a versatile and sustainable material which is true, but importing timber can and is a key factor participating to a higher cost for construction in developing countries. Being divorced of extreme economic drives that are pressing in developing countries would probably yield results that are theoretically possible but practically impossible.

It is obvious that improving the way housing is built is not an easy, single tracked task. The solution cannot rely on a single aesthetic or a manufacturing system that is beyond the abilities of the current industry. Furthermore, even with a well-conceived approach it may not be possible for a single company to provide the variety and capacity to be successful (Lawrence, 2003).

The labour crisis and the inability of the current housing industry to provide customisation, adaptability, and quality, makes a shift to an advanced manufactured system approach inevitable. No system currently exists which fills this void, but there have been many steps in the right direction. It is only a matter of time until a sufficiently developed system emerges which can meet the need of both manufacturers and consumers by taking advantage of current technology and industrial concepts (Lawrence, 2003).

CHAPTER 4 | Housing System Propositions

4.1 Introduction

This chapter builds upon understandings obtained from the analysis of precedents to develop a system that would better fit developing countries from an economic, social and environmental point of view. An attempt is made to formulate a theoretical framework in which the proposed system attempts to offer practical and applicable ideas that open new ranges of flexibility towards mass-customised solution for low cost housing.

The propositions of "Housing System 01" shall be seen and regarded as a nucleus for a more versatile and robust design system. Setting the conceptual framework is the main aim at this point keeping in mind many layers of complexity that can arise from applying it to a full-scale housing unit. The next chapters of this thesis address detailed design and constructability issues attempting to validate the basis for a functioning system. The approach used for this validation is a bottom-up approach in which a few basic elements (3 wall typologies) are studied in extensive detail; going down to the very fine issues of tolerances, assembly logics, CNC fabrication limitations and joint dimensioning based on material mechanical behaviour. Despite concentrating on the detailed aspects of individual elements, this bottom-up approach strengthens the credibility of the overall system. By understanding not only how the module is constructed but also how it behaves structurally, a more robust and efficient system can be developed.

Through the analysis of state of the art in digitally fabricated housing, the following design considerations or critical design issues are believed to represent the most significant and effective factors for the current failure of digitally fabricated housing in responding to housing deficit. From where the author stands, they represent either potentials that are over-seen or problems that are under-estimated. Some of them are context-specific while others are general and applicable in different contexts.

4.2 Critical design considerations

Thinking and policy making need to be moved away from approaching housing in terms of units and numbers but rather a more holistic view of homes as part of communities and places. The value of a home being measured must go beyond a simple market value and look to the length of its contribution to a community and the economic, social, health and prevention benefits.

For those involved in writing design guidelines, there is a fine line between guidelines being so exact that they are rigid and hampering, and guidelines being so subjective that they become hard to understand and interpret. This is the basic difference between *prescriptive guidelines* which are regulatory and rigid, and *descriptive guidelines* which are focused on providing input into the design process and flexibility. The following critical design considerations/criteria are intended to be of descriptive nature. According to Ilene Watson (2001), Descriptive guidelines allow more creativity and are adaptable to the conditions of the site, but can be so open to interpretation that it can be difficult to refuse a development that shows only a minimal response to design issues. However, they are intended as a framework for a potential successful housing intervention in developing countries.

4.2.1 Economic Criteria

1- Affordable Budget: Affordability, like many other concepts is always relative. Maintaining an affordable budget with respect to construction costs in developing countries is of crucial importance to the end-users, decision makers and real estate developers. The benchmarks against which affordability in developing countries shall be measured are quite different from European and American construction markets for affordable housing.

   According to Gardiner and Theobald international construction cost survey in 2011, the average construction cost/square meter for residential buildings in Egypt is EGP 3000 (USD 337 – based on exchange prices in October 2016) for high rise buildings of average 10 floors. If we use this number as an approximate value, then one-floor residential unit of 60 square meters will cost around EGP 180,000 (USD 20,280) which is way higher than income levels for poor population. Low-income housing in Egypt, usually priced around USD 13,946 (EGP 123,800) per unit remains unaffordable and most developers do not supply houses to this income group (Global property guide, 2015). The price of the cheapest social housing units has risen by 14% per year over the last eight years, while average incomes only increased by 1% per year between 2008 and 2013. House prices in Egypt -relative to income- are more expensive than in Western Europe, double most Gulf countries, and four times more expensive than the USA (Center for Affordable Housing Finance in Africa, 2015). With that said, aiming at the right budget represents one of the vital factors upon which a community up-take would be based. A projected budget between USD 5000 to 8000 would be likely more affordable to a greater audience. The author cannot claim that this is easily achievable, but efficient resource management and optimisation of construction processes can work towards great reductions in construction costs.

2- High density housing: Developing countries are usually characterized by abundance of land area which might bring to mind low density housing developments as more appropriate. However, high density housing reduces cost for public infrastructure which directly affects affordability. Vertical stacking of digitally fabricated houses for more than two floors is currently highly theoretical. Most of the built prototypes shown in previous chapters till present time are one or two floor houses. This implies horizontal spread over a larger area of land for a given number of families thus raising cost of public infrastructure. A balance should be reached between these two conflicting factors. Due to scale and research time limitations, exploration will only address two floor buildings.

4.2.2 Social Criteria

1- Flexible space planning: Space planning is directly affected by social factors; for example: open kitchens are not widely embraced in Egypt due to the nature of food that contains fats and grease and cooking activities that have strong odours. In case open kitchens are highly required in the housing unit design in order to save space in such small and limited surface area of units, attention has to be given to adequate natural ventilation to overcome odours.

   Another example, it is a well-known fact that families in developing countries are mainly extended families with relatively high number of children which in turn necessitates gender separation for sleep space planning. Designing or being able to have a flexible space that can be further divided or rearranged based on end-user changing and growing needs, represents a viable solution in these social contexts. The modularity of the system has to address this aspect giving the end-user the ability to adapt his housing unit to his needs.

2- Long-term Living requirements: Maintaining the minimum socially acceptable living space for a family is quite critical. Very tight space planning such as the approach used for designing the *Micro Compact House* is not socially acceptable for long term residence. Nonetheless, efficient space planning is a crucial factor in low-cost housing in order to maintain budgets under control. A smaller home requires less embodied energy to build, has lower heating and cooling needs, needs fewer furnishings, takes less time to maintain and requires less work to fund. Maintaining a tight balance between minimum acceptable space for a given number of residents and the budget for constructing, operating and maintaining the house is fundamental to the success of any housing project.

   For example, the average house size in the US increased by almost 800 ft^2 (75 m^2) between 1973 and 2010 bringing the overall figure from 1660 ft^2 (154 m^2) to 2390 ft^2 (222 m^2)

(United States Census Bureau, 2010). A study performed at Cambridge University found that the UK has the smallest homes by floor space area of any European country with the average new build property covered just 76 m^2 compared with almost double that amount of 137 m^2 in Denmark (Prynne, 2014).

Researchers also found that between a quarter and a third of people in the UK are dissatisfied with the amount of space in their homes despite many properties being classed as under-occupied when being assessed by the number of bedrooms versus the number of residents. They warned that overcrowding can lead to depression, the breakdown of relationships and physical symptoms such as asthma (Prynne, 2014).

3- Community acceptance: In countries with long history of traditional building construction, resistance to adapt new methods of design and construction is expected. This resistance is deeply rooted in the fear of change that usually accompanies new ideas, activities out of the comfort zone. The author thinks this would be the greatest of problems that needs to be faced in this kind of housing. Any technical, environmental criteria can be met in one way or the other. One way to counter act the effects of this fear is to create involvement and participation, therefore using on-site fabrication or localised fabrication facilities creates this kind of end-user involvement and promotes a better community up-take which in turn translates to a more successful housing intervention. However, promoting the concept of Self-Build does not mean that the architect shall be left out of the process. Instead, the architect is seen as a provider of design flexibility and a creator of open access content for further enhancements of the design system.

4.2.3 Environmental Criteria

1- Local sustainable material: In search for a core material that can render this approach to housing construction feasible from an environmental point of view, the following characteristics for the core material were targeted: local, sustainable, recyclable, resilient, cheap and available. The research was lead into the exploration of abundant materials within the specific context of developing countries.

As the range of possible materials is large and diverse ranging from: sand, soft wood, agricultural residues, local timber, composite panels, clay and bricks, the selection had to be context sensitive in order to reach an environmental and financial saving; this led the research into exploring the potential benefits of local agricultural residues as a wasted resource that usually causes environmental problems to dispose of. Section 4.2 discusses this in more detail.

An observed problem with industrial usage of agricultural residues is the high cost of collecting, transporting, and storing the residue material. “Housing system 01” production model envisions overcoming this limitation by building local, small scale panel production facilities close to the rural areas which happen to have a profound need for new residential expansions. This solution promotes sustainability in many aspects, saving on the costs mentioned before and adding value to a by-product that had no or little value. This proximity also lowers the transportation costs from production facilities to housing developments.

2- Dense unit clustering: Besides the positive financial effect of high density housing mentioned before, a positive effect can also be achieved in passive environmental performance using dense clustering in hot climatic zones. Predictability and easy implementation of active solutions caused a loss of the basic knowledge required to create passive structures. The shading provided due to the clustering helps reduce the ambient temperature in and around each house. This concept is strongly present and well-established in the traditional architecture of the Mediterranean and also in the vernacular houses in the Egyptian deserts.

4.2.4 Technical Criteria

1- To the contrary of mechanised production facilities in which produced parts are always identical, flexible production is not dependent on the modular grid of interchangeable parts. Consequently, it is becoming evident in wood frame panel construction that the grids introduced by machine-tool-technology are losing both their relevance and presence. In contemporary wood frame panel construction, it is irrelevant whether an element is adapted to a grid or not. The accuracy of the element’s fit is guaranteed by tool precision, and its positioning is determined by its label (Schindler, 2007).

As Andrea Deplazes (2005, cited in Schindler 2007) points out, the panel has now substituted the bar as basic element of today’s timber architecture. The panel is expandable in any surface dimension, offering a greater potential for flexible construction than the bar. The most rigorous application of ‘penalisation’ as a construction method can be seen in recent wooden ‘solid construction’ with load-bearing panels of nailed or glued cross-layered boards. The wall-sized elements are adjusted to the floor plan and no longer vice versa. The grid is not merely transmuted; it has been fully dispensed with. Windows and doors are simply CNC-cut as holes at any position into the panels.

2- Merging concepts of “flexible modularity” with pre-assembled “Grand blocks” in search for more freedom in formal and spatial expression. The design approach of “Housing System 01” aims at coupling modular construction with parametric tools in order to reach a higher level of customisation. The intent is to construct the wet areas as complete finished blocks in a controlled factory environment and to use parametric modular wall assemblies to construct flexible open spaces for sleeping and living.

   Many prefabricated designs succeed in breaking down a building into modules that can be quickly joined together, but they typically embody a top-down strategy: design a building, and then devise a system to make it work. On the contrary, Housing System V01 began with the wall assemblies as a basis, allowing architecture to grow out of its opportunities and constraints.

   Defining the level of customisation at which the design system aims to arrive is of great importance. Five different strategies can be defined based on the level of end-user involvement in the production cycle: Pure standardization, segmented standardization, customised standardization, tailored customisation and pure customisation. The lowest level of customisation occurs if all stages of the value chain are standardised. On the other hand, firms achieve the highest degree of customisation, pure customisation, if customers are able to have direct impact on the design process at early stages. The other strategies are intermediate forms, which are situated between the extreme levels.

3- Managing and minimising material waste during fabrication: The use of standard size flat stock sheets as modules for dimensioning helps diminish the material waste during the fabrication process.

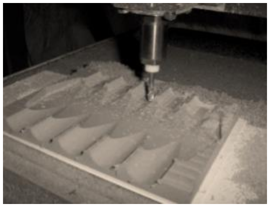
4- An important technical aspect related to social acceptance and community uptake; is creating a system that can be easily understood, managed and assembled by the end-users. This need is manifested in the use of integral joining techniques with no need for construction expertise. This aspect will be elaborated further on in chapter 5. Furthermore, with the high density of the material, the weight of components and assemblies ought to be maintained within reasonable limits for ease of handling and transportation and assembly.

5- Fabrication Method: The various Computer Numerically Controlled (CNC) processes of shaping and reshaping, based on cutting, subtractive, additive and formative fabrication, have provided designers with an unprecedented capacity to control the parameters of material production, and to precisely craft desired material outcomes (Kolarevic, 2008). Knowing production capabilities and availability of particular digitally driven fabrication equipment enables designers to design specifically for the capabilities of those machines. The consequences are that designers are becoming much more directly involved in the fabrication processes, as they create the information to be translated by fabricators directly into control data that derives the digital fabrication equipment. It has therefore become necessary for savvy architects to understand how these tools work, what materials they are best suited for, and where in the tooling process the possibilities lie.

The digital fabrication technologies are mainly divided into 4 main categories –as shown in (Table 4-1) according to the classification adopted by Branko Kolarevic (2003), based on the process of shaping. The tools that can be used for processing sheet materials and are mostly available in Fablabs, hackerspaces and small to medium scale fabrication facilities are laser cutters and 2.5 axes CNC milling machines. They are considered to be the most versatile and easy to use tools available for a wide range of applications compared to their relatively low prices. The standard equipment that are provided by these labs are a defining factor to the development of the housing prototype as the intention is trying to democratize the means of production and make it available and accessible for low-income, low-cost construction. The vast growing network of Fablabs around the globe is making this achievable by disseminating knowledge and educating communities on the potentials of personalised fabrication.

At this point, a design approach that builds constructive elements out of sheet material is seen as most appropriate for further application due to many reasons. Firstly, it promises to be more economic as it involves simple fabrication tasks. Secondly, the design system itself must be simple promoting easy construction by unskilled home owners. Thirdly, the machines themselves are sometimes built using open source data from the internet. Many online forums provide detailed information on how to build your own machine. The fabricator with which this research was conducted had built his own CNC milling machine following the open source instructions of a South African mechanical engineer who created the *MechMate*. The sum of these reasons provides a logical motive to use 2-Dimensional fabrication methods for low-cost housing.

Table 4-1: Digital Fabrication tools Categorisation. Source: based on Kolarevic, 2003

	2-Dimentional	Additive	Subtractive	Formative
				
Process Description	Using of a cutting head that is freely moving in X, Y directions to cut materials using heat, laser or water pressure.	Building shapes in a layer-by-layer fashion.	Carving out from a solid block of material	Using mechanical forces and/or heat to reshape materials into the desired form
Example Machines	Laser cutters, Water jets and Plasma Arc	3D printers, Fused deposition modelling (FDM)	Milling machines, Turning centres	Thermo-forming and CNC bending
Possible Materials	Almost any sheet material	Usually polymeric materials, waxes and paper laminates	MDF, machinable foams, machinable waxes, and some polymers, wood.	Metals with reasonably elastic properties, plastic and fiber composites
Possible Uses	Typically used in manufacturing model components, surgical instruments, wooden toys, furniture, engine components, sheet-metal fabrication, and domestic appliances	Virtually every field related to industrial design, reconstructive surgery, product development, architectural models and bigger applications still under further study.	Milling foam form work for curved panels either in concrete or glass or metal, carving different materials for surface effects, building unique structural components.	Reshaping of metal panels for doubly curved panels, bending of structural members, moulding and casting for a wide range of materials.

4.3 Design strategies

As seen through the analysis of the built prototypes of digitally fabricated housing and the outlined set of critical issues that represent -from the point of view of the author- some of the most important design considerations in search for a more efficient low-cost housing, the following matrix (Table 4-2) recapitulates on how each problem or limitation can be responded to using one or more strategies within the framework of "Housing System 01". What this system is trying to offer is a blend of applicable, practical ideas put together in search for more freedom, efficiency and above all economy. Some of these design strategies are only presented as concepts for further development for future work while others are studied in more detail in the following sections.

Table 4-2: Problem / Proposed solution Matrix

	Proposed Solution or Strategy								
Problem or limitation	Alternative materials	Prefabrication	Parametric modularity	Design Interface	Self-Build	Open source	Adequate living area	Local Fabricators	Simple joint system
Exclusive use of timber	●								
Environmental challenge	●								
Complexity of wet spaces		●							
Design customisation		●	●	●		●			
Limited user involvement				●	●				●
Suitability to context	●								
High labour cost								●	●
Long term liveability			●				●		
Affordability	●				●	●		●	
Community acceptance					●		●	●	●

The ability to find and adopt alternative materials will respond to three main challenges namely: the almost exclusive use of timber; the existing environmental challenge of agricultural residue disposal; and the extreme urge for affordability in contexts that have limited timber resources or mainly depend on imported timber. Grouping "Prefabrication" and "Parametric Modularity" with a user-friendly interface will address the complexity of wet spaces and help respond to customisation needs of the occupants. Affordability can be addressed with the adoption of strategies of self-build, open source, local materials and local fabricators.

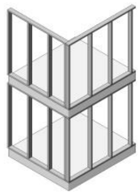
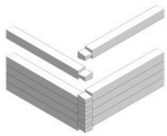
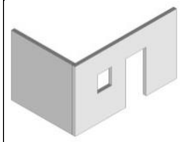
The proposed housing system tries to respond to these findings in a comprehensive manner. However, the focus for the next part of the thesis will be directed towards finding *alternative materials* that can be used for a *simple jointing system* promoting the concept of *self-build*.

Given that the construction logic of "Housing System 01" relies heavily on some concepts that have been usually applied in timber construction, this necessitates having a brief general understanding of categories of timber construction to better understand where the system stands within the spectrum. The main categories of traditional timber construction are: Timber framing; Timber skeleton; and Solid timber construction which includes both log construction and solid panels such as CLT (Cross Laminated Timber).

Table 4-3 shows the most common timber construction methods and their schematic construction logic and load transfer. It also gives examples of countries where they are commonly used.

Traditional timbered structure is seldom used today, which is not suitable for CNC cutting due to its large structural members. In timber frame construction, the replacement of larger cross-section members by nailing several smaller squared sections together is suitable for CNC manufacturing. However, the members of standard sizes are not necessary. Panel construction and skeleton construction systems also employ large timber panels and posts and beams, which does not fit the restriction of economic CNC manufacturing. These timber construction systems have different logics of structural load transfer: log construction transfers load from log to log; timber frame construction mainly uses vertical elements, and horizontal ones as secondary elements; frame construction has horizontal and vertical elements of the same structural importance; panel construction transfers load by large solid wood boards; Log construction instead needs a large amount of timber, which is not economic compared to other construction systems.

Table 4-3: Analysis of the most common timber construction methods.

	Timber Framing (Light Framing)		**Timber Skeleton (Post & Beam)**	**Solid Timber Construction (Massive Timber Structures)**	
Sub-categories	Platform Framing	Balloon Framing		Log construction	Solid Panels
Country in which it is commonly used	USA	USA	Japan	Russia & Nordic Countries	Russia & Nordic Countries
Constructional Logic					
Main Concept	Vertical studs interrupted at floor slabs	Vertical studs more than one storey high	Vertical columns, horizontal beams, inclined bracing	Logs arranged horizontally with integral joining	Walls, slabs and ceilings made of solid CLT or LVL panels
Load Transfer Method	Main vertical – secondary horizontal	Main vertical – secondary horizontal	Horizontal and vertical of same structural importance	Ceiling and roof to foundation by wall logs	Load travels through large solid boards
Structural stiffness	internal and external sheathing	internal and external sheathing	Inclined braces	Integral joining	Shear walls
Suitability for CNC Manufacturing	Yes	Yes	No	No	Yes (if thin sheets are glued)

4.4 "Housing System 01" components

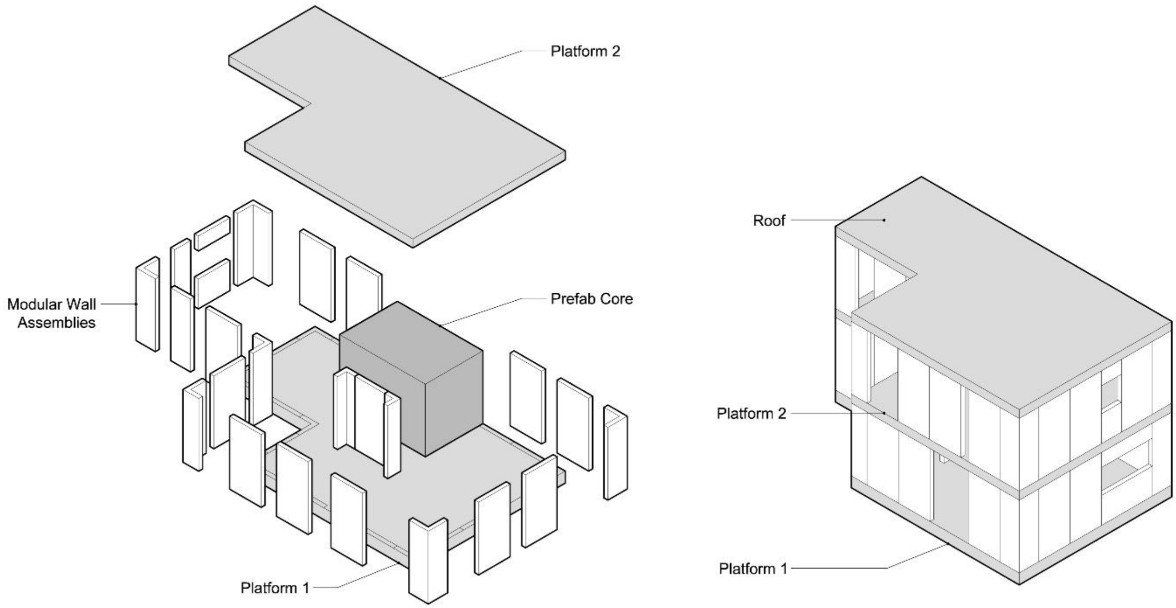


Figure 4-1: Housing system 01 components.

4.4.1 Prefabricated Core

Since the overall percentage of mechanical building systems cost to building's overall cost has dramatically changed over time, building systems are becoming much more complex and demanding with the introduction of new information systems, building management, automation systems and many others (Kieran & Timberlake, 2004).

In the case of "Housing system 01", the core is envisioned to be an off-site prefabricated complex assembly that consists of a bathroom and a kitchen integrating all mechanical systems. The controlled factory environment in which these assemblies are constructed saves on time and effort of on-site construction by minimising the time of connection to public infrastructure. This translates then to economic gain by being able to produce these assemblies in large quantities. In a low-cost housing system, these two spatial elements (Bathroom and Kitchen) are two basic functional modules that are usually acceptable with minimum variation. However, customisation is still achievable by building different models of bathroom/kitchen configurations. The end-user still has complete control on finishing materials, colours, faucets and fixtures. A handful of companies around the world e.g. Add-A-Bathroom, interpod, Sanika, Pivotek (Figure 4-2) already provide this custom service through the design and construction of prefab bathroom and kitchen pods for residential and hospitality projects.

Figure 4-2: Prefabricated bathroom pod manufactured by PIVOTEK, an American company specialised in off-site prefabricated bathroom pods for housing and hospitality. **Source:** Pivotek Linkedin post.

The overall dimensions of this core block are of critical importance to the process of transportation from the factory to the construction site. This aspect varies based on traffic and high way regulations in different countries. In the US for example, there was a restriction of 8 feet

(2.40 m) wide modules that were then pushed to 10 (3.00 m) feet, then 12 (3.60 m) feet then finally with special permissions to 14 feet (4.20 mm) wide trailers.

The layout below shows an example core with the overall dimensions of (3320 x 2255 mm) with external walls of thickness 150 mm except for the wall that contains water supply, drainage and toilet 4-inch discharge tube with a thickness of 170 mm. For the sake of showing the flexibility of the proposed design system, the core itself was designed using straight, L shape and T shape wall assemblies that formulate the second element of the housing system as will be shown later. It can also be designed and constructed using different construction logics as shown previously. The core can be used in many different configurations and orientations with one restriction set to maintaining at least one wall exposed to the outside to secure natural ventilation and lighting.

The most important consideration when dealing with movable pods such as those illustrated is the structural integrity of the pod that will be subject to crane loading and handling. The core must be designed, built and reinforced beyond the structural needs of a fixed pod.

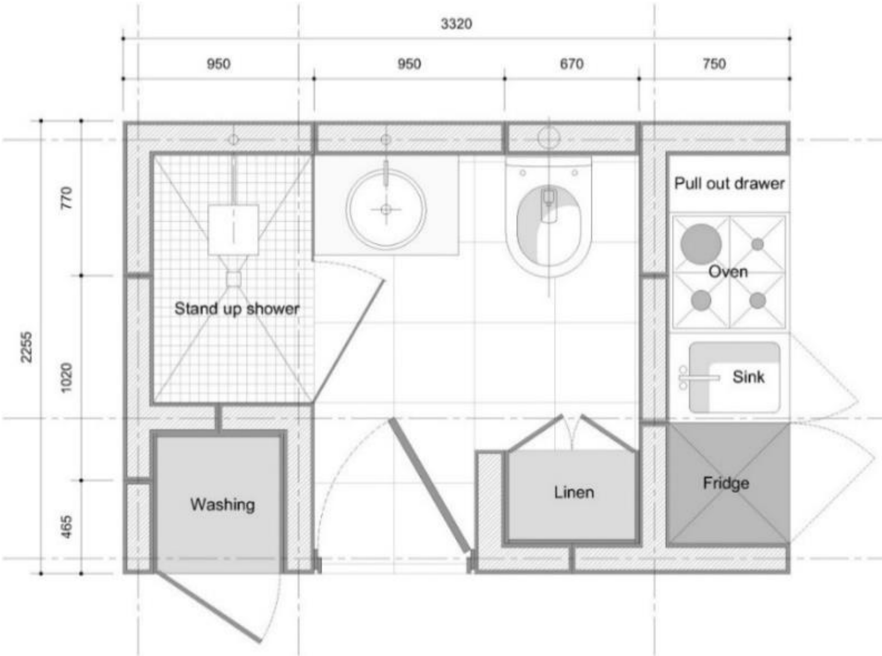


Figure 4-3: Compact prefabricated core with overall dimension that are transportable using generic trucks

4.4.2 Modular parametric assemblies

Since modularity facilitates the production and transportation of parts offsite, combining modularity with parametric control widens the range of possible design solutions achievable using these assemblies. The approach used for the design of "Housing System 01" is based on a logic in which wall, floor and ceiling assemblies are designed to be load bearing structural members. In this system, modularity is not a result of a production tool limitation as much as it is a design approach that divides the housing unit into fragments that are easily manufactured, transported, handled and assembled. All assemblies are meant to be parametrically controlled in order to ensure high flexibility and adaptation to different design needs. The modularity also responds to the necessity of avoiding custom-sized panels by using stock flat sheets available on the market.

The modular parametric assemblies are based on the concepts of "*platform framing*" which is the most widespread mode of light wood framing construction today. Unlike the "*balloon framing*" method, the main feature of platform framing is that the vertical studs are interrupted at each floor level by the floor construction.

Platform framing has these general advantages:

- Studs are only one storey high, so long pieces of lumber are not required.
- Wall sections can be assembled on the floor platforms in a horizontal position, and then lifted in place.
- The interruption provided by the floor slab to the continuous wall assembly gives better fire safety because the wall cavity is interrupted at each level preventing the spread of fire.

In the case of wall assemblies, the constructive logic is based on stand-alone hollow cassettes that are assembled to the neighbouring ones using integral joining. The hollow cassettes allow for easy and flexible wiring. The hollow space inside can be also filled with insulation materials when needed. One idea that can be explored in the future is to fill these spaces with wheat residue that is well-known for its thermal capacity. However, this is not within the scope of this study.

The system provides three basic wall typologies namely L, T and straight wall. They represent the most common wall configurations that are likely to exist in a simple orthogonal housing unit. They will be always referred to as "wall assemblies" to avoid confusion with the word "panel" or "sheet" used mainly to describe the stock material.

For each assembly, the design variables are divided into three main levels. The first is *overall wall configuration parameters* (external variables) and the second level is *internal wall configuration parameters* (internal variables), while the third level is *Automatically generated components* based on the first and second set of variables.

The figure below shows the overall wall configuration parameters (external variables) of the three main wall assemblies (I, L, T) in which wall thicknesses, length and overall height of wall can be parametrically controlled to accommodate for different design situations and offer a wider range of flexibility to the designer.

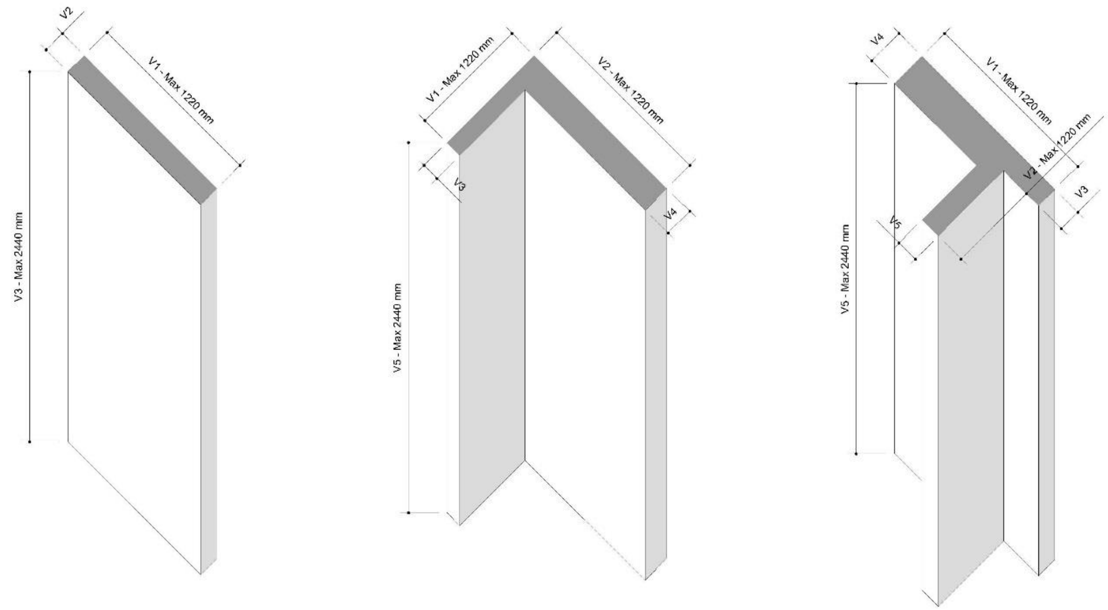


Figure 4-4: Overall wall configuration parameters for three different typologies of walls in Housing System 01

Internal wall configuration parameters (Internal variables) represent variables that can be changed and manipulated on the internal structure of the wall assembly such as: vertical runner quantity and spacing (based on structural needs), material stock sheet thickness, number of vertical sheathing panels. The internal joints of these wall assemblies will be studied in depth in the next chapter.

The third set of components which are automatically generated are those related to the mechanical and structural capacities of the material and the detailed aspects of joint design and allocation. These variables are not of any interest to the end user. They are of great importance to the engineer doing the structural verifications. These variables are expected to be stabilised and built into the parametric setup based on the physical structural behaviour of the detailed joint. This necessitates building prototypes and verifying actual behaviour in order to be able to inform the digital model.

For instance, based on the number of vertical sheathing panels decided by the end-user, a sufficient number of joints to hold these panels to the vertical runners will be automatically generated and positioned in appropriate locations. These locations are a result of precedent testing performed by the engineer that defines these dimensions to be the optimum.

Another example is the edge clearance (the distance between the position of the vertical runner and the edge of the wall assembly) which represents a variable that can be solely defined by the engineer based on joint and wall assembly behaviour.

Algorithmic and parametric design software such as Grasshopper for Rhinoceros, GenerativeComponents from Bentley or Dynamo for Autodesk Revit are all tools that use the same simple logic of (Input – Processing – Output) for the control of geometric entities. From the beginning, the set of variables to be controlled need to be thought of, abstracted and declared. The clear definition of these variables will shorten the time for the creation of the parametric model initial setup and the subsequent modifications. The creation of the interdependencies between objects, equations and actions necessitates understanding the flow of data inside each component of the visual algorithm.

Figure 4-5 shows a quick model prepared in Grasshopper for the straight wall typology. The script shows the set of external and internal wall input variables on the left. How these inputs are interpreted and processed is not within the control of the user that has the sole interest in creating suitable wall assemblies using simple inputs that are best suited for his requirements. The outputs are a mere result of the input data and they are directly translated into 2D profiles for machining.

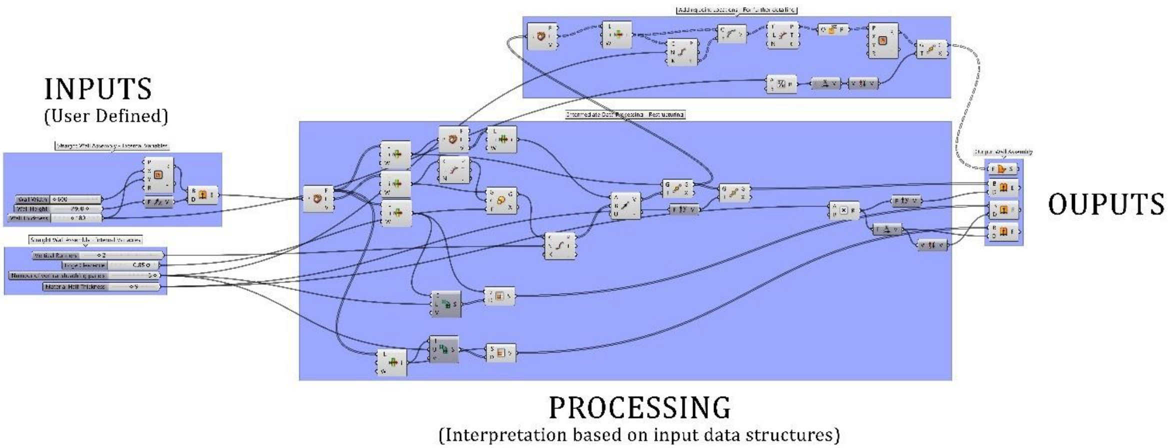


Figure 4-5: Grasshopper script of a straight wall assembly

The following screen shots (Figure 4-6) taken from Grasshopper show two instances of the straight wall assembly changing the overall dimensions of the wall (height, width and thickness) within a predefined range of solutions that best work with the material, fabrication and joint design limitations. The internal wall assembly variables such as material thickness, number of vertical runners, number of vertical sheathing panels can also be controlled and changed based on structural needs. The script has been prepared with the sole intent of showcasing the potential that this (parametric + modular) approach might bring to the design process.

The next section discusses how these separate "chunks" of parametric definitions and information can be integrated into a coherent "whole" through the use of a "Design Interface". A fully-functional interface needs scripting skills that are beyond the author's current capacities coming from an architectural background. More importantly, it is beyond the scope of this thesis. With the complexity of component design and with the intention of generating assembly descriptions in CAD, Grasshopper is not a suitable tool for algorithmic design beyond a certain scale. Some huge visual algorithms or scripts prepared with Grasshopper can be substituted by simpler text-based scripts. Design automation can address these problems with computer programs built for rapid model generation. The advantage at this point would be less computing time, but this calls on architects to acquire scripting skills that are becoming the widespread norm in the construction and engineering industries.

The scope of work within this thesis stops at physical structural testing of the joint with an understanding of the possibility to automate the joint generation process using scripting software. The geometry of the joint can also be automatically generated based on the panel thickness, material behaviour and stress capacity. The G-Code for a CNC milling machine can also be generated automatically at the same step.

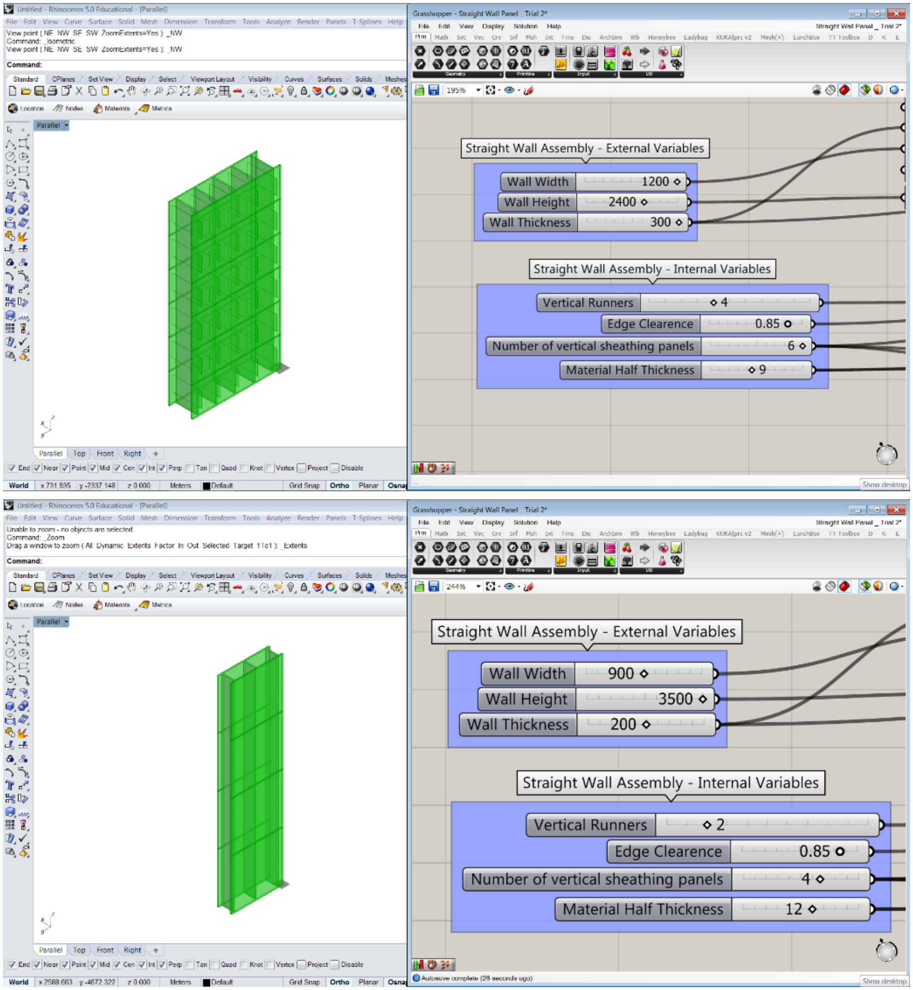


Figure 4-6: Screen shots from Grasshopper showing two instances of the straight wall assembly with different external and internal configuration parameters manipulated.

4.4.3 Design Interface

In the paper "Bridging building information modelling and Parametric design" by (Boeykens, 2012), an interesting discussion is made around the similarities and differences between the logical structures of building information modelling and parametric modelling. The technical approach of building information modelling is inherently parametric. The creation of a digital model, virtual mock-up of a building is done by modelling and adjusting parametric objects. The objects have their own "*intelligent*" behaviour and are configured by setting the property values of all "*exposed*" parameters. Regardless of how a BIM tool is implemented, they behave as scripted objects, with all resulting geometry being generated and recreated upon parameter changes. Whereas the designer manually models geometric detail in a generic 3D CAD system, BIM software limits the amount of direct modelling, using internal algorithms and embedded knowledge about the construction domain.

In contrast to this, in parametric modelling systems, designers develop a recipe for a particular project, which can often be regarded as a composition of geometric entities. Regardless of the chosen technology, they embed and inject mathematical formulas, constraints, calculations and control functions to derive a geometric model from a series of input data. This is usually a combination of both numeric and geometric information, but can be extended with external inputs, such as site conditions, sensor data and even online streams or graphical imagery. So, it can be said that in parametric modelling, the designer controls the generation of objects from an overall logical script or scenario.

While BIM relies strongly on parametric functionality, it is mostly used on an *object-level*. The BIM model thus behaves more like an assembly of rather independent objects. In parametric design, the whole project becomes a single assembly, with full control over both the overall form and the smaller details.

The approach used in "Housing System 01" can be described as using parametric modelling on an object-level. This is because the design approach is modular and fragmented into a group of independent assemblies (wall-floor-ceiling-prefabricated core). The fragmentation and modularity of the design system nictitates addressing the individual assemblies as stand-alone parametric objects. Given that parametric modelling software do not include a semantic definition of the created objects/geometries, the challenge becomes creating an interface in which these assemblies are put together in an overall system that can be actively controlled and predicted.

This section outlines some broad lines of how this interface functions and represents an interesting line of future research, however, it is not part of the scope of the current investigation.

Within this interface, each panel and wall assembly is digitally constructed parametrically. This allows the panels to be customised to almost any design, and arranged to accommodate window and door openings simply by changing the panel dimensions. More importantly, having parameter based properties allows design changes and tweaks to be made with ease e.g. if a panel needs to be extended the dimensions are readjusted and the pre-set parameters inform the panel to re-adjust to the new dimensions. This also makes updating the model easy as there is full control over each building component, e.g. if the cavity batten spacing needs changing the required dimensions are simply typed in. This automatically re-generates the cavity batten spacing in the entire model.

Home Styler, *RoomSketcher* and *Planning Wiz* are three online interfaces for building simple 3D floor plans based on drag and drop libraries of components (Figure 4-7). They are very close to what the author imagines for "Housing System 01". However, the main difference is that these interfaces are not based on elements of a construction system. The outputs achievable through these interfaces are only 2D and 3D visualizations. The interface for Housing System 01 shall provide the capacity to calculate in real time the cost of the design. This is achievable through knowing: the material stock sheet cost, machine cut time based on profile lengths. Other potentially useful information such as the mass of each individual wall and its assembly sequence are all also visible through the user interface.

Constraints can also be embedded into the parametric interface. This means that the user is advised not to exceed certain limits while working on the design of his housing unit. This ensures some critical structural aspects and conceptions are accounted for from the beginning. After the home design is prepared by the end-user, it is sent via the online platform to a structural engineer for final structural verification and advice on any possible optimisations from a structural point of view.

Constraints related to local norms for house planning lie within the scope of *Macro Scale Configuration* so this study is not concerned with studying them. However, we are concerned with constraints that are related to structural behaviour. For example; the user would be constrained from designing a very long free-standing wall, instead he will be advised to add perpendicular supports distributed at certain intervals to achieve more structural stability.

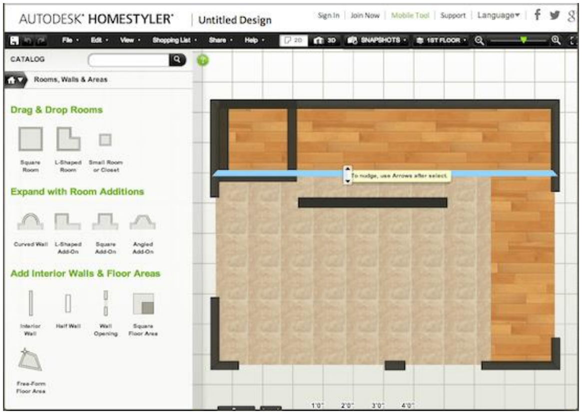


Figure 4-7: Autodesk Home Styler user interface where libraries are shown on the left-hand side while the design canvas space is seen on the right.

While the Instant house (Botha & Sass, 2006) utilises CAD/CAM to fabricate plywood components into a bi-lateral assembly, the investigation of an interlocking concrete block assembly by Griffith uses CAD/CAM to manufacture a cradle moulding device appropriate for local adoption in rural applications (Griffith et al. 2012). Each of these techniques proposes a feasible methodology for creating designs in a virtual environment to physical output for production in the local context. However, following their trajectory of digital manufacturing tools in the global context would suggest that all design decisions have to be taken before production starts, and that the craftsman cannot use his/her experience, becoming merely an assembler of pre-manufactured parts because the assembly sequence is already determined by the designer (Peinovich & Fernández, 2012).

The proposed design system addresses this limitation using the modular parametric approach. The end-user still assembles a prefabricated set of elements with a certain sequence however the flexibility is shifted towards the parametric control over the different internal and external assembly variables demonstrated before. The layout design of the housing units is however entirely open to design and end-user requirements.

The following schemes were all designed using the design system components previously mentioned comprising straight wall, L shape wall, and T shape wall assemblies in addition to prefabricated core. The intent here is to show the flexibility offered by this design system. There are infinite possibilities of how these components can be utilised for designing a wide range of housing units customised to different end-user requirements, an inherent characteristic of modularity. The three wall assemblies are highlighted in different colours. Red for straight wall assembly, blue for L shape wall assembly and Green for T shape wall assembly. The prefabricated core is highlighted with a light grey solid hatch.

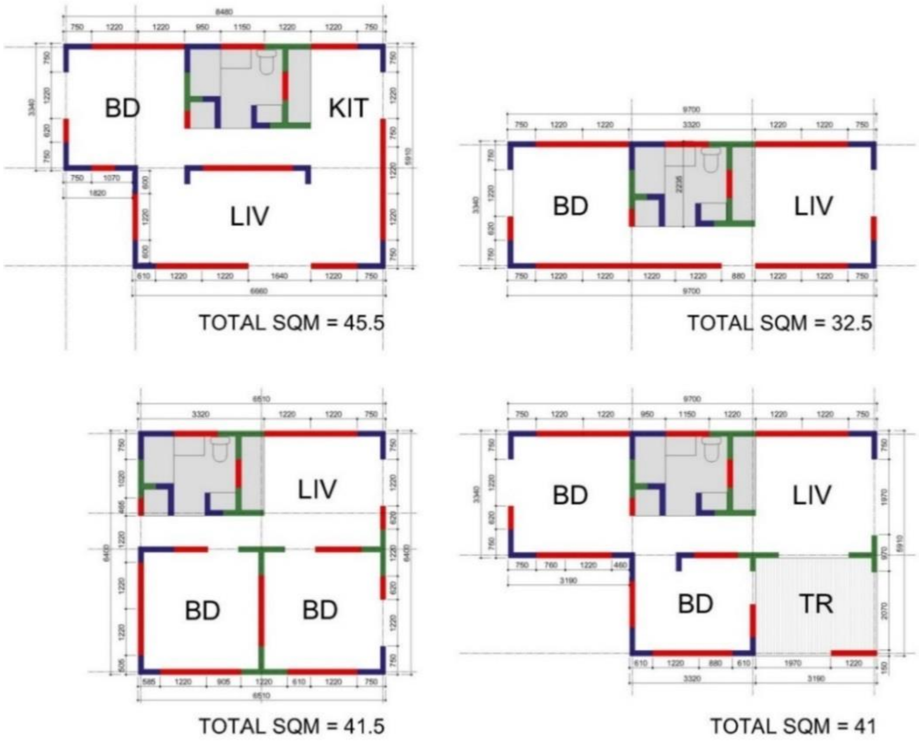


Figure 4-8: Schematic layouts using Housing system 01 components.

Windows and doors can be installed at this stage on site but due to the highly accurate machine-led precision cutting of all parts, construction tolerances can be made very tight and accurately crafted fittings can be obtained. Conceivably, if the 3D model can be incorporated into the window manufacturer's CAD software, further accuracy and assembly speed could be obtained. It is conceivable that the entire house could be erected and made watertight in just over a week, compared to a typical period of several months for a 'normal' house-construction.

The floor assemblies are also envisioned as parametric cassettes with dense waffle joists to provide more stiffness and load resistance to the slab. The composition of the assembly is a perpendicular grid of intersecting half-lap joists inscribed between two flat layers of agricultural residue panels to which they are attached using integral attachments (Due to research time limitations, the floor and ceiling assemblies are not going to be studied within the scope of the thesis, but they will be further detailed and analysed in future work).

4.5 Material selection

Besides having a growing population and lack of adequate mass housing solutions, a large number of African countries have long traditional agricultural history. These countries still face a yearly challenge in the harvest season. Egypt for instance produces around four million tons/year of rice straw residue that must be disposed of (Garas, Allam, & El Dessuky, 2009). Unfortunately, the current practice is burning most of these residues forming huge clouds of smoke commonly called the "Black Cloud" above the capital and surrounding cities and villages. The environmental impacts of such practice are utterly harmful causing multiple lung diseases needless to mention all the other negative effects.

Straw has some limited structural uses in Egyptian country side such as: Grinding and mixing with clay and water to be used as building blocks; Above roofs as an insulation material as it has a relatively high heat capacity. It is also prepared in pallets that are shipped off to paper manufacturing facilities. It can be used as an incubator for vegetables and fruits as it helps them ripe. It is sometimes used as a filling material for mattresses and pillows. Sometimes, mixed with clay and animal solid waste it is used as a bio fertilizer.

There has been on-going research exploring the use of condensed, treated rice straw as a cementitious building block (Mansour, Srebric, & Burley, 2007) (Akmal, Fahmy, & El-Kadi, 2011). Researchers in the National Research Centre in Egypt also explored straw bale construction as an alternative economic environmental construction method for low cost housing (Garas, Allam, & El Dessuky, 2009). It proves to be a promising viable solution yet few researchers have started exploring prospective use of rice straw and other agricultural residues in flat sheets as a principal material in a structural manner. This particular application is of great potential and interest to the field of sustainable digital fabrication in which the author is currently involved.

Agricultural residues definitely have industrial uses beyond paper making. They can be used to make construction materials and biofuels. Environmental Building News cited in (Hayes M. , 1998) offer the following assessment of the immense possibilities for using agricultural residues:

> *"If we used all of the available straw for the exterior walls of straw-bale buildings, 2.7 million 1,000-ft2 (93 m^2), single-story houses could be built each year. If we turned that straw into structural compressed-straw panels, they could provide the*

exterior walls, roofs, interior partition walls, and floors of 1 million 2,000 ft2 (186 m²), two-story houses per year. Or, that straw could be used to produce 22 billion ft² (2.1 billion m²) of 3/4" (19 mm) particleboard, which is five times the current total U.S. production of particleboard and medium-density fibreboard (all thicknesses). Clearly, the potential is significant."

A wide range of agricultural residues can be compressed and utilised in planar sheets. The selection is then based on availability in local markets. In this case, the selection of rice or wheat straw as the base material promises to address more than one issue concurrently; first, minimising the environmental impact of abundant un-used agricultural residues. Second, adding economic value to materials that previously had no/little value. Third, lower the initial cost for the construction of the house if used in a structural manner. Fourth, fits the available relatively cheap digital fabrication technologies available through fablabs, hacker spaces and educational facilities.

Today panel products using wheat straw and other crop residues are being commercially manufactured in a number of countries including Turkey and China. Several countries utilised agro-fibers for the production of particleboard or other composite panels. So far there are at least 30 plants that utilize agricultural waste materials in the production of particleboards around the world (Güler, 2015). Utilisation of agricultural fibers as a raw material does not only bring solution for raw material deficit in the particleboard industry, also brings some reduction in consumption of forest. The use of agricultural residues as a raw material in the forest industry is not new and it dates back to 1900s for panel industry (Güler, 2015).

The material selected for utilisation and further analysis is *ECOboard* which is a wheat straw, formaldehyde-free resin bonded particle board produced by Novofibre Panel Board (Yangling) Co. ltd in China and placed in the European market by ECOboard International B.V. in Netherlands. The material has been tested and validated according to the regulations of the European parliament (the Construction Products Regulation) for internal use as a structural component in dry conditions.

4.6 Characterising the material

The usage of particle boards of vegetable fibres and agricultural residues in building construction in this structural manner represents an interesting line of exploration. To be able to design an efficient jointing system and define its proper dimensions, the author along with professors from the structural and geotechnical engineering department at La Sapienza University decided to perform a set of laboraotry tests. They are intended as a verification of the basic values of mechanical properties provided by the material manufacturer. The performance data published by manufacturing companies for commercial use tend to be to some extent over-estimated when compared to realistic performance usually for marketing reasons. Therefore, it became vital to verify the actual performance of the selected panels.

According to the data provided through ECOboard website and reports provided to the author by the company CEO Mr. Waldo Chotkoe (See Appendix B), the following values showed in (Table 4-4) for the mechanical resistances of 18 mm thickness boards were obtained.

Table 4-4: Test report of ECOboard 18 mm thick panels. **Source:** Based on the material leaflet sent to the author upon request via email.

Test	Unit	Condition	ECOboard	MDF – E1
Bending Strength	MPa	Min 1	38.3	29
Elasticity	MPa	Min 1600	3810	2980
Screw Pull	Surface	Min 1100	1520	1000
Internal Bond	MPa	Min 0.35	0.80	0.51
Swelling in Thickness	%	Max 8%	3.40%	10%
Moisture Content	%	Max 13%	6%	9%
Formaldehyde	mg/100g	E1 Max 0.9	0	0.5 – 0.9

Compared to similar products of agricultural residues, it still showed significant high resistance. In the study prepared by Güler (2015), he reported on experiments performed on 8 different types of agricultural residue panel composites with different densities that are comparable to ECOboards. Table 4-5 shows the composition of each panel type that was tested.

Table 4-5: Experimental design composite panels. **Source:** Reproduced based on Güler, 2015

Board Types	Raw Materials	Density (kg/m^3)	Resin Ratio (%)		Pressure (N/mm^2)	Pressing Time (min)
			Outer Layer	Core Layer		
A	Hazelnut husk	700	10	8	2.4 – 2.6	7
B	Hazelnut Husk	600	10	8	2.4 – 2.6	7
C	Peanut Hull	700	11	9	2.4 – 2.6	7
D	Peanut Hull	600	11	9	2.4 – 2.6	7
E	Cotton Stalk	700	10	8	2.4 – 2.6	6
F	Cotton Stalk	600	10	8	2.4 – 2.6	6
G	Corn Stalk	700	10	8	2.4 – 2.6	6
H	Licorice Root	700	10	8	2.4 – 2.6	6

The values obtained for Modulus of Rupture (MOR) had a minimim of 5.94 MPa and a maximum of 15.67 MPa. He also reported values of Modulus of Elasticity (MOE) between 974 MPa and 2700 MPa as shown in Table 4-6.

Table 4-6: Some of the mechanical properties of composite panels. **Source:** Partial Reproduction based on Güler,2015

Board Types	Density (kg/m³)	MOR (N/mm²)	MOE (N/mm²)	Internal Bonding
A	700	11.90	1547	0.50
B	600	8.18	974	0.34
C	700	9.90	1276	0.31
D	600	5.94	814.4	0.24
E	700	15.67	2705	0.53
F	600	11.40	2004	0.35
G	700	9.13	1419	0.20
H	700	12.00	2142	0.33

Another important resource is a general technical report published by Forest Products Laboratory, Forest services, Department of agriculture (Cai & Ross, 2010), in which a set of values for static bending properties of different wood and wood-based composites were reported upon. The different panel products included hardwood, medium density fibreboard, particle board, oriented strand board and plywood. Table 4-7 shows the values obtained from this report. Comparing them to those in the data sheets of ECOBoard, it is found that ECOBoard sits as a median value between different composite panels. Comparing the provided values of Bending Strength with materials like MDF, OSB, Plywood, Softwoods and Hardwoods, it was found to be surprisingly resistant.

Table 4-7: Static bending properties of some commonly used panel products. **Source: (Cai & Ross, 2010)**

Material	**Static Bending Properties**	
Panel Product	**Modulus of Elasticity (MPa)**	**Modulus of Rapture (MPa)**
Hardboard	3100 - 5520	31.02 – 56.54
Medium-density fiberboard	3590	35.85
Particleboard	2760 - 4140	15.17 – 24.13
Oriented strandboard	4410 - 6280	21.80 – 34.70
Plywood	6960 - 8550	33.72 – 42.61

With this kind of uncertainity faced by the author and with conflicting positions of the material within the spectrum of composite panels, it was critical to initiate a series of simple mchanical tests on the singular sheet material in order to better understand the basic mechanical properties.

The initial tests were performed on the single sheets of the material itself (not in assemblies) to define basic mechanical characteristics. The tests followed loosely the European Norm EN 789:2005 which specifies “Test methods for determining some mechanical properties of commercial wood-based panel products for use in load-bearing timber structures.” It is critical to note however, that the norm was not fully met due to various limitations that will be thoroughly discussed in their relevant positions and elaborated more in Appendix A.

The tests included in the European Norm EN 789:2005 include: bending, compression in the plane of the panel, tension, panel shear and planar shear. According to the scope defined in the norm, the tests shall be performed only once for each panel product, unless there is a reason to suspect a significant change has occurred in the properties of the product.

The reason for following EN789 instead of EN310 for the mechanical properties is that EN789 gives safer values for Modulus of Rapture (MOR). For example, the bending test in EN789 is a 4-point test instead of 3-point test applied by EN310, this guarantees that deflection values are measured in the zone of uniform moment (Figure 4-9). The overestimation of MOR of three-point bending is due to the evaluation point of bending strength and the depth and length of test piece. The evaluation point of bending strength for three-point bending test is located pointwise at the mid-span whereas the four-point bending test is located at the weakest point between the loading noses (Tsen & Jumaat, 2012).

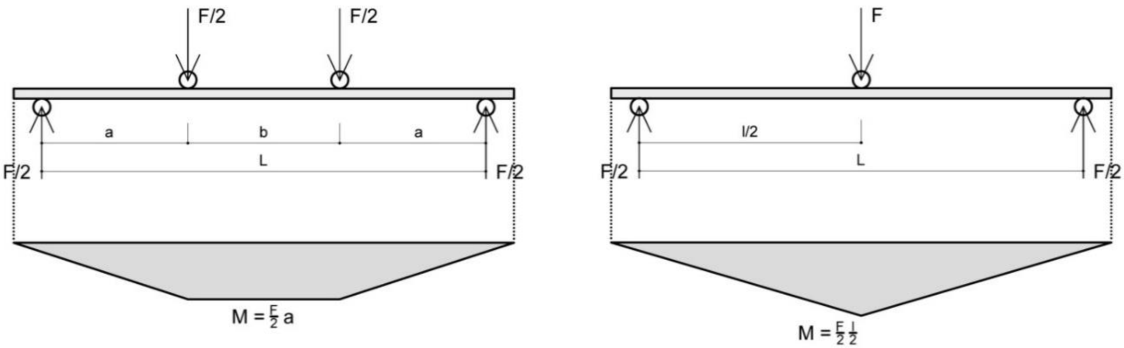


Figure 4-9: 3-point bending vs 4-point bending tests

Due to time and material availability limitations, the author decided to perform the following tests two times in opposite directions with respect to fibre -if any- to verify if the material behaves in the same manner in the two different orientations: 4-point bending, Axial tension, Axial compression.

ECOboards have a moisture content of around 7% at production (ECOboard, 2016). This percentage starts to vary with different ambient conditions during transport and processing. It is important to obtain dimensional stability by processing the material in environments that closely resemble the expected equilibrium moisture content. This equilibrium content is mainly dependent upon the relative humidity and temperature of the environment in which the material is processed. All mechanical tests performed in the laboratory were under ambient temperature, humidity and pressure.

Generally, the standard boards come in various thicknesses: 9, 12, 15, 25 mm and density 500 – 850 kg/m^3 while soft boards come in 12, 35, 40 mm and density 350 to 530 kg/m^3. Standard size panels are 2440 x 1220 mm (8 feet x 4 feet). The median density of the 18 mm thick panels measured in laboratory under ambient conditions is 830 kg/m^3.

The purchased panels came from the vendor already cut in half-size (1200 x 1200 mm) for ease of transportation. It was impossible to define a certain directionality of the fibres of the panels using visual examination. Given the doubts outlined before about the homogeneity of the material composition, and even if two random sheets were chosen, there would be a high probability that both sheets have the same directionality. Therefore, the team decided to always cut the test pieces for every mechanical test from the same sheet in two opposite orientations.

The detailed information on the preparation of test pieces, loading arrangements, methods of measurement and test procedures are thouroughly discussed and elaborated in Appendix A. However in this section only a brief description of the test followed by results and calculated values are mentioned.

4.6.1 4-Point Bending Test

According to the Norm EN789, the test pieces shall be of rectangular cross section, in which the depth is equal to the thickness of the panel (18 mm) and the width is (300±5) mm. The length shall be calculated based on the nominal thickness of the panel. Due to not being able to define the directionality of the panels using visual examination, the two test pieces for the bending test needed to be extracted from the same sheet. This was not possible using the dimensions provided by the norm as the two pieces would not fit into the 1200 x 1200 mm sheet. A reduction of 10% was applied to length and width dimensions of the test piece making its new overall dimensions: 890 x 270 x 18 mm. The same reduction was applied proportionally to all test arrangement. Figure 4-10 shows the test setup used for the 4-point bending test. Two identical test pieces were subject to constant loading rate till failure. More details about the procedure of the tests available in Appendix A.

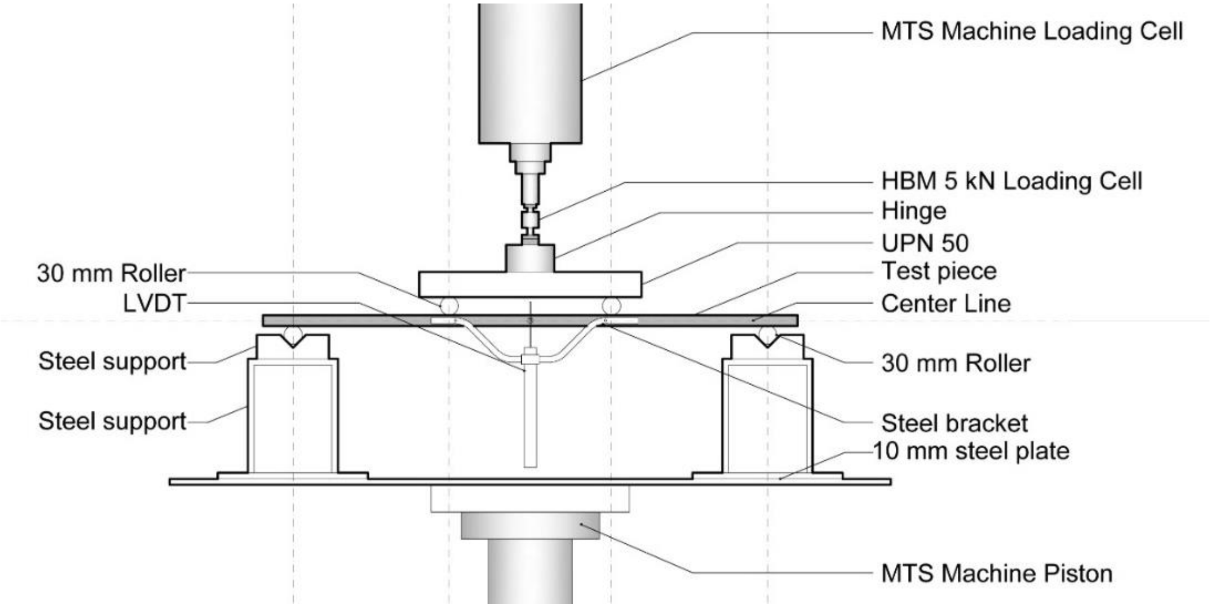


Figure 4-10: 4-point bending test setup

Plotting the graph between Load and Deformation (Figure 4-11), a consistent behaviour of the two test pieces is seen in the elastic zone with an almost identical slope.

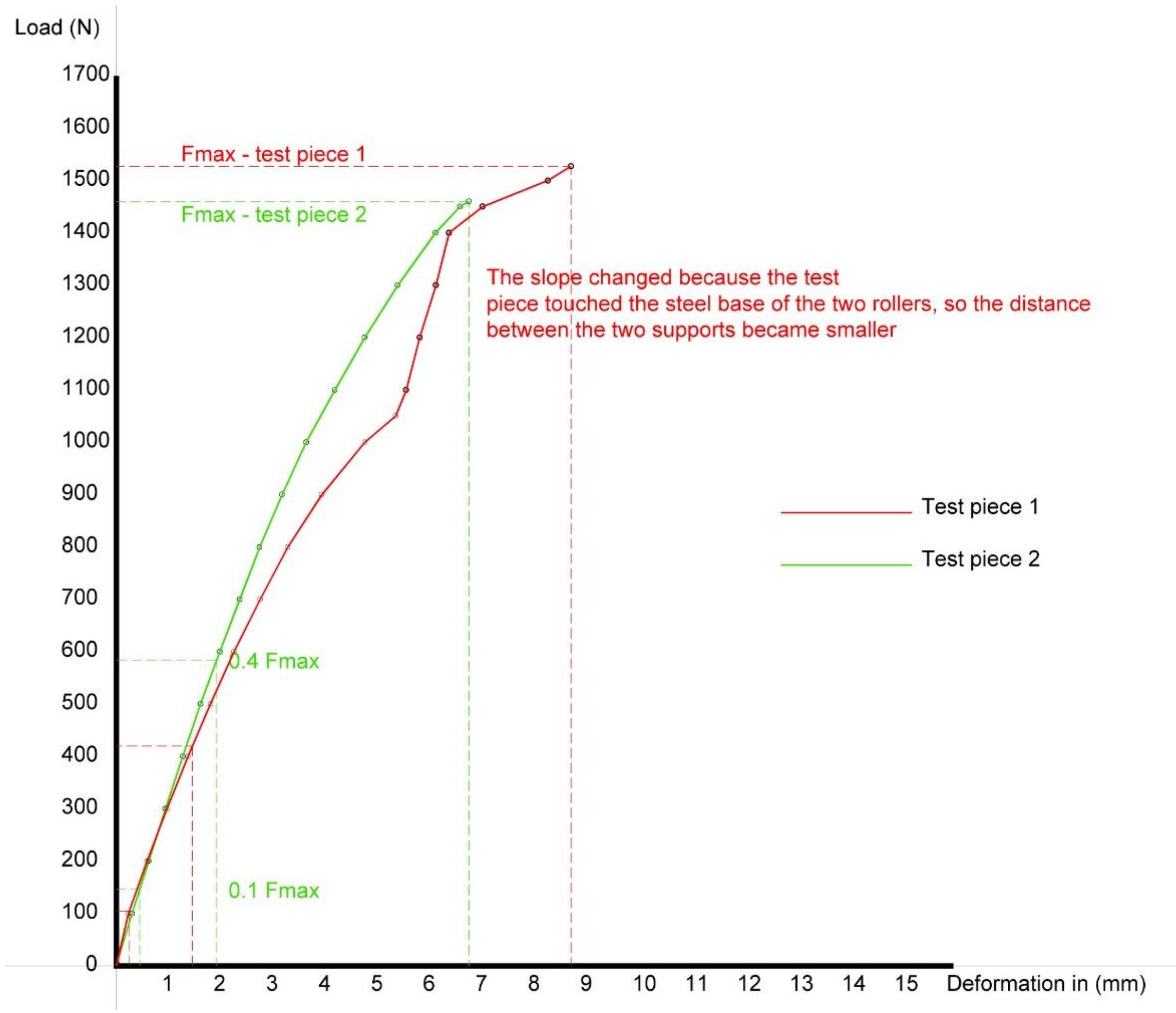


Figure 4-11: Load - Deflection for test piece 1 and 2 in 4-point bending

Figure 4-12: (Left): 4-point bending test setup. (Right): Brittle Material Failure in both test pieces.

The material showed a consistent brittle behaviour for both test pieces at almost the same load as shown in Figure 4-12. Following the equations provided by the norm for the calculation of modulus of elasticity for test piece 1 and 2:

$$E_m = \frac{(F_2 - F_1)l_1^2 l_2}{16(u_2 - u_1)I}$$

$$E_m = \frac{(420-105)(250^2)(260)}{16(1.45-0.24)(131220)} = \mathbf{2014\ N/mm^2\ or\ MPa} \text{.......} \textit{Test piece 1}$$

$$E_m = \frac{(584-146)(250^2)(260)}{16(1.92-0.44)(131220)} = \mathbf{2290\ N/mm^2\ or\ MPa} \text{.......} \textit{Test piece 2}$$

And for calculating bending strength of the test piece:

$$f_m = \frac{F_{max} l_2}{2W}$$

$$f_m = \frac{(1560)(260)}{2(270 * \frac{18^2}{6})} = \mathbf{13.9\ \frac{N}{mm^2}\ or\ MPa}$$

The moment of capacity of the test piece:

$$M_{max} = \frac{F_{max}\, l_2}{2}$$

$$M_{max} = \frac{(1560)\,(260)}{2} = \mathbf{202800\ N.mm}$$

Where

E_m is the modulus of elasticity in bending
F_2-F_1 is the increment of load between $0.1F_{max}$ and $0.4F_{max}$
u_2-u_1 is the increment of deflection corresponding to F_2-F_1
l_1 is the gauge length
l_2 is the distance between an inner load point and the nearest support
I is the second moment of area of the test piece ($\frac{bt^3}{12}$ where b = panel width, t = panel thickness)
W is the section modulus ($bt^2/6$)

4.6.2 Axial Tension Test

Given that the tensile strength of ECOboards was not reported upon in the material data sheet of the supplier, it was critical to understand the behaviour in pure tension with the main aim of optimising the design of the jointing system.

The loading arrangement of the tension test followed the standard method of EN789 which states that the load shall be applied to the test piece uniformly. As for the rate of load application, a constant rate through which maximum loading till failure can be reached within 300 seconds (±120 seconds).

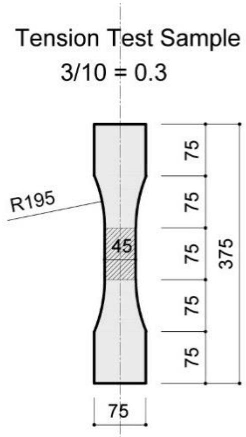


Figure 4-13: Reduced tension test piece dimensions.

Following the norm, the test piece shall have the shape shown in Figure 4-13, but due to testing machine limitation, a reduction to 30% of original size was made to fit the maximum width for the pulling clamps of the equipment (Zwick/Roell Z250). This reduction guarantees a uniform distribution of the pulling force on the cross section of the material and thus a more credible result for the axial tension test. The reduction was made applying a scale factor of (3/10) to the overall dimensions maintaining the proportions of the test piece.

Figure 4-14 shows the test setup where the test piece is gripped between the loading heads of the machine with two 60 mm strain gauges glued on both sides of the test piece. The median strain value was used to plot the graph between stress and strain.

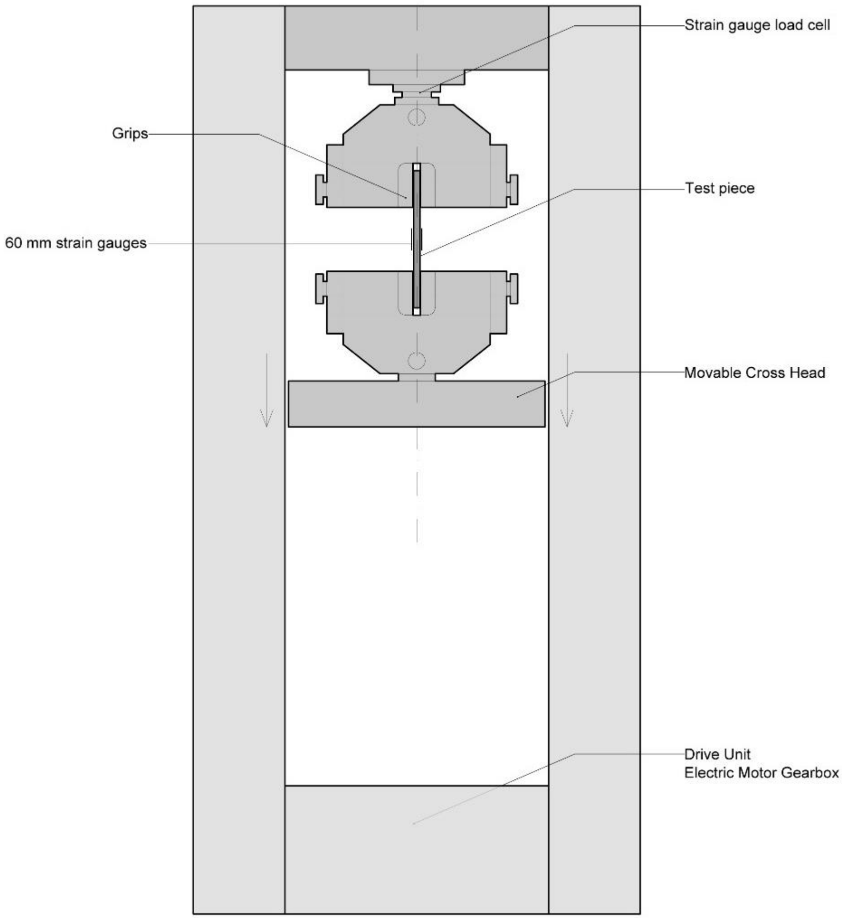


Figure 4-14: Axial tension test setup.

The data obtained from the loading test are time in (seconds), two strains gauge readings at specified time intervals (unitless) and Load in (kN), see appendix A for more details. The two graphs were plotted using the average value of the two strains on the X axis and the stress on the Y axis.

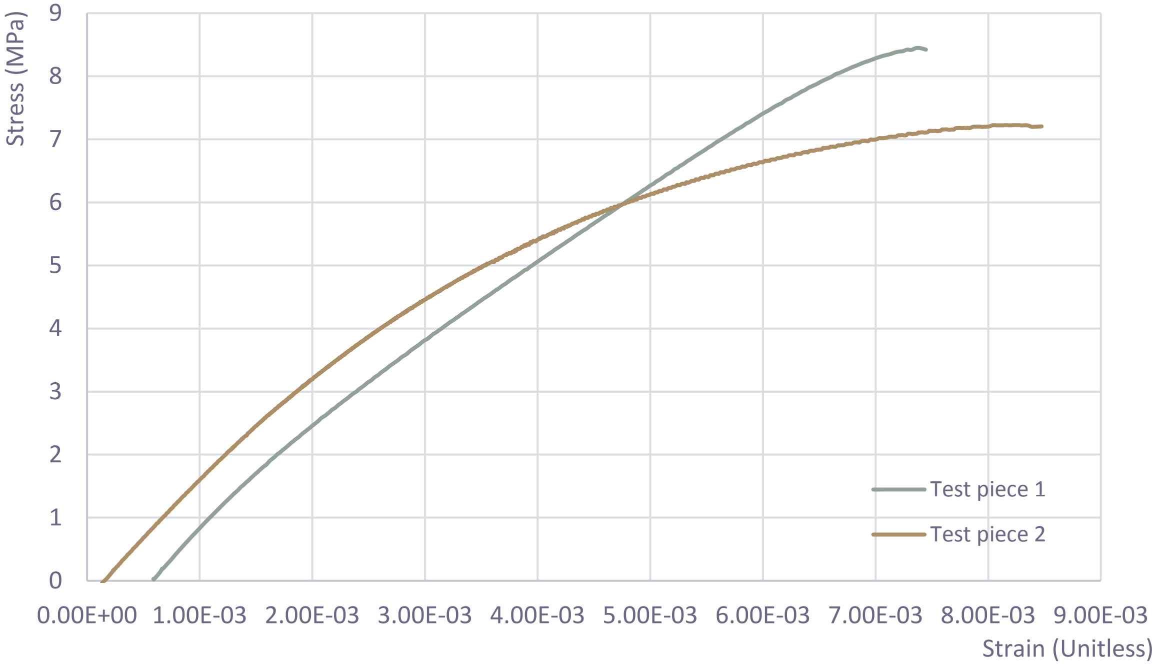


Figure 4-15: Axial tension test results for 2 test pieces in different panel orientations.

In the linear elastic zone of the graph, both test pieces show consistent behaviour. The tension modulus of elasticity of the test piece was calculated according to the formula:

$$E_t = \frac{\Delta Stress}{\Delta Strain}$$

$$E_t = \frac{(\sigma_2 - \sigma_1)}{(\varepsilon_2 - \varepsilon_1)}$$

$$E_t = \frac{(3.368-0.842)}{2.67*10^{-3}-1.01*10^{-3}} = \mathbf{1521\ MPa\ (N/mm^2)}$$ ....*Test piece 1*

$$E_t = \frac{(2.888-0.772)}{1.78*10^{-3}-5.28*10^{-4}} = \mathbf{1730\ MPa\ (N/mm^2)}$$ ....*Test piece 2*

The tension strength f_t of the test piece calculated from the following formula:

$$f_t = \frac{F_{max}}{A} = 6840/810$$

$$= \mathbf{8.44\ N/mm^2}$$

Where

A is the cross-sectional area of the test piece at mid-section
$\boldsymbol{\sigma_2 - \sigma_1}$ is the increment of stress between $0.1\sigma_{max}$ and $0.4\sigma_{max}$
$\boldsymbol{\varepsilon_2 - \varepsilon_1}$ is the increment of strain corresponding to $\sigma_2 - \sigma_1$

It was observed that the failure of the material in tension was consistent with brittle materials as previously shown in bending tests too. Figure 4-16 shows the failure of the two test pieces under axial tension where they failed at almost similar loads (5.50 and 6.80 kN).

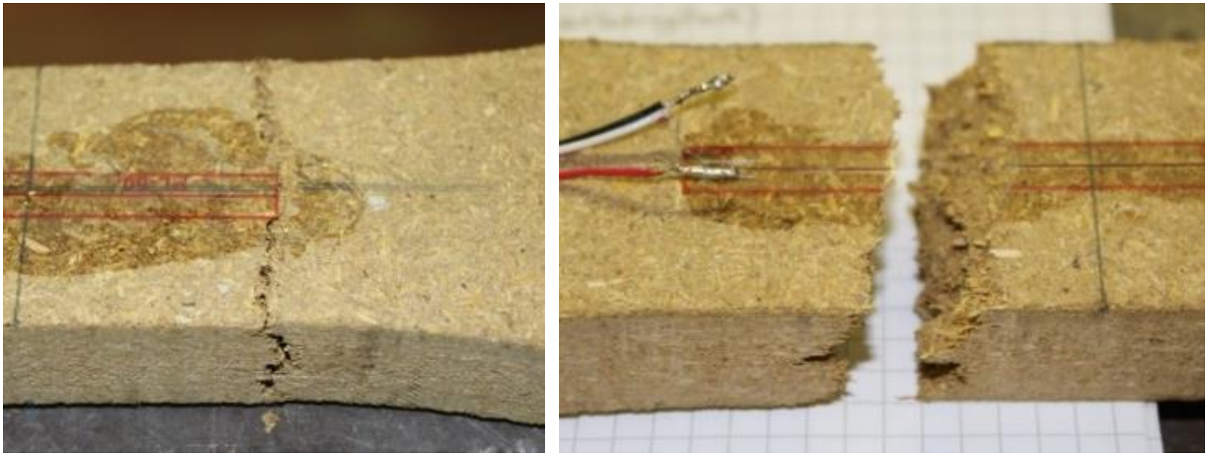


Figure 4-16: (Left) test piece 1 (Right) test piece 2; failure under axial tensile load

4.6.3 Axial Compression Test

Figure 4-17 shows the test setup where the test piece is placed between the loading head of the machine with two 60 mm strain gauges glued on both sides of the test piece. The loading arrangement of the compression test followed the standard method of EN789 which states that the load shall be applied to the test piece through a spherical connection at the top. As for the rate of load application, a constant rate through which maximum loading till failure can be reached within 300 seconds (±120 seconds).

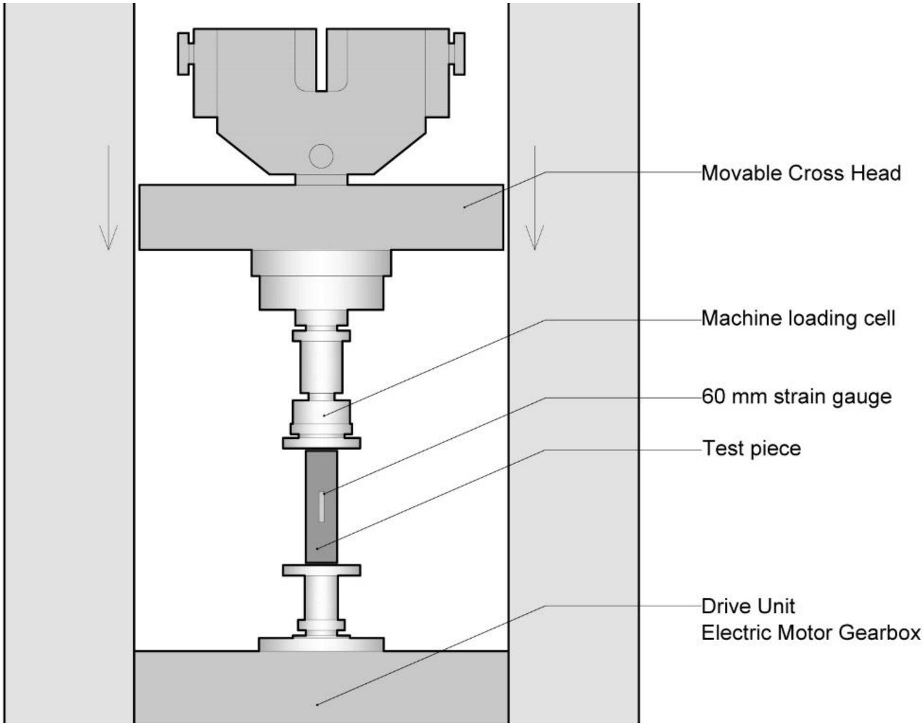


Figure 4-17: Axial compression test setup

The data obtained from the loading test are time in (seconds), two strains gauge readings at specified time intervals (unitless) and Load in (kN), see appendix A for more details. The two graphs were plotted using the average value of the two strains on the X axis and the stress on the Y axis.

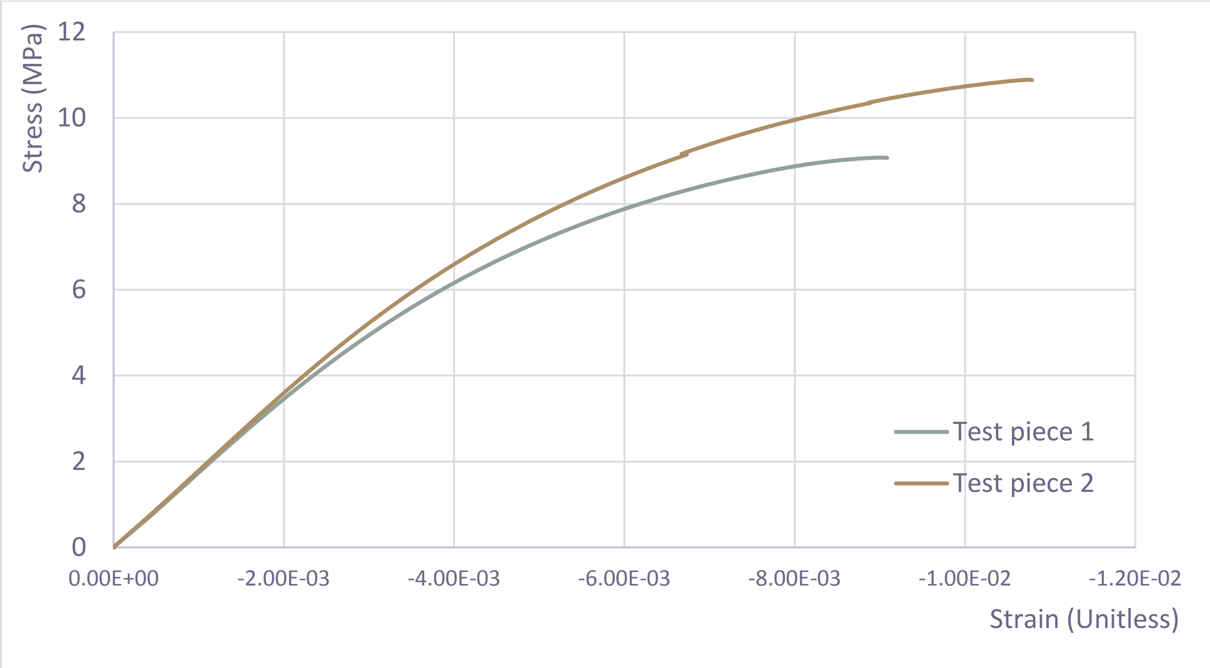


Figure 4-18: Axial Compression test results for 2 test pieces in different panel orientations.

The compression modulus of elasticity of the test piece was calculated according to the formula:

$$E_c = \frac{\Delta Stress}{\Delta Strain}$$

$$E_c = \frac{(\sigma_2 - \sigma_1)}{(\varepsilon_2 - \varepsilon_1)}$$

$$E_c = \frac{(3.628 - 0.907)}{2.10 * 10^{-3} - 5.32 * 10^{-4}}$$ **=1735 MPa (N/mm²)** ....*Test piece 1*

$$E_c = \frac{(4.352 - 1.088)}{2.45 * 10^{-3} - 6.11 * 10^{-4}}$$ **=1774 MPa (N/mm²)** ....*Test piece 2*

Where:

σ_2- σ_1 is the increment of stress between $0.1\sigma_{max}$ and $0.4\sigma_{max}$
ε_2- ε_1 is the increment of strain corresponding to σ_2- σ_1

The Average compression strength f_c of the test piece calculated from the following formula:

$$f_c = \frac{F_{max}}{A} = 41330/3795$$

$$\mathbf{= 10.89\ N/mm^2}$$

It was observed that the failure behaviour was consistent with natural wood failure modes. The first test piece failed with shearing (Figure 4-19– c). The second test piece failed with a combined mode consistent with crushing and splitting (Figure 4-19– e). The material showed a consistent behaviour for the two test pieces with no observable difference between panel orientations. Given the artificial nature of the material being a composite with its characteristics depending primarily on the bonding material (resin) therefore, a coherent result was expected with no major deviations. It came as no surprise that the material performance in compression was better than the performance in tension.

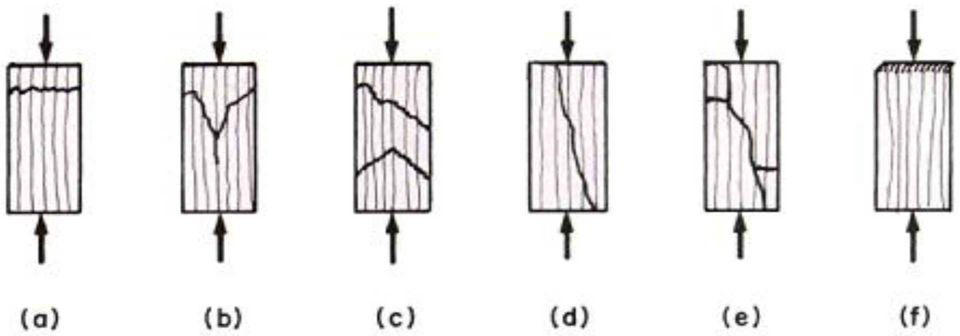


Figure 4-19: Failure types of non-buckling clear wood in compression parallel to grain: (a) crushing, (b) wedge splitting, (c) shearing, (d) splitting, (e) crushing and splitting, (f) brooming or end rolling. **Source:** http://classes.mst.edu/civeng120/lessons/wood/failure/index.html

4.6.4 Interpretation of Results

As previously illustrated through the mechanical tests, ECOboard high density sheet material has a brittle behaviour that can be attributed to its short fine fibres and the dependency of its strength on resin adhesives. The material can be characterised as highly homogeneous with no obvious fibre directionality. Results show almost identical behaviour in opposite panel orientations. Within the elastic zone, the material shows consistent secant moduli of elasticity in tension and compression as the calculated values are almost identical (based on 2 tension tests and 2 compression tests).

It is important to highlight that the results of these tests shall be regarded as only indicative because they have been done only twice due to budget and time limitations of this thesis. However, the results give a good indication and represent an important input for the next phases of the research where the calculated values for elastic and rapture moduli will be used as inputs for further joint detailing and dimensioning.

4.7 Initial verification of design system

In order to understand if these load bearing wall assemblies can function in a structural manner and to define the internal variables of one wall assembly such as the number of vertical studs, a preliminary structural analysis was essential to perform using rough preliminary calculations. This analysis hereby aims at defining the average expected loads that the wall assembly shall be designed to bear. The four housing schemes shown previously in Figure 4-8 were used as reference scenarios to perform this exercise.

The load scenario is to calculate the overall forces (Dead and Live loads) from the reference schemes and divide them by the sum of wall lengths comprising each residential unit. This is done in order to have a rough approximate figure of the loads that the unit length of wall assemblies shall be designed to bear. It is clearly understandable that design loads are not usually uniformly distributed and they shall accommodate for worst case scenarios and critical loads. However, this preliminary exercise is not by any means a substitute of a detailed structural analysis that is case-specific.

The design input loads have been stabilised at the following values based on common practice in residential structural calculations.

- Live Load (L) for residential buildings = 2 KN/m^2 (200 kg/m^2)
- Dead Load (D) based on average slab and finish materials = 2 KN/m^2 (200 kg/m^2)
- Wall thickness of 200 mm was used as a standard dimension.

4.7.1 Calculation Scenario:

The wall composition is based on using 18-mm thick boards for the whole assembly as shown in Figure 4-20. In this configuration, the effective area for load bearing is calculated as the sum of lengths of cut sections multiplied by board material thickness (18 mm) which results in 0.042 m^2. By calculating the areas of each of the four residential schemes and the perimeter of walls (internal and external), we can predict the load per unit length of the wall using the following equations:

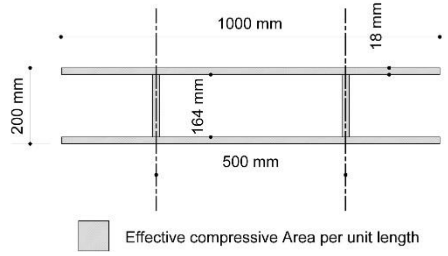


Figure 4-20: The effective compressive area per unit length based on a preliminary assumption of vertical stud spacing of 500 mm and material thickness at 18 mm.

Total Load = Area of residential unit x Dead and Live Load
= 45.50 m^2 x 4 KN/m^2 = 182 KN

Equation 1

Effective Compression Area = Sum of wall lengths x Effective load bearing area per unit length of wall
= 41.1 m x 0.042 = 1.72 m^2

Equation 2

By dividing total load (Equation 1) by effective compression area (Equation 2), the load per unit area that the wall is expected to bear can be calculated.

Load per unit area = Total Load / Effective Compression Area
= 182 KN / 1.72 m^2= 105.40 KN/m^2

Equation 3

The commercial data[4] sheet of the 18-mm thick ECOboard does not set a value for the compressive strength of the material. Instead, it gives a value for modulus of rapture in bending (MOR) to be around 38 MPa (38000 KN/m^2). According to the results of the axial compression test performed by the author in both panel orientations, maximum pressure that the material can resist is around (10 MPa - 10000 KN/m^2). Comparing this value to the value obtained from Equation 3 (105.4

[4] These values were obtained from the material leaflet sent to the author upon request via email. It is available as an attachment to this thesis (Appendix B)

KN/m²), we can safely say that the material's capacity to handle axial compressive stresses gives the designer a considerably large margin for safe design. It is understandable that the maximum load that the wall section is capable of supporting is not a function of the material stress capacity only, it is related to its geometrical aspects and overall configuration. This is what lead to an extra verification where the geometrical aspects of the cross section are considered.

4.7.2 Extra Verification

Assuming the vertical wall assembly to be a free-standing column of dimensions 1000 * 180 * 2800 mm, an extra verification is made which is to calculate Euler's critical load on the components of the previous cross section to predict the maximum load that it could bear before buckling. The following assumptions are made while using Euler's formula:

- The material of the column is homogeneous and isotropic.
- The compressive load on the column is axial only.
- The column is free from initial stress.
- The weight of the column is neglected.
- The column is initially straight (no eccentricity of the axial load).
- Pin joints are friction-less (no moment constraint) and fixed ends are rigid (no rotation deflection).
- The cross-section of the column is uniform throughout its length.
- The direct stress is very small as compared to the bending stress (the material is compressed only within the elastic range of strains).

For one vertical runner with the cross section of 18 mm x 164 mm and area = 2952 mm², the area moment of inertia is calculated following this equation:

$$I = \frac{bh^3}{12} = \frac{164 * 18^3}{12} = 79704\ mm^4$$

The two-dimensional radius of gyration is used to describe the distribution of cross sectional area in a column around its centroidal axis. The radius of gyration is given by the following formula:

$$i = \sqrt{\frac{I}{A}} = \sqrt{\frac{79704}{2952}} = \sqrt{27} = 5.196\ mm$$

Assuming two cases, the first case where a vertical runner of height 2800 mm (average residential floor height) is a free-standing, unsupported length. The ratio of the effective length of a column to the least radius of gyration of its cross section is called the slenderness ratio and is given by the following equation:

$$\lambda_{2800} = \frac{h}{i} = \frac{2800}{5.196} = 538.87$$

Therefore, the critical compression stress can be calculated according to the following equation:

$$\sigma_{critical} = \frac{\pi^2 E}{\lambda^2} = \frac{(3.14)^2(1700)}{(538.87)^2} = 0.0577 \frac{N}{mm^2}$$

And the critical load:

$$P_{critical} = \sigma_{critical} * Area = 0.0577 * 2952 = 170.33\ N = 0.17\ kN$$

This value is notably small which is understandable given the very thin cross section of the vertical runner. Therefore, another assumption is made where fixation points are assumed at a vertical spacing of 400 mm so that the vertical runner becomes constrained at this interval.

$$\lambda_{400} = \frac{h}{i} = \frac{400}{5.196} = 76.98$$

Therefore, the critical compression stress can be calculated according to the following equation:

$$\sigma_{critical} = \frac{\pi^2 E}{\lambda^2} = \frac{(3.14)^2(1700)}{(76.98)^2} = 2.828 \frac{N}{mm^2}$$

Where E = modulus of elasticity of column material (calculated from two lab compression tests, See section 4.6.3)

And the critical load becomes:

$$P_{critical} = \sigma_{critical} * Area = 2.828 * 2952 = 8348.25\ N = 8.34\ kN$$

This value is much higher and more credible as the components of the cross section of the wall assembly are not expected to perform separately, instead, they are expected to perform better when put into a complex assembly increasing the overall performance. Two vertical runners would be able to support 8.34 kN each, thus raising the overall sum to 16.68 kN. With the collaboration of the sheathing panels to the overall capacity of the system in compression, we can safely say that the overall assembly can be highly resistant for its intended residential purpose.

The question here is not only about the materials capacity to resist vertical compressive loads, it is understandable that more complex forces and local stresses will be acting on the wall assemblies, therefore further analysis and tests are needed to test the stability of the proposed construction system.

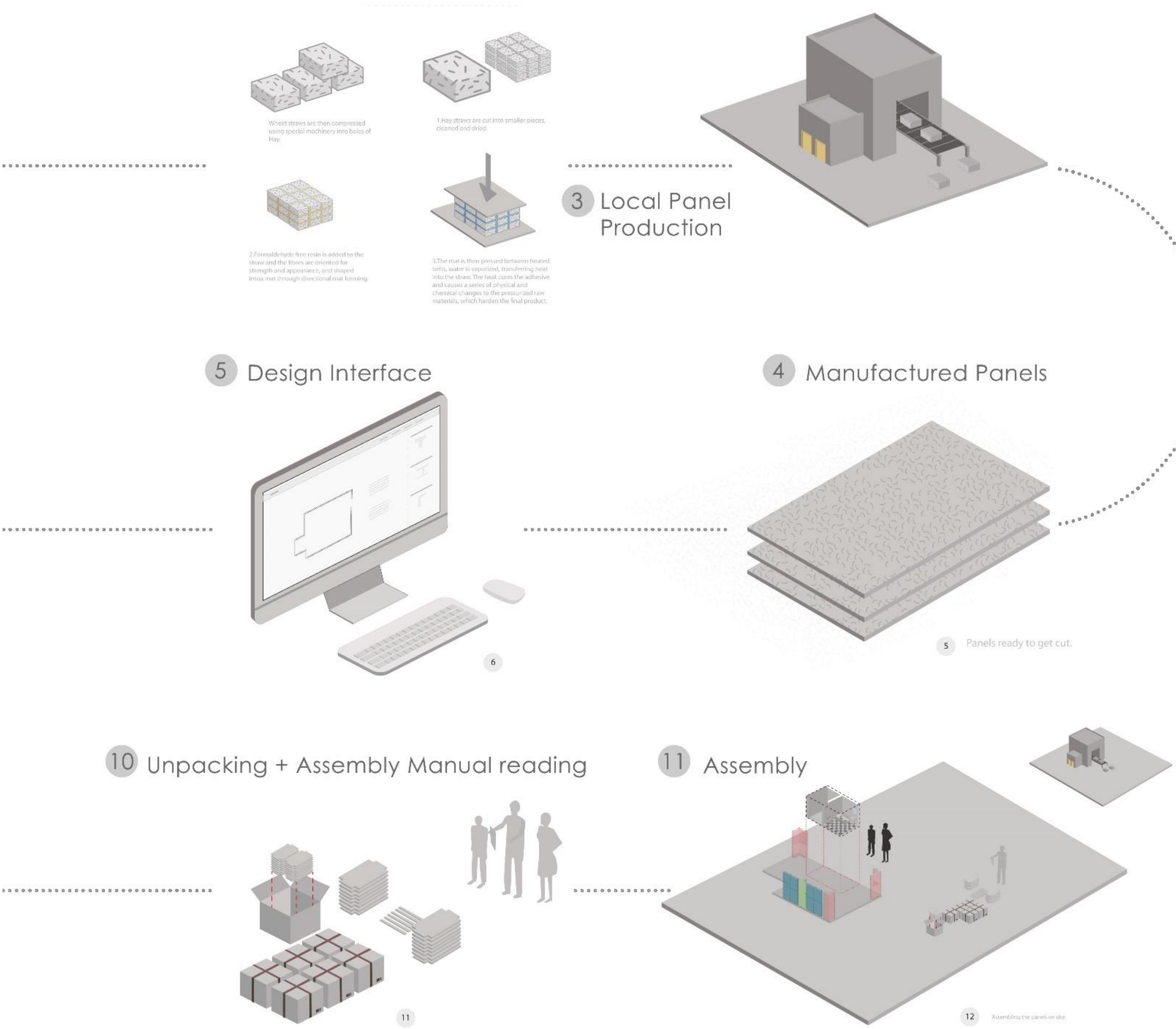
4.8 Summary

This chapter demonstrated a set of critical design considerations that are seen as fundamental for the success of low-cost housing projects in the light of analysing state of the art projects. It then discussed how the proposed "Housing System 01" would respond to these considerations within the framework of a mass customised solution. The diagram in the next two opposite pages describes the process of housing realisation as imagined through "Housing System 01".

Defining the "selection of a local material" as one of the most important aspects for better control over costs, a set of experimental mechanical tests were initiated to characterize high density ECOboard wheat straw panels and understand their capacity to represent a viable alternative for timber panels widely used in housing in general and in digitally fabricated housing in specific. Within the outlined vision of creating modular assemblies that are load-bearing using this specific material as the core material, it was important to verify if this was feasible from a structural point of view. Simple theoretical schematics and calculations were performed in which the material promised a wide margin for safe design.

Upon these understandings, the next chapter will start detailing a specific integral jointing system with no glue or mechanical attachments and afterwards test it as principal joining within the individual wall assembly and between different wall assemblies.


1 Harvesting wheat
2 Wheat Straws
7 Flat Packing
6 Numerical Control Cutting
8 Panels are packed into cardboard boxes and transfered to the construction site.
7 A panel is loaded into the CNC machine, then the head starts to cut through the panel -according to the provided design- creating the different ****
8 Prefab Core and Flat Panels Shipping
9 Onsite foundation
Prefab core placement
9 Shipping the panels to the
10 Unpacking the panels at the construction site.


Wheat straws are then compressed using special machinery into bales of Hay.
1.Hay straws are cut into smaller pieces, cleaned and dried.
2.Formaldehyde free resin is added to the straw and the fibres are oriented for strength and appearance, and shaped intoa mat through directional mat forming.
3.The mat is then pressed between heated belts, water is vaporized, transferring heat into the straw. The heat cures the adhesive and causes a series of physical and chemical changes to the pressurized raw materials, which harden the final product.
3 Local Panel Production
5 Design Interface
4 Manufactured Panels
6
5 Panels ready to get cut.
10 Unpacking + Assembly Manual reading
11 Assembly
11
12 Assembling the panels on site.

CHAPTER 5 | Joinery Design

5.1 Introduction

Joinery is a part of woodworking that involves joining together pieces of timber or lumber, to produce more complex items. Some wood joints employ fasteners, bindings, or adhesives, while others use only wood elements (integral joining). One consequent product of timber framing is joint, which has one or more of the following functions: arranging the loads, achieving a certain form or scale, displaying pleasant decorative effect, etc. (Cao, 2015). A notable thing about joints is that, although their designs are affected by various factors, the most fundamental concern must be their structural functions in the frame. Performance of timber structures predominantly depends on the efficiency of the connections (Aicher, 2014).

This chapter presents a quick overview of classical joinery used in timber construction. It is then followed by the inspirations for the design of the principal joinery detail used in the construction of "Housing System 01" wall assemblies. The final part of the chapter deals with the step-by-step detailed design of snap-fit joints, which is a typology of joint widely used in consumer products in plastics. The detailed design follows the design manuals of BASF and BAYER plastic manufacturers. The mechanical values of the material obtained through laboratory testing have been employed for the numerical calculations and dimensioning of the snap-fit joint.

This chapter will attempt to revisit traditional joinery details in the light of using CNC machining and agricultural residue panels. While (Robeller, Mayencourt, & Weinand, 2014) have already addressed design considerations for the design of snap-fit joints in Laminated Veneer Lumber (LVL) panels, the application of these joints to agricultural residue panels is open to investigation. The author will attempt to answer the question of whether snap-fit joints can be used in a structural manner in a wall assembly made of wheat straw. What is the structural performance of such assemblies? It is expected that the joints will behave differently when compared to LVL or CLT sheets as the material composition, bonding, homogeneity and internal structure are different. What are the best performing joints which can inform the design of the housing construction system?

5.2 Wood joinery background

There is perhaps no more evident example of how joinery techniques of timber structural members can be complex and efficient than the Japanese classical joinery. There are various ways to join timber members. Beams can be tied with ropes, carved and assembled or connected with nails, screws and glue. Joining is a practice that depends on high level craftsmanship to be able to build these structures. Master jointers were dedicated craftsmen responsible for splicing and connecting elements of a building. Many factors had to be considered. The connections had to be strong enough to transfer forces such as bending, torsion and shear, yet appearance was as important. A variety of techniques sometimes simple, sometimes complex were developed. The solutions adapted in Japanese joinery can only be described as spectacular, as they took into account time dependent processes, such as shrinkage or slippage caused by dynamic loading.

The book "Wood Joints in Classical Japanese Architecture" by (Sumiyoshi & Matsui, 1991) presents a detailed study of splicing and connecting joints in the traditional Japanese architecture. The main objective was to transfer the implicit knowledge to the next generation of craftsmen and to protect the accumulated knowledge from being lost. The authors of the book performed structural testing on the joints they presented to understand the failure behaviour. They clearly stated in the beginning of the book that the use of these joints in contemporary architecture is yet to be evaluated. The book only describes the original characteristics of the joints. Some modifications might be required to make them effective for today's building technology.

Moreover, it is important to note that all performed tests were done on joints built using natural wood lumber sections which have characteristics that are quite different to manufactured Cross Laminated Timber (CLT) or Laminated Veneer Lumber (LVL) and above all Agricultural Residue Panels. Thus, the reinterpretation of these joints in contemporary architecture using new enabling tools of information and fabrication represents a new pool of possibilities for building construction.

Many of the traditional Japanese joints relied heavily on the precision of the craftsmen in measuring, cutting and aligning pieces together in perfection; a concept that still holds in the field of digital craft. The tools of computer numerical controlled fabrication allow precision processes to be applied and repeated to different parts which in turn guarantee better quality control and high accuracy construction.

5.2.1 Traditional Wood Joints

A broad categorisation of wood joints is: permanent and temporary. Joints can be categorized in numerous ways based on their application, typology, geometry or many other different criteria. Due to the vast variety of joints that were and are still used in building construction, categorisations are neither comprehensive nor inclusive of all possible joints. Typologies of joints include integral joining, fasteners or adhesives. Some literature categorises joints based on their geometrical configurations such as lengthening joints and intersecting joints. Others refer to end-end, end-edge and edge-edge joints. Most of the widely-used wood working joints can actually be categorized under more than one of the previous categories.

The following figure shows some of the most common joints in wood working used in furniture applications and some structural applications. Other nomenclatures are often used to refer to the same joint. For instance, in Figure 5-1, the joint "Through Dado" on the uppermost left corner is usually called a "Housing Joint" in different references. "Glue Joint" is referred to as "Butt Joint".

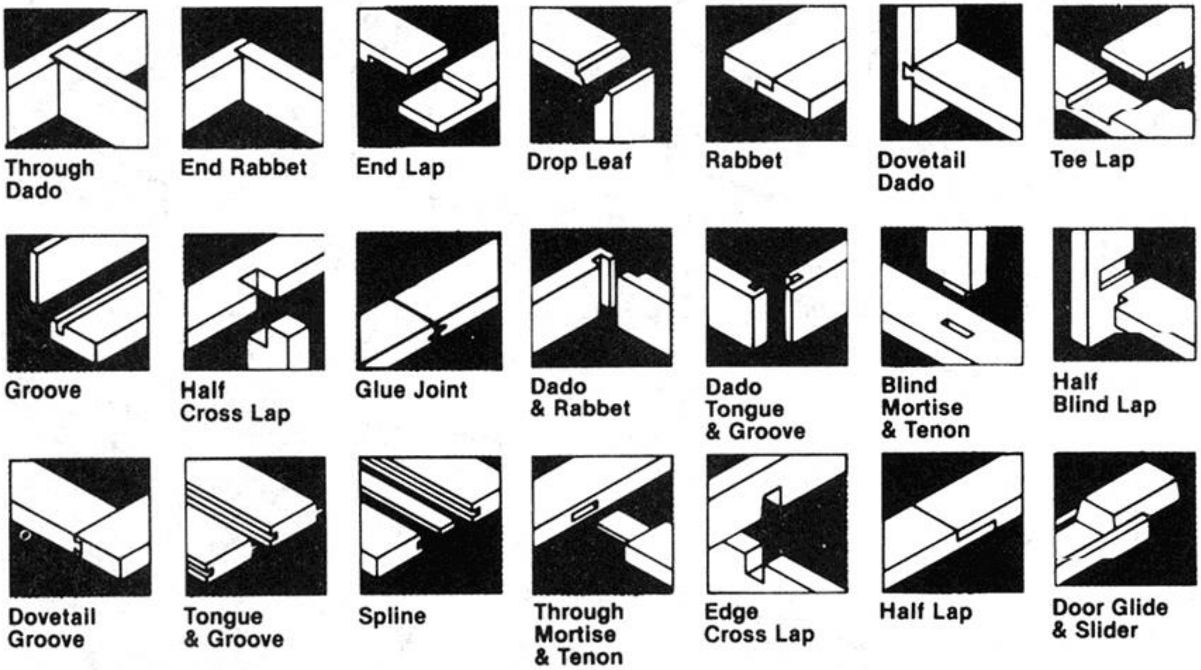


Figure 5-1: Most Common Traditional Wood Joints **Source:** http://www.core77.com/posts/43001/Reference-The-Ultimate-Wood-Joint-Visual-Reference-Guide

As previously mentioned there is a great number of joints that are used in different applications of wood working. The author found that there are eight joints that can be considered the most common in building construction, doors, windows and furniture applications.

1- **Butt Joint:** For the creation of a butt joint, the end of a piece of wood is placed against another piece and fastened either using a metal clip, a nail or a screw. Butt joints are stable and can hold up fairly heavy loads. In combination with metal fasteners, it is widely used in framing construction.

2- **Mitred Butt Joint:** The mitred butt joint is very similar to the standard butt joint, in that it typically joints two boards or profiles at their ends, or one board at an end meeting the side of another board. The difference is in how those ends meet. In a standard butt joint, the end or ends meet at a 90-degree angle. In a mitred butt joint, the end or ends are cut to a 45-degree angle. The angled boards or profiles are secured together either with nails or screws, and are often easier to fasten to one another than a standard butt joint as the screw is inserted perpendicularly and not inclined.

3- **Half Lap Joint:** The half lap joint is normally used when two pieces of wood need to be joined in the middle, rather than on the ends. To create this type of joint, a small notch needs to be created in each of the two boards. The notches then fit together to join the boards. Depending on how tightly the notches are cut, you may not need more than a small amount of wood glue to hold them together. Obviously, because some of the wood is being removed from each of the boards, this does result in a slightly weaker join than some other types. However, because they allow you to join the boards in the centres, rather than on the ends, this can be an ideal way of creating some types of frames.

4- **Tongue and Groove:** The tongue and groove joint can be considered the most widely used in all types of wood working. This type of wood joint holds two boards or profiles together along their edges, rather than their ends or in the centre. In a tongue and groove joint, the edge of one board is notched out into a groove. The edge of the joining board is extended into a thin tongue that fits the groove. Often both tongue and groove are curved slightly so that the tongue needs to enter the groove at an angle. When the boards are laid side by side, they “lock” together and cannot be separated unless one is lifted up at an angle first.

5- **Mortise and Tenon:** The Mortise and Tenon joint is one of the oldest forms of wood joints used till present time. Like the tongue and groove joint, it involves one board or profile being fitted inside of a second board. The mortise is a square hole carved into the side of a board. The Tenon is a protruding piece coming off the end of a second board. The Tenon fits very tightly inside the mortise, extending through to the other side of the mortised board. This type of joint is very useful for creating trestle tables and exposed beams where nails would detract from the beauty of the workmanship.

6- **Dado Joint (Housing Joint):** The dado is a simple joint with most applications in furniture making. Like the tongue and groove joint, it involves a notch cut into one board where the other board will fit. Unlike the tongue and groove, however, this type of joint joins the edge or end of one board to the center of another. It's often used in joining two pieces of plywood together, or for putting together the backs and sides of cabinets and dressers with the top.

7- **Rabbet Joint:** The rabbet joint is a dado cut along the edge of a board, rather than into the centre of it. It's usually used for joining cabinets or for making boxes where two edges need to fit together tightly. It has different variants according to the specific application needed.

8- **Dovetail Joint:** The dovetail joint is one of the most beautiful and frequently sought-after joints in furniture and cabinet making. The joint is considerably strong and relies on the workmanship; no nails or metal fasteners are required. To make a dovetail joint, notches are cut into the ends of two boards. The notches are precisely detailed so that they will fit together very tightly. Due to the tight fit of the notches, this type of joint rarely comes loose, so the finished piece can often sustain very heavy use.

This specific joint (Dovetail) is of interest for further analysis due to its aesthetic and rigidity. With the proliferation of digital tools, these joints can be re-interpreted and reproduced by means of digital tools. Some detailed aspects of the joint are to be revisited but the basic concept remains the same.

5.2.2 Integral Joining

Out of all types of joints, emerges the question of why use specifically integral joining. Integral attachments are believed to be the oldest known method of joining. Rigid interlocks form one category of this general concept, including connections like mortise and Tenon, finger or dovetail joints, which were common handcrafted joining techniques in traditional carpentry and cabinetmaking as previously illustrated. However, with the industrialisation and its proliferation of machine-tool-technology, these joints were widely replaced by mass-produced metal plate connectors and fasteners. Only recently, the increasing use of information-tool-technology in timber construction companies and Application Programming Interfaces for the algorithmic generation, analysis of integrated joints, has caused a resurgence of integral attachment techniques (Robeller, Mayencourt, & Weinand, 2014).

As part of striving towards economy within this research, integral joining represents a logical direction to pursue and further explore, because the characteristics and behaviour of the joint are embedded into its geometrical shape. Efficient joints are considered to possess a shape that has optimal strength and deformation properties within the context of their function. Joint efficiency is a relative criterion, which is obtained by shape optimisation (Vischer, 2015). This in turn translates to saving on material and labour involved in fabrication off-site and assembly of the joint on-site. Moreover, joints fabricated from flat panels offer the flexibility of being easily machined into irregular shapes. Other advantages also include reducing the number of pieces, reducing suppliers, maintaining less shipping and handling. Nevertheless, it also has some disadvantages such as more up-front engineering, possible break during or before assembly.

Elastic interlocks represent one important category of integral attachment techniques. While snap-fit joints are a common attachment technique in the consumer electronics, plastics and automotive industry, possible applications for the jointing of timber panel structures have been rarely studied. Snap-fits are also considered an environmentally friendly form of assembly because of their ease of disassembly, making components of different materials easy to recycle.

5.3 Jointing concept

As shown before, the approach used for the design of “Housing System 01” is based on a logic in which wall assemblies are designed to be load bearing structural members. The constructive logic is based on stand-alone hollow cassettes that are assembled to the neighbouring ones using snap-fit easy-to-disassemble joints.

Generally, the position and orientation of a given rigid body in space is defined by three components of translation and three components of rotation, which means that it has six degrees of freedom. The design of the joint started from analysing and understanding the degrees of freedom of a standard lengthening dovetail joint. As shown in Figure 5-2 in a standard dovetail, translation is limited in two axes – in this case vertical Z and horizontal X but is completely free in Y. For the same joint, rotation is restricted only around Y axis but free around X and Z axes. (Therefore, the degree of freedom of this joint is 3). The design then moved one step further and evolved into more complexity. A “lapped dovetail” joint that is mainly used in furniture and cabinet making was also analysed. This joint, constraints the translation in X, Z axis and one of the Y directions as the joint can be disassembled moving the component on the right in the positive direction of Y axis maintaining the other component in-place.

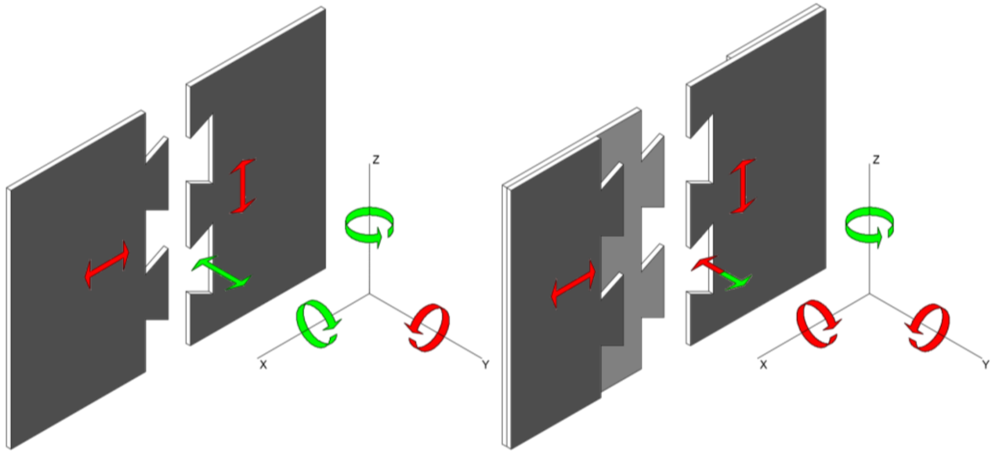


Figure 5-2: A diagram showing the degrees of freedom of a standard dovetail joint (Left) and a lapped dovetail joint (Right). Red arrows show restricted movement while green arrows show freedom.

While this joint represents an interesting approach towards the jointing of two wall assemblies, however it poses a big challenge from a constructability and handling point of view when scaled to full-size. Despite the strength provided by the dovetail shape which limits movement in X axis, being only able to install a wall assembly to the neighbouring one from one side (either internal or external) represents a strong limitation.

The author had always outlined and sketched ideas in which snap-fit joints would be the only type of joint used for assembly. However, with further analysis and literature review on snap-fit joints a decision was taken to mix snap-fit with friction-fit (tab and slot) joints. This was due to the fact that while snap-fit joints can resist a certain retention force, they do not provide any shear resistance. Generally, the snap-fit joint is considered as a special type of tab-and-slot-joint, with an integrated retention feature (Robeller, Mayencourt, & Weinand, 2014).

In order to be able to scale up these joinery concepts to the full-size wall, extra considerations had to be made. With more complex forces and stresses to consider in a structural wall assembly, and with the intention of using only integral joining, the design of the joint evolved into a double sided lapped joint with a non-protruding snap-fit key insert/spacer as shown in Figure 5-3. Snap-fit joint is not only used to retain the components of the wall assembly itself but it is also used to maintain two wall assemblies using the key inserts/spacers.

One of the various design iterations shown in Figure 5-4 utilised a non-protruding cantilever arm. However, this solution was disregarded as the brittle nature of the material will make the joint very delicate. The edge that maintains the assembly has a thickness equal to half the material thickness (9 mm) which is very delicate to maintain the expected pulling forces. A decision was then made to use protruding cantilever arms with the understanding that the wall assemblies will be further covered in interior and exterior claddings for final finish and weather proofing.

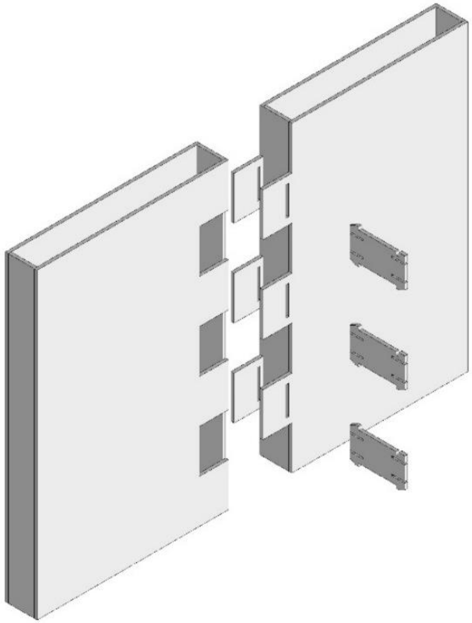


Figure 5-3: (Right) An intermediate development of the joint where the concept of key inserts/spacers was first introduced.

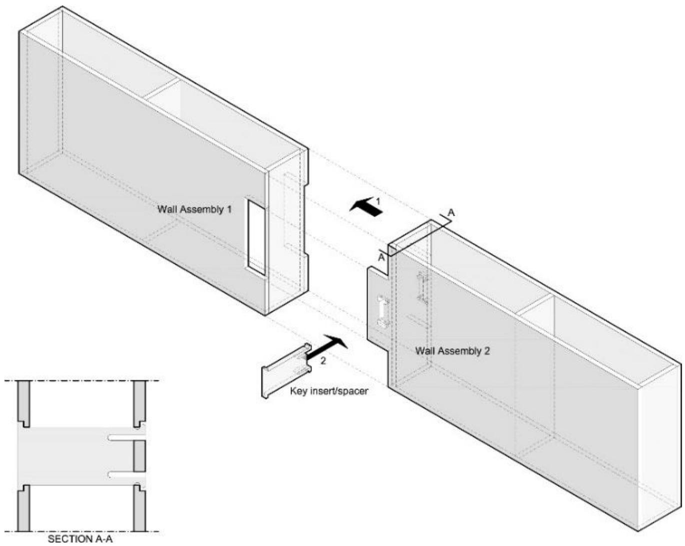


Figure 5-4: (Left) One of the later iterations and developments of the joint between two straight walls. Section A-A shows the non-protruding key insert.

Figure 5-5 shows an exploded view of a straight wall assembly where the two vertical runners are designed as continuous members to which interior and exterior sheathing panels are attached using snap-fits and friction fits. In this case, the sheathing panels contribute to the load-bearing capacity of the whole as shown previously in the structural schematics in section 4.7.1 and 4.7.2. If a wall assembly higher than 2400 mm -the stock sheet maximum height- is required, a vertical lengthening (S) joint is used within the vertical runner and has to be positioned so that it is not aligned with the sheathing joints in order to maintain stability and avoid weak zones.

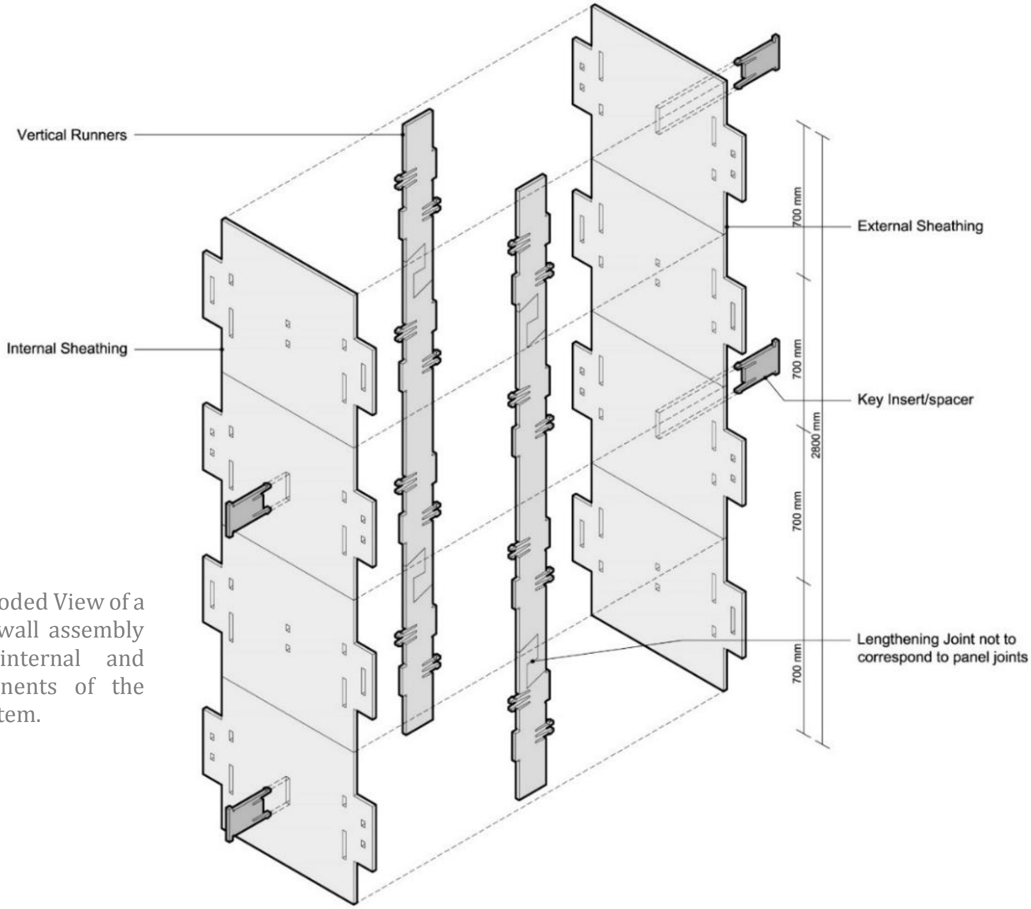


Figure 5-5: Exploded View of a typical straight wall assembly showing the internal and external components of the construction system.

A similar lengthening joint is used in the basic structural C-section of WikiHouse, which is the basic module for all WikiHouse prototypes. The joint needs no locking feature because the runner is kept in place and aligned by the slots in the sheathing panels. While the datasheet values of mechanical behaviour show the wide capacity of the material against different stresses, the wall assembly is expected to magnify the ductile behaviour of the overall structure through joint tolerances.

Given that construction systems that depend on compression contact surfaces like CNC-cut plywood structures tend to be subject to highly irregular mechanical behaviour (Vischer, 2015), the physical prototyping of these joints becomes a must to verify the viability of using them in a structural manner.

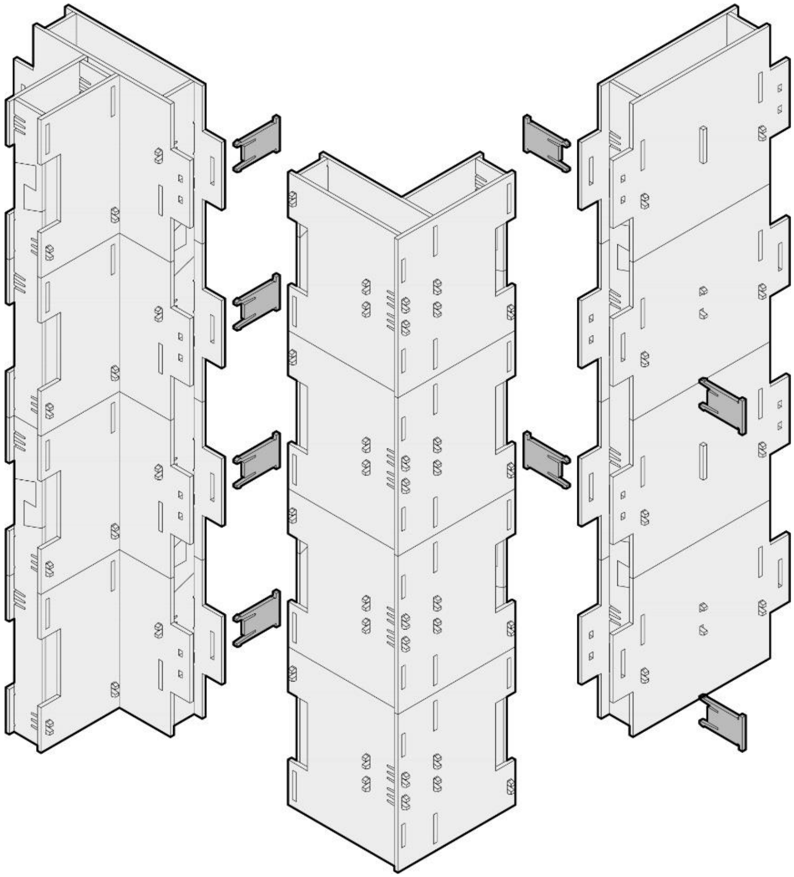


Figure 5-6: A diagram showing one possible instance of the 3 main wall typologies. Key inserts are used as spacers within each wall assembly and as locking features between different wall assemblies.

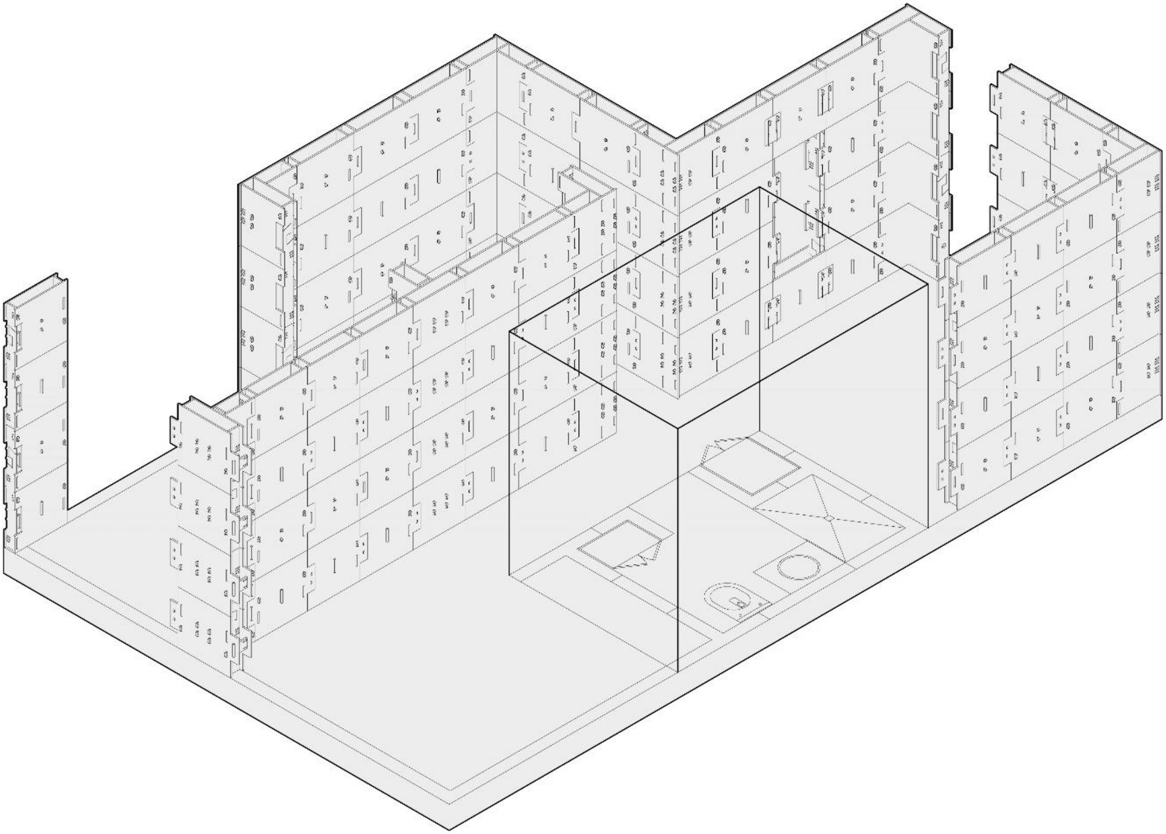


Figure 5-7: A schematic showing the use of the different components of Housing System 01 in one housing unit.

The bottom-up approach that was adopted through-out the design of the housing system and further into the experimentation phase necessitated focusing the study on some certain aspects while postponing others. This was done to avoid adding too many factors and layers of complexity to the design system at this initial phase. For example, the wall-floor and the wall-ceiling attachments were not studied in detail.

In the following section of the chapter, a detailed design of the snap-fit joint is presented following the design guidelines and best practices adopted by major plastic manufacturing companies like BASF and BAYER. A notable limitation was met by the author in this phase of the research as the literature resources about snap-fits in materials other than plastics are quite limited. However, the basic design considerations are mainly the same. Later in the chapter, the author attempts to point out special considerations for CNC milling that inform and affect the design of the joint in the digital model. This might be an implicit knowledge or even a well-established knowledge in building construction using standard plywood sheets; but when it comes to less adopted agricultural residue panels, the behaviour of the material in machining, edge conditions and tolerances is still open to exploration.

5.4 Detailed snap-fit joint design

A Snap-fit joint consists mainly of one male part and one female part. The temporary bending of the cantilever part allows for the fit of the two pieces using the material's elastic behaviour. After the joining operation, the two parts return to a stress-free state (Robeller, Mayencourt, & Weinand, 2014).

The joint calculations/dimensioning can be approached in two different ways. Material first: were a material has been already chosen with known allowable strain and then dimensions are designed to fit it. Dimensions first: were primary dimensions are fixed and then a material research is performed to select an appropriate material that allows using those dimensions. In our case, a material selection has been already done, so the next stage is to define the proper dimensions for the joint. Following the Design guidelines set by BASF Snap fit design manual, the following section shows a step by step application of those principles on the joint design in agricultural residue panels.

When designing a cantilever snap, it is not unusual for the designer to go through several iterations (changing length, thickness, deflection dimensions, etc.) to design a snap-fit with a lower allowable strain for a given material (BASF, 2007). Through the fabrication and testing of these design iterations, an optimal design that accounts for different necessities of the joint can be reached.

The following figure shows a general classification of different snap-fit elements based on their geometries.

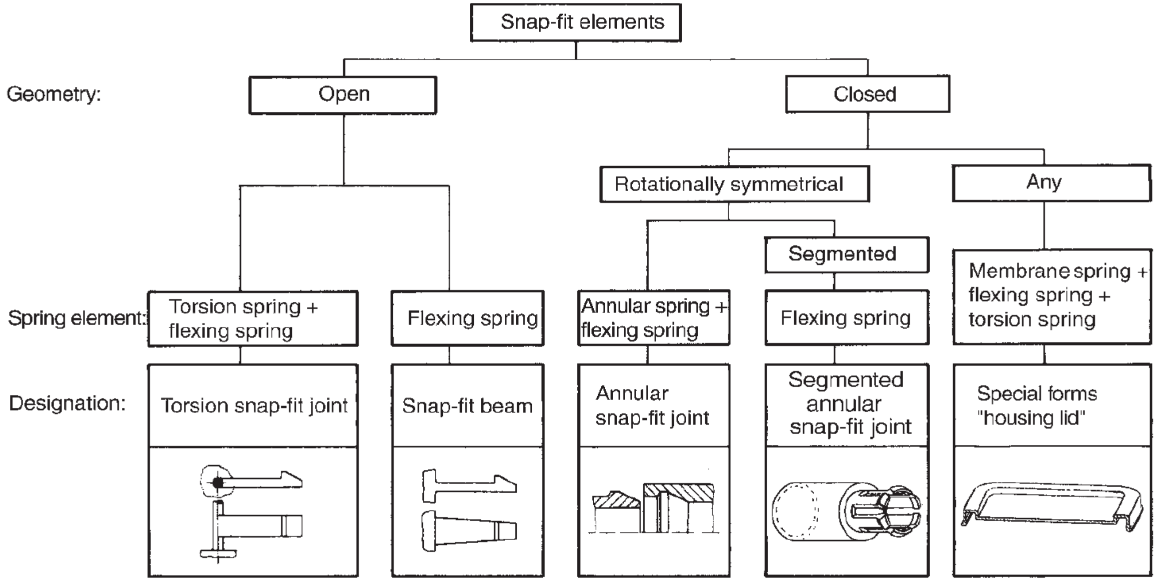


Figure 5-8: Classification Scheme for snap-fit elements based on geometrical considerations.
Source: Gunter Erhard, 2006

Most engineering material applications with snap-fits use the cantilever design. Other types of snap-fits, which can be used, are the "U" or "L" shaped cantilever snaps (Figure 5-9). These are used when the strain of the straight cantilever snap cannot be designed below the allowable strain for the given material (BASF, 2007). They are also utilised when the space available for a straight beam is not sufficient.

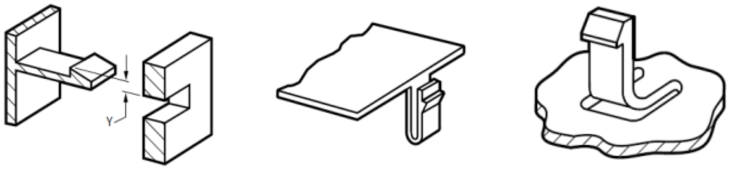


Figure 5-9: Three of the most common Snap fit joints largely used in the plastic industry. **Source: (BASF, 2007)**

Although snap-fits can be designed with different materials, the design manuals developed by BASF and BAYER deal exclusively with different thermoplastics because of their high flexibility and their ability to be easily and inexpensively moulded into complex geometries. Within the scope of this research and with the aim of simplifying the process of fabrication, only straight cantilever joints will be used. Other more complex joints like “U” and “L” shape cantilever snaps with the presence of under-cuts necessitate the use of complex fabrication –such as subtractive multi axes robotic fabrication tools- which would significantly raise fabrication time, cost and complexity. Using them can also pose big challenges to the integrity of joints made of timber due to fibre directionality that cannot be maintained through the snap beam element.

5.4.1 Common Nomenclature of snap-fit joints

The geometrical parameters of the parts define the force needed to assemble or disassemble it and the separable or inseparable characteristics of the joint. The joint is mainly designed according to the mechanical load during assembly and its corresponding assembly force (Robeller, Mayencourt, & Weinand, 2014). The following figure shows some common nomenclature gathered from multiple plastic design guidelines that usually use different terms to define the same elements.

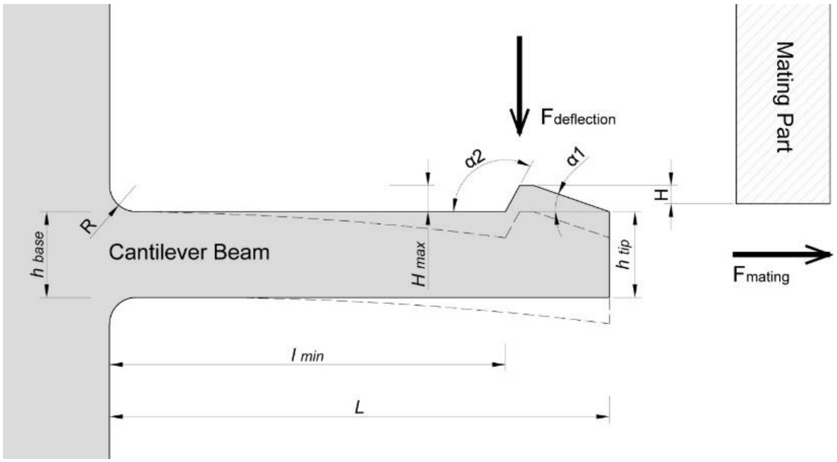


Figure 5-10: Snap-fit basic parameters and nomenclature. **Source:** Based on (BASF, 2007; Gunter Erhard, 2006)

Where:
$\alpha 1$ = Joining Angle
$\alpha 2$ = Retaining Angle
b = Breadth of cross section (beam breadth)
h_{base} = Height of cross section at base
h_{tip} = Height of cross section at tip (if a tapering cantilever is used)
l_{min}= beam length
L= Overall beam length
H_{max} = "Under-cut" or "Overhang"
$H_{deflection}$ = Deflection due to insertion.

5.4.2 How snap-fits work

The cantilever edge typically has a gentle ramp on the entrance side and a sharper angle on the retraction side as shown in Figure 5-11. The small angle at the entrance side (α) helps to reduce the assembly effort, while the sharp angle at the retraction side (α') makes disassembly very difficult or impossible depending on the intended function. Both the assembly and disassembly force can be optimized by modifying the angles mentioned above. A usual entrance angle between 20-25° is a common practice and it can be adjusted and optimized during design iterations.

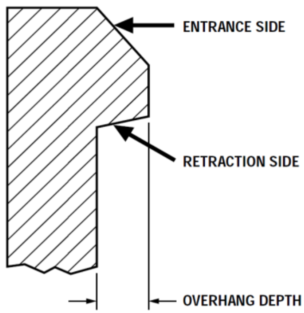


Figure 5-11: The overhang distance defines the amount of deflection during assembly. **Source: (BASF, 2007)**

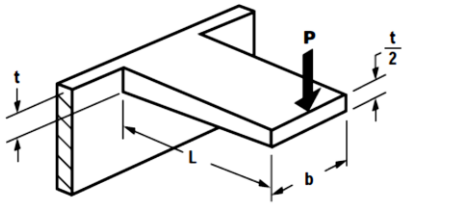
The main design consideration of a snap-fit is the integrity of the assembly and strength of the beam. The integrity of the assembly is controlled by the stiffness (k) of the beam and the amount of deflection required for assembly or disassembly. Rigidity can be increased either by using a higher modulus material (E) or by increasing the cross-sectional moment of inertia (I) of the beam. The product of these two parameters (EI) will determine the total rigidity of a given beam length.

The integrity of the assembly can also be improved by increasing the overhang depth. As a result, the beam has to deflect further and, therefore, requires a greater effort to clear the overhang from the interlocking hook. However, as the beam deflection increases, the beam stress also increases. This will result in a failure if the beam stress is above the yield strength of the material. Thus, the deflection must be optimized with respect to the yield strength or strain of the material. This is achieved by optimising the beam section geometry to ensure that the desired deflection can be reached without exceeding the strength or strain limit of the material.

The assembly and disassembly force will increase with both stiffness (k) and maximum deflection of the beam (Y). The force (P) that is required to deflect the beam is proportional to the product of the two factors: P= kY

The stiffness value (k) depends on beam geometry. Stress or strain induced by the deflection (Y) is shown in Figure 5-12. The calculated stress or strain value should be less than the yield strength or the yield strain of the material to prevent failure. When selecting the flexural modulus of elasticity (E) for hygroscopic materials, i.e., agricultural residue panels, care should be taken. In the dry state, the datasheet value may be used to calculate stiffness, deflection or retention force of snap design. Under normal 50% relative humidity conditions, the physical properties are expected to change, therefore, ideally both scenarios should be checked. Given the steep timeline for the testing phase of this research only one scenario can possibly be tested which is in this case, the mechanical lab testing value performed by the author previosuly.

The cantilever beam formulas used in conventional snap-fit design underestimate the amount of strain at the beam/wall interface because they do not include the deformation in the wall itself. Instead, they assume the wall to be completely rigid with the deflection occurring only in the beam. This assumption may be valid when the ratio of beam length to thickness is greater than about 10:1. However, to obtain a more accurate prediction of total allowable deflection and strain for short beams, a magnification factor should be applied to the conventional formula. This will enable greater flexibility in the design while taking full advantage of the strain-carrying capability of the material.



II) Uniform Width, Height Tapers to t/2 at Free End

Stiffness: $k = \frac{P}{Y} = \frac{Eb}{6.528} \left(\frac{t}{L}\right)^3$

Strain: $\varepsilon = 0.92 \left(\frac{t}{L^2}\right) Y$

Figure 5-12: Stiffness and Strain formulas according to BASF design guidelines. Source: (BASF, 2007)

5.4.3 Numerical Calculations

The mechanical tests were intended to characterize the overall mechanical properties of the material. However, to be able to define the right dimensions for the snap-fit joint, the following material design values are needed: Secant Modulus of Elasticity in bending and Maximum allowable strain. From the previously performed mechanical tests (See section 4.6 and Appendix A), average values are calculated based on the two tests of axial tension, axial compression and 4-point bending.

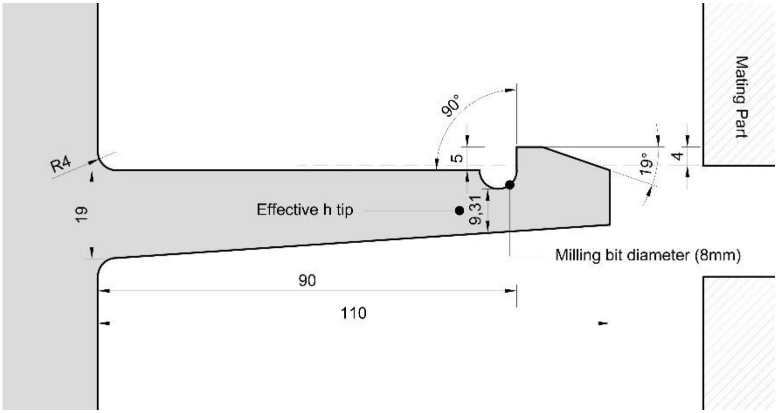
- Median Value for Modulus of Elasticity in Tension = 1700 MPa
- Tension Strength = 7.5 MPa
- Median Value for Modulus of Elasticity in Compression = 1700 MPa
- Compression Strength = 10 MPa
- Median Secant modulus of Elasticity (in bending) = 2100 MPa.
- Yield Strain = 2/3 Maximum Strain = 2/3 * (8.5 * 10^{-3}) = 5.66*$10^{-3.}$ When a material has a brittle behaviour, this implies having no yield point therefore a safe value of 2/3 of maximum strain was used as maximum permissible strain. The maximum strain in turn was calculated as an average strain of the four tests performed in tension and compression.

One of the usual approaches for snap-fit design is to start from a group of design approximations or assumption (Figure 5-13). In this case, an initial rough geometry for both part and mating part was sketched. The cantilever beam length (l) is assumed to be 90 mm, and the height at base (h_{base}) to be 19 mm. A tapered cantilever was also used in order to minimize the uneven distribution of strains on the material. For all the calculations below, it is assumed that the mating part of the snap-fit remains rigid while all the flexural stresses happen in the cantilever beam (BAYER, 2012). This assumption represents an additional precaution against material failure.

The cantilever base connects to the wall using a root radius of 4 mm. While the guidelines propose a ratio of 0.6 between radius of fillet and height of beam (R/h_{base}), it however acknowledges that this would result in a large base at the cantilever connection with the supporting wall. It calls upon the designer to reach a compromise between a large radius to reduce stress concentration or a smaller radius to avoid residual stresses due to the creation of a thick section adjacent to a think section (BAYER, 2012).

The entrance angle was assumed at 20^0 following a design example illustrated by Paul Tres in his Automotive Plastic Design seminar. The retraction angle is kept at 90^0 to ensure that the disassembly is not too easy under circumstantial pulling forces.

Figure 5-13: The initial assumptions used for the design of the snap-fit joint, taking into consideration milling machine limitations, required geometry and some best practice assumptions like entrance angle = 19 and retraction angle 90.



According to the snap-fit design manual developed by BAYER and given the maximal permissible strain of the material ε, the maximal deflection for a cantilever with decreasing height to one-half at the tip over the length:

$$H_{max} = 1.09 \frac{\varepsilon l^2}{h_{base}}$$

$$H_{max} = 1.09 \frac{(5.66*10^{-3})(90^2)}{19} = 2.64 \text{ mm}$$

Using an alternative equation given by the "Automotive Plastics part design seminar" developed by Paul Tres[5]:

$$H_{max} = (L - l_{Min}) \frac{\tan \alpha 1 \tan \alpha 2}{\tan \alpha 1 + \tan \alpha 2}$$

[5] Paul A. Tres is a best-selling author and an international speaker and lecturer on plastic product development and design. The lecture notes were provided to the author by a professor in Sheffield university who attended the seminars organized by Mr. Paul Tres in the US.

If $\alpha 2$ = 90˚, then:

$$H_{max} = (L - l_{Min})\ \tan \alpha 1$$

$$H_{max} = (110 - 90)\ \tan 19 = 3.03 \text{ mm}$$

As seen from the previous equations, two different values for the overhang were obtained using the same inputs. However, both numbers are almost equal. Such a small overhang value shall be safe for assembly and disassembly but is too small to maintain a sufficient contact surface between cantilever arm and mating part. A bigger overhang would require either a longer arm or going beyond the maximum allowable strain of the material (2/3 Maximum strain). Another possible strategy is to give some freedom for the assembly by allowing a bigger tab opening in the mating part. Physical testing at this point is critical to verify if the integrity of the cantilever arm can be maintained within the designed limits.

During the assembly, the deflection force P at the tip of the cantilever at H_{max} is given by:

$$F_{deflection} = \left(\frac{bh^2}{6}\right)\left(\frac{E\varepsilon}{l}\right)$$

$$F_{deflection} = \left(\frac{18 * 19^2}{6}\right)\left(\frac{2100 * (5.66 * 10^{-3})}{90}\right)$$

$$F_{deflection} = 143\ Newtons$$

The force necessary to assemble the joint, called "Mating Force", depends on the friction coefficient of the material μ, the insertion angle and the deflection force. Both the deflection and friction force must be overcome by the mating force:

$$F_{mating} = F_{deflection} \frac{[\mu + \tan(\alpha)]}{[1 - \mu\tan(\alpha)]}$$

$$F_{mating} = 143 * \frac{[0.009 + \tan(19)]}{[1 - 0.009\tan(19)]}$$

$F_{Mating} = 25\ Newtons$, where μ is the static coefficient of friction calculated by sliding one piece of the material upon another and measuring the sliding angle, μ = Tan(sliding angle). Test is unreliable due to difficulty of assigning friction values for such a material, further confirmation needed)

5.5 Summary

Numerous calculations, iterations and fabrication trials were performed to maintain the integrity of the beam. While keeping the cantilever base height at 19 mm, two different trials were made changing only the length (l_{min}) of the cantilever beam. One trial at a length of 90 mm, the second at a length of 76 mm (Figure 5-14). While the longer beam length allowed for easier deflection and accordingly easier assembly, it was easily broken under hand-applied force. The shorter beam however, showed better overall resistance given that sufficient tolerance is considered for the opening tab in the mating parts.

Figure 5-14: Numerous snap fit arms were fabricated and manually tested for ease of assembly and disassembly. (Left) short cantilever arm (76 mm), (Right) Long cantilever arm (90 mm) that was easily broken.

Given the accuracy with which these calculations are made, fabrication tolerances also have a considerable effect on the overall performance of the cantilever beam. The fabricator was provided with a CAD file for the first joint trial in which one-millimetre tolerance was designed to accommodate for the accumulated tolerance effect that might arise with the assembly of a big number of pieces. However, on an individual scale, the joint was found to be very loose. The subsequent fabrication trials were modelled at zero tolerance and assumed a machining tolerance of 0.3 mm directly from the Computer Aided Manufacturing (CAM) software. For the tab holes in which the snap fit enters and this value proved satisfactory for the individual and accumulative tolerance requirements.

CHAPTER 6 | Fabrication and Testing full scale assemblies

6.1 Introduction

In this chapter, the previously discussed arguments are put together into a coherent whole. This chapter showcases the process of modelling, fabricating and assembling three partial prototypes of the three wall typologies that represent the basic modules of the housing system. They were built at full-scale using the snap-fit dimensions previously calculated. Snap fits were used within the wall assembly itself and between different wall assemblies fabricated using a CNC milling machine. Milling limitations and design considerations that needed to be incorporated in the final design of the joint are also discussed. The assembly sequence and the challenges faced during assembly are discussed in detail. Towards the end of this chapter, the structural performance of the straight wall assembly -rather than single material sheet- was tested through an axial compression loading test till failure.

6.2 Modeling the prototypes

The five full-size stock sheets (10 half size sheets 1200 x 1200 mm) that the author was able to acquire were barely sufficient for the mechanical testing and the construction of the three wall typologies. The size of the assemblies was decided at around 700 x 700 mm starting from the assumption that four vertically stacked sheathing panels would give a reasonable height for a residential unit (4 x 700 = 2800 mm). The second motive for designing the prototypes at these dimensions is the high density of this material (830 kg/m^3), which makes the weight of one half size sheet 21 kilograms. Thus, it becomes important to consider the constructability and ease of handling for the prototype and eventually for the full-size wall assemblies.

The three wall assemblies were modelled using Rhinoceros 3D modeler. The nested cut-sheets were prepared in AutoCAD and saved in .dwg format (Figure 6-2). The first nesting layout prepared by the author was further enhanced and optimized by the fabricator to minimize material waste and machine cutting time. Usually a typical CAM software has a functionality for automatic or manual nesting based on the user preference. When the material has no specific directionality, fabricators prefer to use the machine-generated automated nesting.

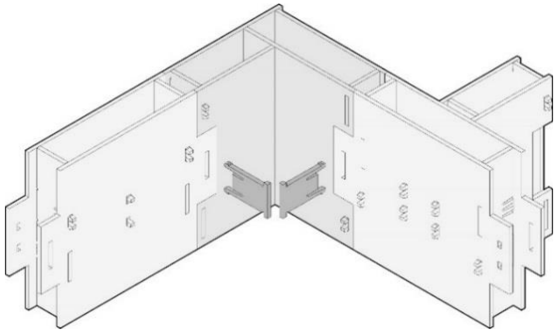


Figure 6-1: 3 wall typology prototypes modelled in Rhinoceros 3D modelling environment.

Parametrization using visual scripting such as Grasshopper was not included at this stage of the investigation as the initial joint iterations were limited in number. The time spent on the initial setup of the parametric model exceeded the time needed to manually change some limited number of variables for the sake of testing and fabricating a proof-of-concept mockup. For a final product, it is however projected for future work to setup a model that accounts for the design variables of each wall assembly as discussed previously in section 4.4.2.

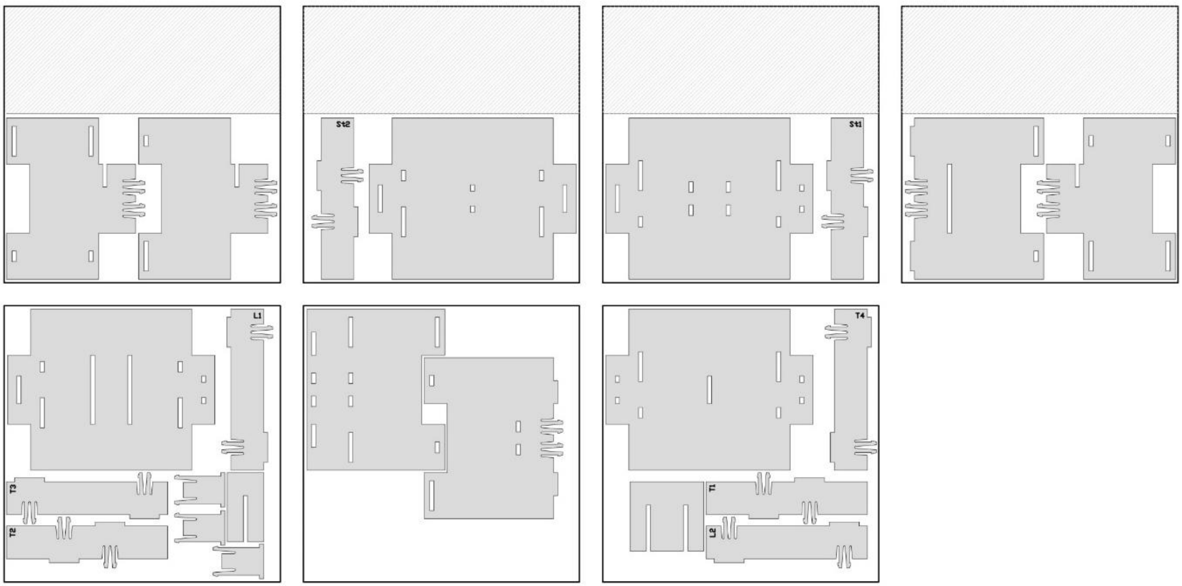


Figure 6-2: Nested cut sheet for the 3 wall prototypes.

6.2.1 Milling Considerations

For experienced practitioners of digital fabrication, some special and well-known considerations must be well-regarded during the preparation of workpieces for milling. Some aspects related to machining limitations are inherent to milling machines and they need to be considered early in the work piece (joint) design. They will be briefly discussed here to outline their importance.

6.2.1.1 Rounded Corners

The milling machine has an inherent limitation that relates to the roundness of the tool bit. It is not possible through the use of thin bits to have right angled inner corners. A relief hole needs to be generated at the corner and then the angle is milled. The CAM software almost always provides the possibility of adding different corners treatments according to the designer's preference. The diagram below shows different corner treatments that are possible to achieve using an eight-millimetre router bit. (A) perpendicular corners are not achievable using routing. (B) unnecessarily big relief holes (dog bone). (C) T-bone corner treatment wrongly oriented with very small contact surfaces (D) T-bone corner treatment in a better orientation with bigger contact surface area. (E) optimized relief hole position with good distribution of contact surfaces (dog-bone).

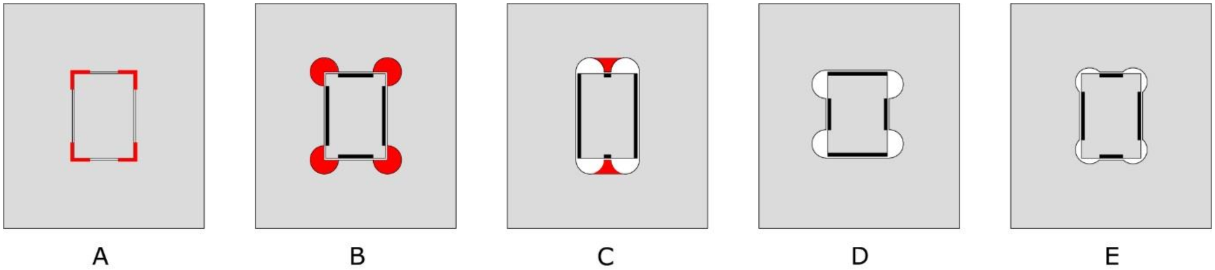


Figure 6-3: Different corner treatments using CNC milling

6.2.1.2 Workpiece Fixation and Tabs

Due to the very high spinning speed that the router bit has (10000 r.p.m), workpieces tend to rotate and in worst cases fly away if not properly fixed to the working area. There is a wide variety of solutions addressing the issue of workpiece holding such as T-slots, vices, clamps, screws, tooling plates, and modular fixturing. Some CAM software allow the definition of a set of points through which the routing head shall never pass. Within these points screws can be used to hold-down the workpiece to the spoil board (the sacrificial material supporting the cut piece from underneath) during cutting. After the end of the machining, screws are manually removed.

If the routing is intended as a cut-through (routing the full-thickness of the material) then tabs shall be created to maintain the position of the internal cut piece and prevent it from flying away (Figure 6-4). In general, CAM software allow the automatic or manual positioning of these retaining tabs that must be manually cut and sanded after the end of the milling.

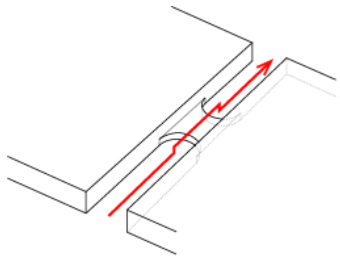


Figure 6-4: Adding tabs to secure cut piece in place during milling

6.2.1.3 Sawing (Manual and Machining):

According to the handling and machining guides[6] of ECOboard, the material can be sawn both manually and by machine, without causing the material to splinter or fibres to be torn out of the panel. For manual sawing of ECOBoard, a fine- toothed saw is recommended, whereas for mechanical sawing, the saw blades normally used for particleboard can be used. The panel material must be fed across the saw blade at a high enough feed rate. At too low a feed rate, the saw blade teeth will not cut, but instead crush and rub down on the panel material, whereby 'burning' may occur and fine dust is generated. The friction heat, which is generated by the pressure on the teeth, may significantly reduce the lifetime of the saw (working time).

6.2.1.4 Profiling (Milling)

Profiled or milled edges can be difficult to achieve due to the porous nature of the ECOBoard material particularly with the medium and Low-density boards. It is therefore recommended that a High Density ECOBoard is used for profiled edges. A detailed fine edge can still be difficult to obtain even with a High-Density board. The application of milling as cut-through did not represent any particular challenge. However, even with straight cut-through milling, some edge conditions were questionable and had to be manually sanded.

6.2.1.5 Cutting speed and Feed Rate

For profiling or milling of ECOBoard, a cutting speed of 60 to 80 m/s is recommended. The cutting speed (Vc), expressed in m/s, and is determined by the diameter and speed of the cutting tool.

The feed rate for milling or profiling operations initially depends on several parameters:

- Desired finish, which in turn depends on the desired result in the end application.
- Strength of the cutter: The rule of thumb here is that the maximum feed rate is limited by the value: $vf < d/2$ where vf = feed rate (m/min) and d = diameter of tool (mm)

[6] Handling and machining guides of ECOboard were sent to the author via email based on the request made to the distributor in the Netherlands. All reports will be added as an appendix at the end of the thesis.

For example; a cutter with 4mm diameter, a maximum feed rate of 2 m/min can be used without any risk of the cutter being broken. For milling the prototypes, we used a single flute straight 8-millimeter diameter router bit with a feed rate of 3 m/min at 10000 r.p.m. These settings proved satisfactory for most of the cut pieces.

6.3 Final milling

A local fabricator was found via the Rome Makers Community[7]. Mr. Sergio Subrizi, originally a photographer, built his own Do-it-yourself CNC milling machine called the MechMate[8]. In a guest post on the open electronics webpage (Subrizi, 2014), Sergio explains how using online forum information and blue prints, he was able to source all the necessary materials and learn the know-how to build a fully functional CNC milling machine. This specific machine and this entrepreneurship mindset that was found working with Mr. Sergio was a very lucky coincidence that even further strengthens the approach proposed within this thesis. Working with local entrepreneurs who are willing to create their own machines and fabrication facilities validates the possibility of creating shadow economies and profoundly change the dynamics of the existing housing market.

A simple Grasshopper functionality was used to calculate the total lengths of profiles to cut in order to estimate the overall cost for cutting. The total amount was around 76 linear meters representing 23 profiles out of which 8 are vertical runners, 3 keys, 2 strengthening plates, 10 front and back sheathing panels. The speed that was used for cutting all final pieces was set to 3 m/min. The overall working time of the machine was 68 minutes. The price set for machine time

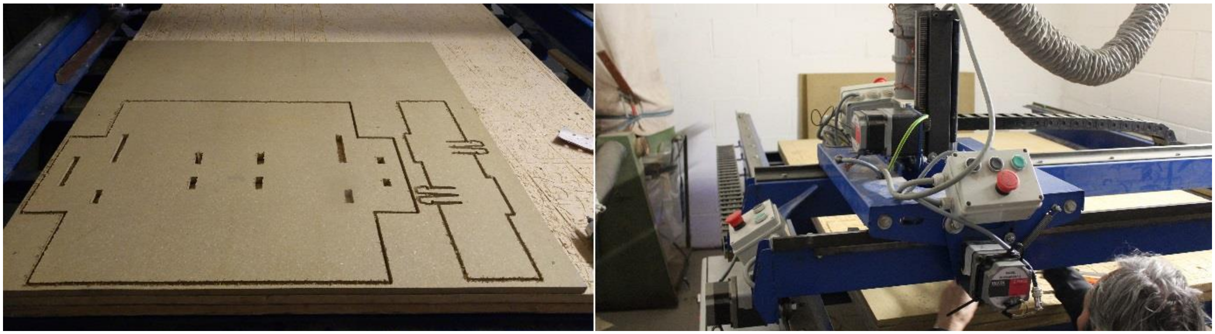


Figure 6-5: CNC milling of the final prototype parts

[7] Rome Makers Facebook page.

[8] MechMate is an open source machine designed by Gerald Dorrington, a mechanical engineer in South Africa who created his project in 2005. More details are available on http://www.mechmate.com/

was 1€/min which brings the total cost for the manufacturing of the 3 mockups to around 90€ including precutting preparation, nesting and actual machine cut-time.

Manual sanding of all machined edges was needed as the material edge quality was sometimes questionable. However, using sanding paper with fine grit was very easy and yielded acceptable results. The combination of rotation speed and feed rate during milling needs to be revisited considering best edge conditions for that specific material.

Figure 6-6: Sanding and sorting individual components of the prototypes.

6.4 Assembly sequence

This section shows in detail the assembly sequence of the three wall typologies partial prototypes. Hand pressure and a rubber mallet were used for fitting the pieces together following the schemes of assembly. These assembly sequence diagrams are intended for the prototypes with the understanding that it will change when dealing with full height assemblies due to handling issues. The main components that comprise the assemblies are internal sheathing, external sheathing, vertical runners, internal strengtheners and key inserts/spacers.

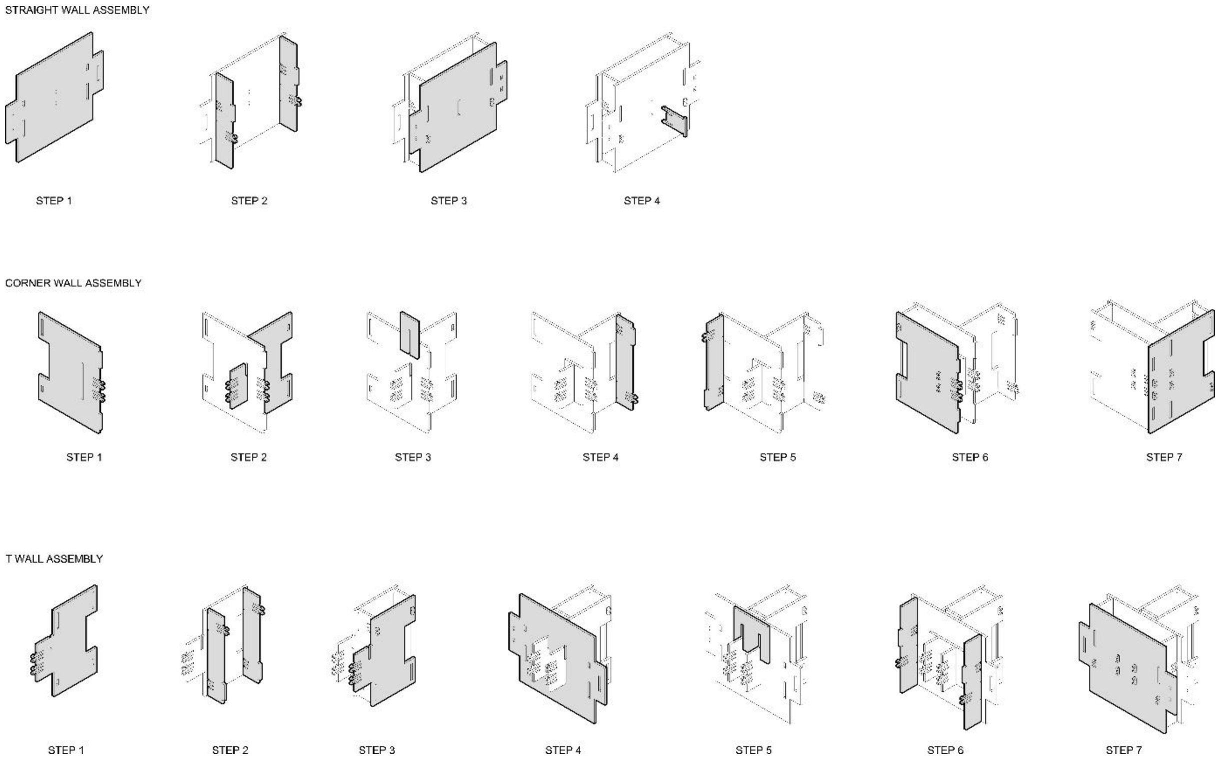


Figure 6-7: Three wall typologies assembly sequence. The assembly guide that the end user will be using would have similar schemes to guide him through the construction

6.5 Built prototypes

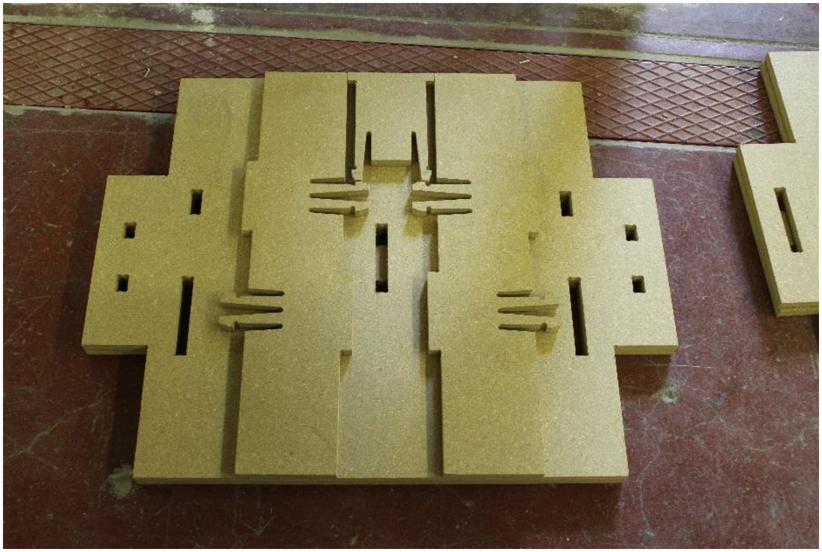


Figure 6-8: Sorting of cut pieces before assembly

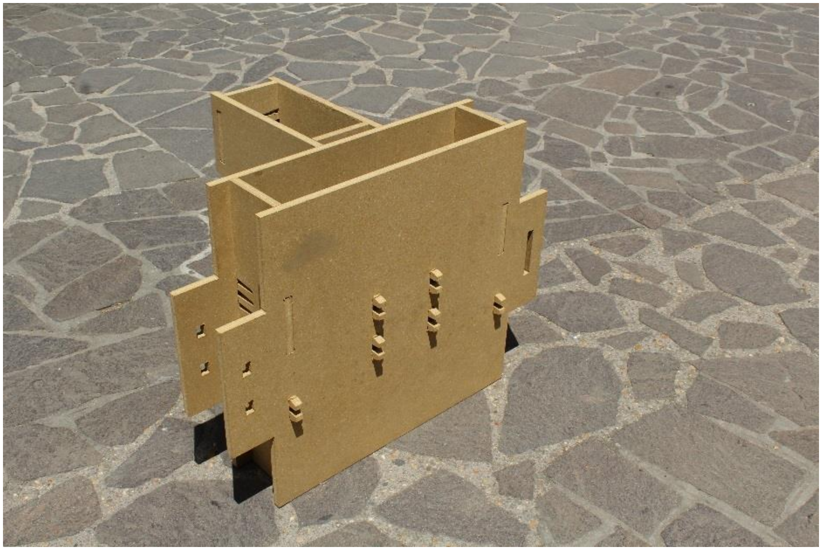


Figure 6-9: Full scale T wall assembly

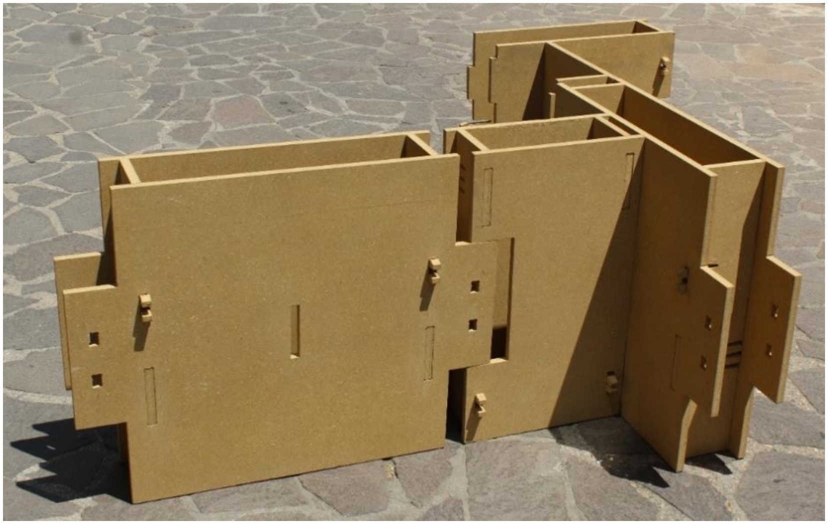


Figure 6-10: Full scale physical prototype of the three wall typologies – View 1

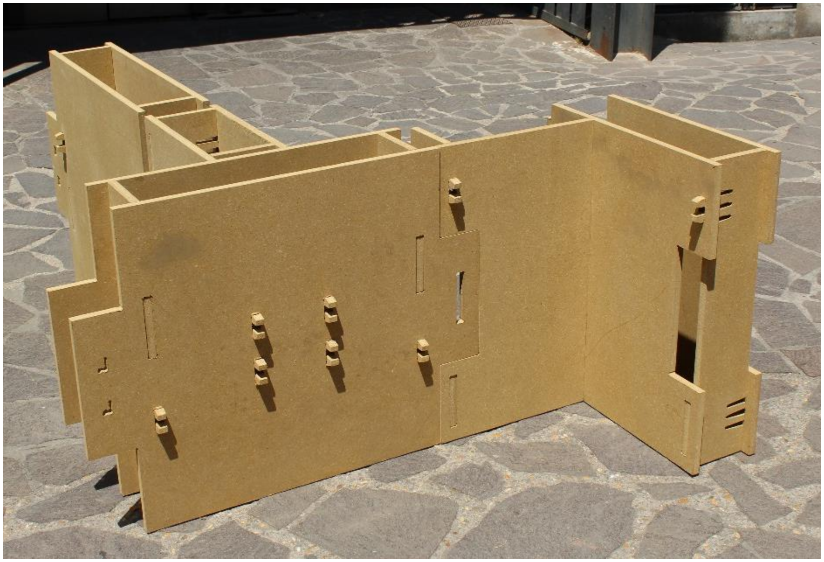


Figure 6-11: Full scale physical prototype of the three wall typologies – View 2

6.6 Prototypes evaluation

6.6.1 Limitations and challenges

While the process of assembly was smooth and quick in which the author on his own was able to assemble the three wall typologies with very little help in around one hour, some challenges were faced during assembly that require further enhancement and optimisation. This section provides some insights on these issues and the prospective steps that shall be taken to address them.

- Some of the snap-fit cantilevers were broken during assembly, specifically 4 out of 58 cantilever arms which is around 7%. The brittle nature of the material was a very noticeable aspect during assembly. These failures might be attributed to local material weak zones or to applying high strains – beyond the capacity of the material - during assembly of more than one cantilever in the same time. However, it is evident that the dimensions of the snap fit cantilever in fragile materials is a critical issue that needs further analysis. On the contrary, the half-lap joint insert used in step 2 of the L wall and step 3 of the T wall assemblies (Figure 6-7) showed high resistance and strong fit during the construction of the prototype. This type of jointing can be further explored as a substitute to cantilever snap-fits in brittle materials. These enhancements or possible joint concept trials are part of the future work foreseen after this thesis.

- Upon assembling the three prototypes, they showed a very small misalignment that might affect the overall quality of the system. A future enhancement would be to add partial horizontal elements (aligners) that can ensure that the wall assemblies are axially aligned as shown in Figure 6-12. While the scope of these proof-of-concept prototypes did not expand to include details of floor attachments, better alignment can be achieved if a continuous element (continuous aligner) is introduced at floor level upon which all assemblies are installed and thus aligned.

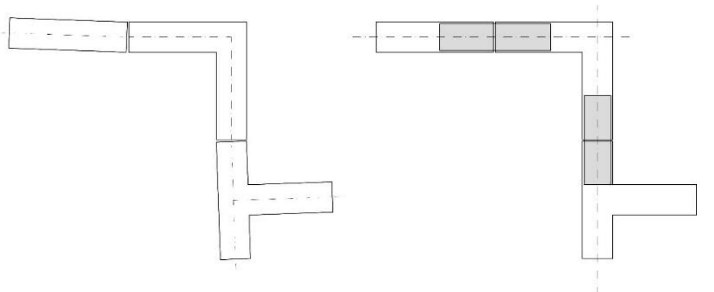


Figure 6-12: (Left) Misalignments of wall assemblies - exaggerated for the sake of graphical representation, (Right) Possible alignment elements to be included for future enhancements.

- It was observed that the overall rigidity of the assemblies increases with the increase of number of components and their bi-directionality. For instance, the L wall was more rigid than the straight wall and the T wall was more rigid than the L wall and so on. This is quite logic as the contact surfaces between different components increase and thus increase the system's global rigidity. The straight wall was more prone to skewing in the horizontal plane while the two other assemblies where much better on that front. This confirms the necessity of adding horizontal profiles within straight wall and between different assemblies.

- The integrity of the edges in direct contact with snap-fit were prone to fiber crushing due to high friction during assembly. The bonding strength of the exposed edges in this material is questionable. It is important to find the right tolerance balance that would account for this edge weakness while not compromising the retaining force of the cantilever arms.

Figure 6-13: Cantilever head pressing against edge fibers of hole caused fibre crushing which in turn affects the contact surface between cantilever head and mating part.

6.6.2 Structural Evaluation

The original plan for structural testing was to perform all different variations of structural loading based on ASTM standards, such as: Compressive loading, Tensile Loading, Horizontal Transverse Loading, Transverse Strength, Vertical Transverse Loading, Concentrated Loading and Racking Loading. Moreover, according to the American Society for Testing and Materials (ASTM) Subcommittee E06.11 (Standard Test methods of Conducting Strength Test of panels for Building Construction); there shall be at least three specimens for each test. Specimens shall be constructed to represent sections of the wall, floor, or roof assembly. The specimens shall be representative as to material and workmanship and shall be of the largest practical size to predict structural performance attributes of the assembly. Unsymmetrical assemblies shall be tested in each axis for which the results may be different.

However, due to very tight research time and budget limitations, the author along with professors from the department of structural and Geotechnical Engineering decided to start with one axial compression test that would give some indication about the performance of the designed wall assembly.

The objective of the work at this point is to understand the performance of the wall assembly using the proposed jointing system. The plan is to subject the straight wall assembly to compressive loading till failure measuring the out-of-plane buckling and the in-plane compressive deformation of the assembly on both sides. Buckling may occur even though the stresses that develop in the structure are well below those needed to cause failure of the material of which the structure is composed. Further loading will cause significant and somewhat unpredictable deformations, possibly leading to complete loss of the member's load-carrying capacity. If the deformations that occur after buckling do not cause the complete collapse of that member, the member will continue to support the load that caused it to buckle. If the buckled member is part of a larger assemblage of components such as a building, any load applied to the buckled part of the structure beyond that which caused the member to buckle will be redistributed within the structure.

This test does not follow norms for testing structural load bearing panels. It is only intended as an exploration of the stability and failure behaviour of the wall assembly. The interest at this point is to evaluate the resistance of the snap-fit joints against the buckling of the sheathing panels out-of-plane. The expected failure load under compressive loading is around 300000 kN (30 Tons) assuming a uniform axial compression on the effective cross section of the wall assembly.

However, the assembly is not expected to arrive to this theoretical load because the cross section of the wall is not a standard profile that was created under controlled manufacturing conditions and quality control. Instead, it is the sum of 4 components assembled with a certain degree of precision. This test is expected to give initial important indications towards understanding the behavior of the assembly and thus the optimisation of the designed joint. Only one specimen is tested for the joint configuration, therefore, the results must be interpreted as a trend. More tests should be conducted to consolidate these preliminary observations.

6.6.2.1 Test piece

The straight wall assembly as demonstrated before has the overall dimensions of 700 x 700 mm (excluding the two side protruding wings). It consists of 2 vertical runners of thickness 18 mm spaced at 600 mm and two sheathing panels (one internal and one external) of thickness 18 mm attached to the runners using two snap fits and two friction fit joints on each side. Each snap-fit on one side corresponds to a friction fit on the other.

The original design of the wall panel included one key insert at the central zone of the assembly to keep the distance between both sheathing panels constant (in compression) and to resist buckling (in tension) (Figure 6-14). However, 3 different trials were made to assemble these key inserts and they all failed during insertion. A final decision was made to go forward with the testing with no keys given that the spacing between the vertical runners is kept at 600 mm which is already equal to the spacing largely usual used in "Platform Framing".

During the test, an assumption was made that the system is symmetrical as the precision of computer numerical control milling ensures the symmetry of the wall assembly components.

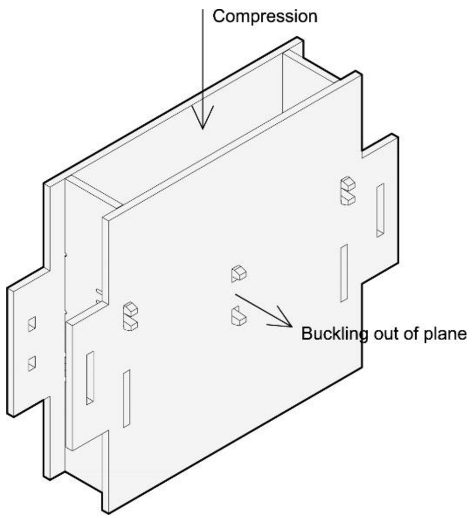


Figure 6-14: The expected test piece behavior under axial compression. The greatest concern is verifying the capability of the snap fit to resist the buckling of the sheathing panel out-of-plane.

6.6.2.2 Setup

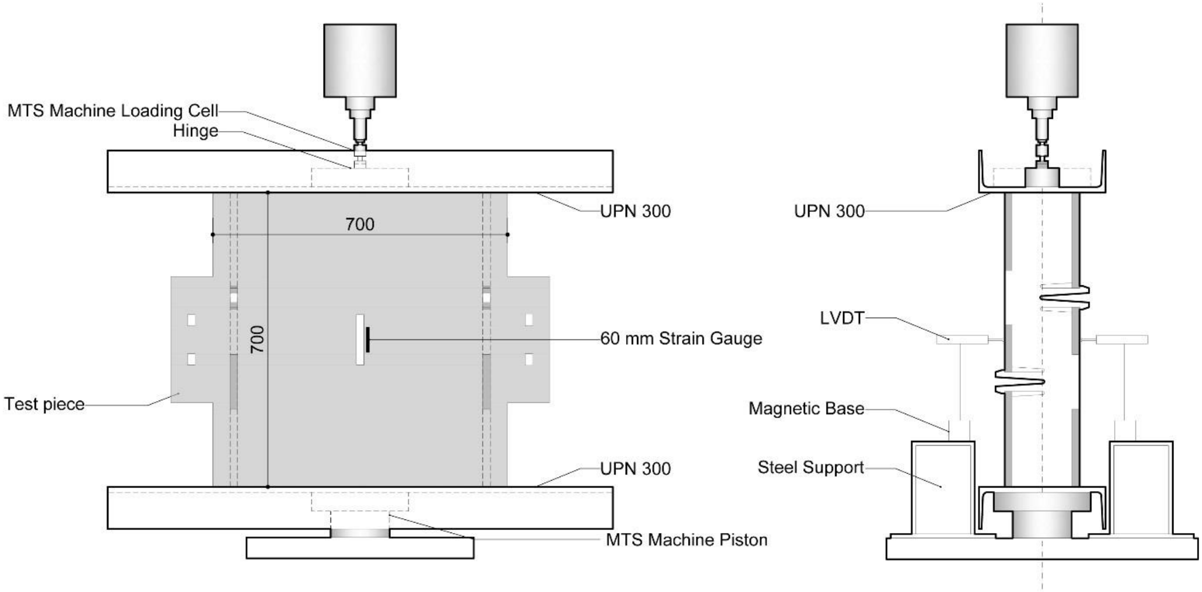


Figure 6-15: Illustration of wall compression test setup.

The test setup attempts to maintain the symmetry of load distribution in both directions. Two UPN 300 steel profiles of length 1200 mm were used; one as a lower support for the test piece and through which the compression load is applied (through MTS Machine piston) and the upper profile as a rigid body towards which the test piece is compressed. The weight of the upper UPN profile was defined to be 54.5 kg. This weight shall be added to the overall load that the test piece is resisting.

Two Linear Variable Deferential Transformers (LVDT) were placed perpendicular to both sides of the test piece at midpoint of both surfaces (in close proximity to central key insert holes). The two LVDTs were placed on magnetic bases placed on the MTS machine base. Two 60 mm strain gauges were glued vertically on both sides of the wall to measure compressive deformation in the plane of the wall.

The next set of figures illustrate in a step-by-step manner the process of test preparation.

Figure 6-16: Step (1): UPN 300 profile placed on lower MTS piston and used as support base for test piece. The test piece was aligned to center of UPN profile in both directions in order to maintain symmetry of load distribution.

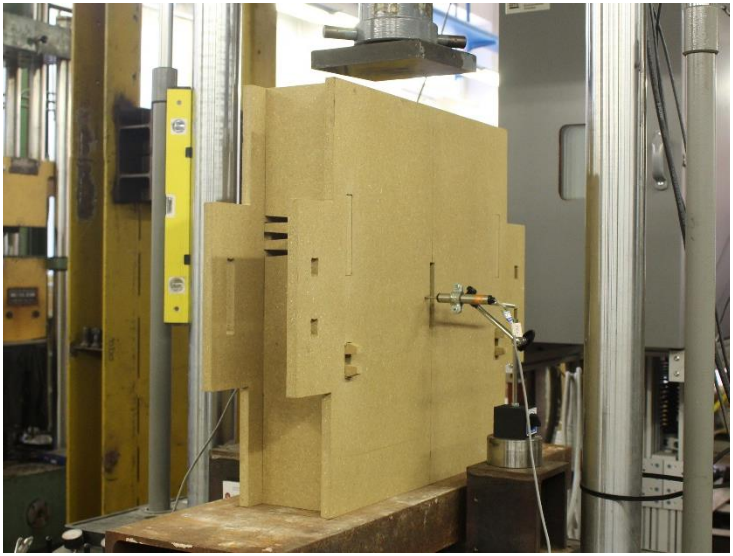


Figure 6-17: Step (2) Test piece placed on lower base and two LVDT measuring equipment are placed on both sides of test piece on magnetic bases.

Figure 6-18: Step (3) Complete test setup where a 300 UPN profile is placed above test piece with manual alignment to center of upper loading cell. Two 60 mm strain gauges were attached on both sides at central zone of sheathing panel leaving an offset of 5 mm from central key insert hole.

6.6.2.3 Procedure

A preload of 5 kN was applied at the beginning of the test. Manual alignment of test components was performed after the preloading including checking the positions of the LVDTs with respect to test piece surfaces. A uniform rate of load application was assigned at 1 mm/min. Load was applied till failure in a duration of 314 seconds. The test was video recorded from the start till failure.

Six different readings were obtained during the test: Two strain gauges (unitless), two LVDTs displacement (mm), MTS Compressive Loading Force (kN) and MTS piston displacement (mm). The following scheme (Figure 6-19) shows the distribution of the measurement instruments and their respective names. This is important to help understand the directionality of the instrument readings.

The sign convention used for the LVDT readings is shown in Figure 6-20 where the compression of the tool tip is considered positive.

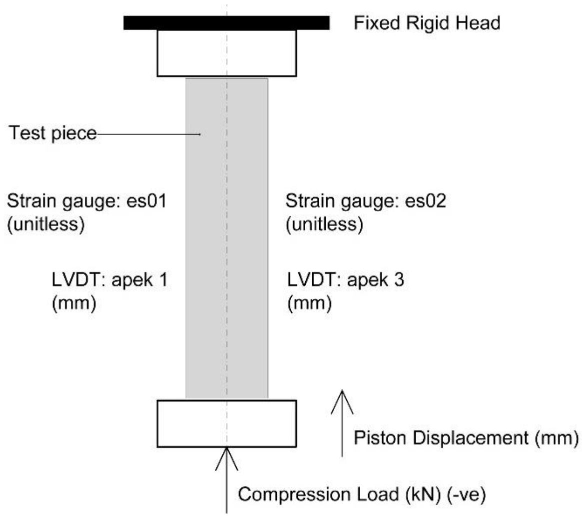


Figure 6-19: Nomenclature and positioning of test equipment corresponding to data test results in Appendix C.

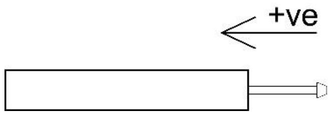


Figure 6-20: Sign convention adopted for LVDT readings

6.6.2.4 Results

The first graph shows compression load in kN on the vertical axis and the two LVDT displacements in mm on the horizontal axis. The apek-1 LVDT displacement (indicated in Green) had a negative reading of 2.5 mm which indicates that the surface buckled to the right. The apek-3 LVDT displacement (indicated in Blue) had a positive reading of 6.5 mm which indicates that the surface buckled also to the right. The overall buckling of the test piece was mono directional. However, only the right-hand side sheathing panel of the test piece failed under the maximum load of 140 kN (14 Tons Force).

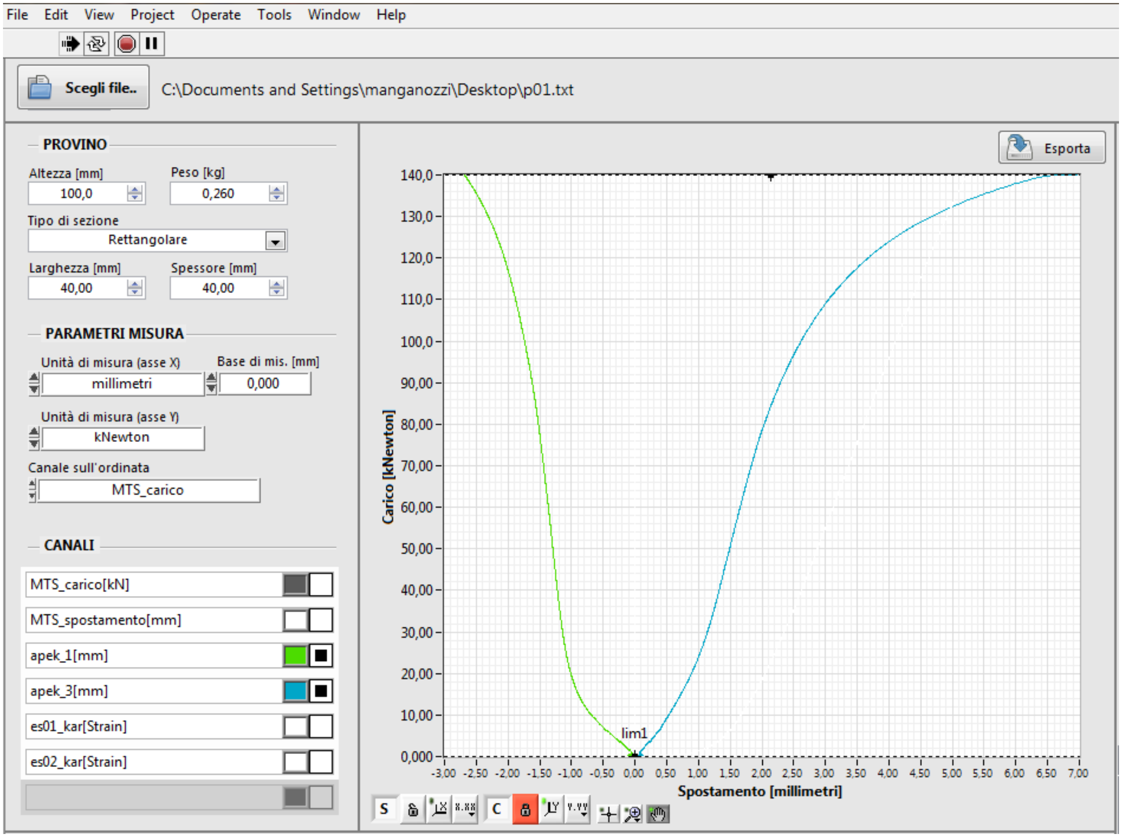


Figure 6-21: Load - LVDT Displacement in Buckling under axial compression load

The following graph shows load in kN on the vertical axis and the two strain gauge deformations on both sides of test piece on the horizontal axis. The first strain gauge (es01) which is on the left side of the test piece (represented in purple) shows a maximum strain of 0.004 at maximum load (140 kN). The second strain gauge (es02) which is on the right side of the test piece (represented in blue) shows a maximum strain of 0.0025 which corresponds to approximately 125 kN.

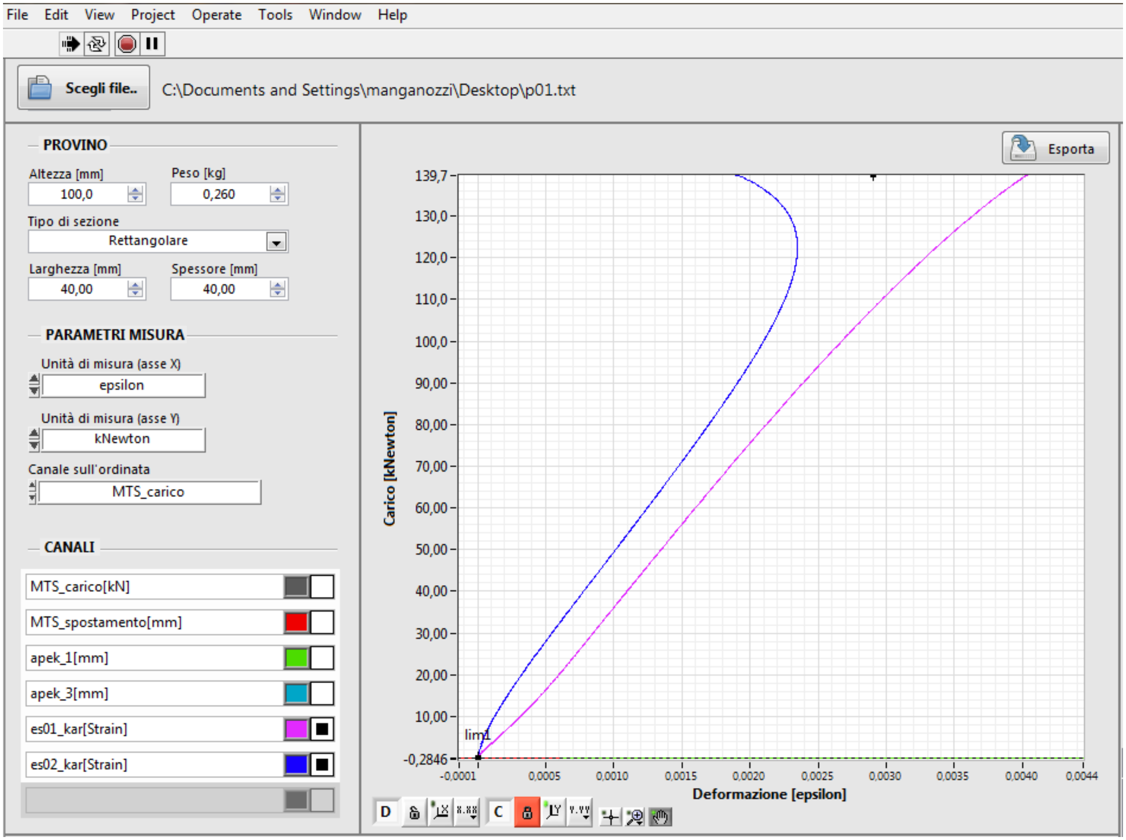


Figure 6-22: Load - Deformation under axial compression load

The failure of the test piece occurred at 140 kN (14 Tons-Force) where one sheathing panel broke (Figure 6-23) breaking the heads of the snap-fit cantilever arms. The failure of the panel was consistent with the fragile nature of the material.

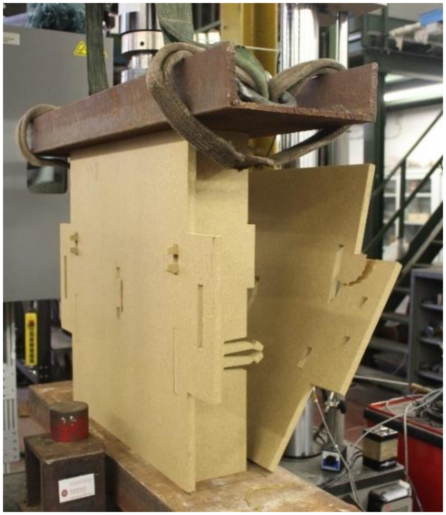


Figure 6-23: Test piece failure under axial compression. One sheathing panel buckled towards the outside and was maintained solely by the snap-fit cantilever arm head till failure.

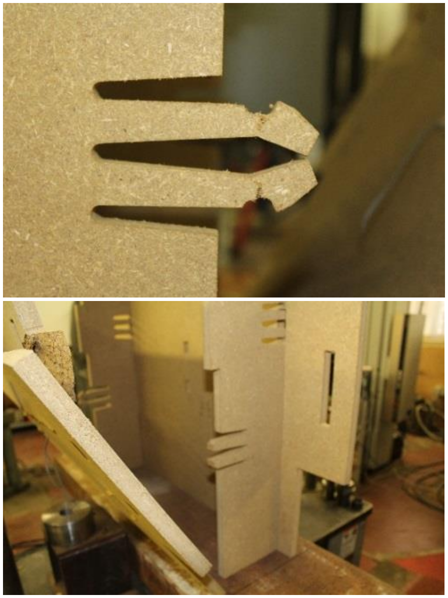


Figure 6-24: Snap-fit cantilever arm failures close-up.

Although no key inserts were used at the centre of the test piece, the wall assembly behaved better than expected with the presence of only 4 snap-fits on the two vertical runners. The overall behaviour of the assembly can be expected to improve with the insertion of key inserts, however they need to be restudied using a different material or re-dimensioned using the same material.

As explained before in section 4.4.2, the parametric setup of the wall assembly model allows manipulating the internal configuration inputs to include more vertical runners in order to have a more resistant wall based on structural requirements.

Figure 6-25 shows a simple 4 x 4 room scheme in which the highlighted wall is analysed based on assuming a non-walkable slab for the roof and an intermediate walkable slab between ground floor and upper floor. The wall has the overall dimensions of 0.70 x 0.18 x 2.80 m.

The dead load of the slab is calculated assuming a grid of half lap jointed joists of height 0.20 m confined between two layers of flat panel decking. All joists and decking panels are calculated at thickness 18 mm of the same ECOboard material which has a density of 830 Kg/m^3.

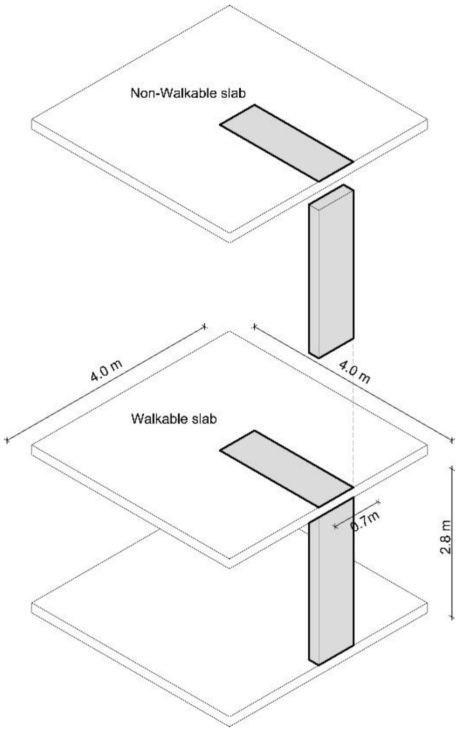


Figure 6-25: Structural scheme for a 2-storey space of 4 m x 4 m

Table 8: Dead and Live Design Loads used for the structural calculations

Type of Load	**Unit**	**Walkable Slab**	**Non-Walkable Slab**
Own weight	Kg/m^2	65*	65*
Finishes and Non- structural loads		150**	150**
Life Load		300**	75**
Total		**515**	**290**

* Assuming a safety factor of 1.3
** Assuming a safety factor of 1.5

The weight of the upper highlighted wall is 70 kg using the internal configuration of the prototype showed before with two vertical runners and two sheathing panels.

The overall load carried by this wall = Load of upper non-walkable slab + Load of middle walkable slab + Load of upper wall

Overall load = (0.7 x 2 x 290) + (0.7 x 2 x 515) + (70) = 1197 kg = 1.2 T

It can be concluded that the wall assembly shows good resistance to axial compression that already exceeds the load bearing requirements of this sample scenario wall. It is understandable that this axial compression test is not sufficient to judge the overall performance of the system because the forces acting on one or two-storey building are much more complex and are acting on the structure concurrently. However, this test gives a primary understanding about the stability and resistance of the snap-fit joints and their capacity to resist the buckling of the sheathing panels. Further enhancements and better performance can be expected through re-dimensioning the snap-fit joints for the key-inserts or using a different material.

CHAPTER 7 | Conclusions

7.1 Summary

This research started from a socially pressing problem that is low-cost housing deficit. The questions and arguments presented by the author were always driven by a sense of responsibility not only towards the community and environment, but also towards the practice of the profession of architecture in developing countries. The author thinks that technological capacities that are making design and production tasks easier and more efficient should be put to beneficial and meaningful use in developing countries.

The thesis started from a social activist point of view who then became an architect; a structural engineer and finally a production engineer, exploring the tools at his disposal and better understanding their capabilities. The interdisciplinary approach that was crucial to this type of research added a lot to the author even on a personal scale. Moving from one role to the other and from one discipline to the other across the boundaries -that are usually set by the practitioners themselves- gave some fluidity to the research activities performed during the thesis.

It is important at the end to redraw and highlight the route and the milestones through which the research have passed. Maybe other researchers reading this thesis will find some interest in knowing how it started, evolved, changed, adapted and sometimes transformed.

Generally, the housing field is a vast field of study with maybe tens of aspects to consider in order to reach a successful housing development. The author chose to address a certain economic typology which is "Low-cost" motivated by extreme refugee displacement and urban migrations.

As illustrated through the thesis, many approaches can be adopted to address the lack of housing. From a technological point of view, two types of housing construction are prevalent: *Prefabricated*; and *On-site* housing construction. Prefabricated housing is then further divided to different typologies such as modular, panelised, sectional and kit of parts. Digitally fabricated housing instead represents a branch of prefabricated housing even though it does not completely lie within the umbrella of prefabrication as some current contemporary research is exploring on-site additive manufacturing of housing units as demonstrated before through *Contour Crafting* and *D-shape technology*.

At that point an analysis of the precedents in digitally fabricated housing was fundamental in order to understand the limitations and the opportunities that this construction technology has. After the analysis, the author saw the potential in the synergies between digital fabrication and off-site prefabrication. In other words, being able to parametrize a set of assemblies opens new spatial and functional possibilities that go beyond the interchangeability of traditional modular housing. Coupled with flexible tools of digital fabrication, a new housing production model was proposed in which digital fabrication promises to offer efficiency, customisation, flexibility and speed.

Pressing on the absolute necessity of reducing costs three major decisions were needed: material selection, fabrication tool and joining method which are in the matter of fact all inter-related. At that point, agricultural residue panels produced in flat sheets were chosen, as they can be fabricated using relatively cheap machinery (2D cutting/milling) and put together using integral snap-fit joining. With all these decisions made, a design system was outlined. Verification was needed for all the previous assumptions. This is what lead the research into an experimental phase in which material tests, joining tests and structural tests were fundamental to understanding the constructability and thus the applicability of the designed system.

As mentioned before the research started with a very ambitious plan of finding sufficient funds to build a full-scale prototype of a house. With the steep timeline of the research and exploring new dimensions related to material selection and mechanical behaviour and lab testing, a decision was made to limit the scope of the thesis to the partial wall typologies and physical prototypes showed previously.

7.2 Results

The results of this research work are seen as a starting point for an interesting and socially engaged line of research. They can be manifested in two main types:

Theoretical outlines are those results related to the propositions of a housing system that merges the concepts of off-site complete prefabrication with localized decentralized digital fabrication in search for speed, efficiency and practicality of constructing low-cost housing. The promotion of the concept of self-build in which the end-user contributes actively and willingly in the simple construction of his house. Proposing a complete economic model that involves adding value to agricultural waste, building panel factories in close proximity of agricultural fields, calling for the active participation of the end-users in the construction activities, minimising the environmental impacts of waste disposal; all represent tangible results that are achievable and comprehensible for end-users but also for decision makers.

The propositions of “Housing System 01” shall be seen and regarded as a nucleus for a more versatile and robust design system. Setting the conceptual framework was the main aim at that point keeping in mind many layers of complexity that can arise from applying it to a full-scale housing unit. The research addressed detailed design and constructability issues attempting to validate the basis for a functioning system. The approach used for this validation is a bottom-up approach in which a few basic elements (3 wall typologies) were studied in extensive detail; going down to the very fine issues of friction fit tolerances, assembly logics, CNC fabrication limitations and snap-fit dimensioning based on material mechanical behaviour. Despite concentrating on the detailed aspects of individual elements, this bottom-up approach strengthens the credibility of the overall system. By understanding not only how the module is constructed but also how it behaves structurally, a more robust and efficient system can be developed.

Experimental/Lab based Results: Those can be traced back to the mechanical tests performed for characterising the wheat straw panels and evaluating their suitability as an alternative for timber-based panels. The experimentation extended also to new joinery techniques and reinterpreting old aspects of traditional timber joinery.

It can be concluded that this material with its characteristic fine fibres is not best suited for delicate joining. It can be safely concluded that snap-fit design within brittle materials is highly questionable using standard equations and design guidelines that have been intended for more elastic materials. While the joints were designed with high factors of safety and within the elastic limits of the material, the brittle nature was still very effective upon the integrity of the snap-fit joint.

The best performing joint instead, was the *half-lap joint* used within the L and T wall assemblies as explained before. It was found to be very rigid and stable during and after assembly. "*Compression joints*" can be revisited within the mechanical resistance capacities of this material, as the material was found to be very resistant in compression compared to tension. It is critical to avoid pure tension forces when designing joints using this material as its brittle behaviour is very dominant.

As seen in the wall compression test, the system and the joint show very good resistance in axial compression and load bearing capacity and thus promise to provide a strong basis for an efficient system. The high density of the material is mainly responsible for this high capacity in compression. As the intention is to promote self-build, handling the components of the system becomes an important issue. The straight wall prototype had an overall weight of approximately 27 kg, while L and T walls exceeded 30 kg.

7.3 Future outlook

The outlook for this research is still very ambitious. The production and economic model proposed by this thesis needs to be taken further and into real market. It is well understood that real market dynamics will influence how this model fits itself into the construction world of low-cost housing. The sustainable approach that this thesis advocates needs further consolidation. The author suspects there will be strong resistance in the local construction markets towards new technological solutions such as those proposed within this research work.

Enhanced Joints

Based on hands-on experience with fabrication and assembly, some aspects of joint design showed potential for improvements and further enhancements. The author intends on building a number of enhanced joints and prototypes in collaboration with the Department of Structural and Geotechnical Engineering at La Sapienza to use the available expertise and laboratories.

Further Structural Testing

The author is interested in verifying the capacity of an overall housing unit rather than its individual components. Usually simulating and predicting the structural behaviour of such complex assemblies is a challenge as it relies heavily on the homogeneity of the material. With more forces and critical scenarios, other structural tests are important to further validate the construction logic. The original plan for structural testing was to perform all different variations of structural loadings according to the ASTM standards such as: Compressive, Tensile, Horizontal Transverse, Transverse Strength, Vertical Transverse, Concentrated and Racking Loading. This was not feasible due to time, machinery and budget limitations. It is however foreseen to perform compressive loading and to model the behaviour of the material in Finite Element Software (FEA) studying bigger scenarios in which different wall assemblies are put together at full scale under accurate design loads.

Design Interface / Web-based interface

For the sake of the proof of concept prototypes, a limited number of iterations were needed which in turn did not necessitate the preparation of a parametric model. It is projected however for the future developments of this research to have an interface in which wall, ceiling and floor modules can be interactively modified in a simple user-friendly customisation interface. This web-based design interface is always available and infinitely patient as described by Larson (cited in Huang et al., 2006). This in turn translates into more customizability for the end-user where he gets involved in the earlier design phases and not only as an assembler of pre-cut pieces.

BIBLIOGRAPHY

3dprintcanalhouse. (2013). *http://3dprintcanalhouse.com/construction-technique*. Retrieved June 18, 2015, from http://3dprintcanalhouse.com/

Aicher, S. G. (2014). *Materials and Joints in Timber Structures: Recent Developments of Technology.* Dordrecht, Heidelberg, Newyourk, London: Aicher, S., Garrecht, H., & Reinhardt, H. W.

Akmal, T., Fahmy, M., & El-Kadi, A. (2011). Rice-straw based cement brick microclimatic thermal impact assessment in Cairo, Egypt. *World Renewable Energy Conference.* Linköping: Linköping University.

Alvarado, R. G., & Turkienicz, B. (2010). Generative House: Exploration of Digital Fabrication and Generative System for Low-cost Housing in Southern Brazil. *Proceedings of the 14th Congress of the Iberoamerican Society of Digital Graphics*, (pp. 384-387). Bogota. Retrieved from http://cumincad.scix.net/cgi-bin/works/Show?sigradi2010_384

Barnes, T. G., & Feldman, G. (1982). *Breakdown and Rebirth 1914 to the present: A documentary history of modern Europe.* Lanham, MD: University Press of America, Inc.

BASF. (2007). *Literature and News - Design Guides.* Retrieved November 10, 2016, from BASF Plastic Portal North America: http://www2.basf.us/webplasticsportal/cre?gui=1&dtitle=searchResult&dtext=1&objecttype=ktn_technical_documents&ktn_t_doctype=Design_Guide

BAYER. (2012). *Snap-Fit Joints for Plastics.* Retrieved from FabCentral: http://fab.cba.mit.edu/classes/S62.12/people/vernelle.noel/Plastic_Snap_fit_design.pdf

Boeykens, S. (2012). Bridging Building Information Modeling and Parametric Design. *9th European Conference of Product and Process Modelling* (pp. 453-458). Reykjavik: Taylor and Francis Group (London).

Botha, M., & Sass, L. (2006). The Instant House: A Model of Design Production with Digital Fabrication. *International Journal of Architectural Computing*, 109-123.

Brew, J. S. (2005). Resource efficient wood framing technology from Japan. *The 2005 World Sustainable Building Conference SB05Tokyo*, (pp. 2653-2658). Tokyo.

Cai, Z., & Ross, R. J. (2010). *Wood Handbook, Chapter 12: Mechanical Properties of Wood-Based Composite Materials.* Madison, WI: Department of Agriculture, Forest Service, Forest Products Laboratory. Retrieved January 24, 2017, from Forest Products Laboratory: https://www.fpl.fs.fed.us/documnts/fplgtr/fplgtr190/chapter_12.pdf

Callicot, N. (2001). *Computer Aided Manufacture in Architecture, Pursuit of Novelty.* Oxford, Auckland, Boston, Johannesburg, Melbourne, New Delhi: Architectural Press.

Canadian Centre for Architecture. (2007). *Greg Lynn: Embryological House*. Retrieved June 15, 2015, from http://www.cca.qc.ca/en/collection/6-greg-lynn-embryological-house

Cao, M. (2015). *Comparative Study of Traditional Jointing Techniques of Vernacular Timber Framings in New England, America and Jiangnan, China and Some Applications Conservation Practice (Masters Thesis).* New York: Columbia University Academic Commons.

Center for Affordable Housing Finance in Africa. (2015). *Housing Finance in Africa: A review of some of Africa's housing finance markets.* Parkview, Gauteng: Centre for Affordable Housing Finance in Africa.

Davies, C. (2005). *The prefabricated home.* Wiltshore: Reaktion Books Ltd.

Davis, D., Burry, J., & Burry, M. (2011). Untangling Parametric Schemata: Enhancing Collaboration through Modular Programming. *Designing Together: Proceedings of the 14th International conference on Computer Aided Architectural Design* (pp. 55-68). Liège: Les Éditions de l'Université de Liège.

Dol, K., & Haffner, M. (2010). *Housing Statistics in the European Union.* Delft: OTB Research Institute for the Built Environment, Delft University of Technology.

ECOboard. (2016). *ECOBoard Standard*. Retrieved February 8, 2017, from www.eco-boards.eu: http://www.eco-boards.eu/sample-page/ecoboard-standard/

ECOboard. (n.d.). ECOBoard Handling & Fabrication Guidelines. Delft: ECOboard Europe B.V.

EN789. (2005). *European Standards UNI EN 789:2005.* Milano: Ente Nazionale Italiano di Unificazione.

Fabfoundation. (2015). *http://www.fabfoundation.org/fab-labs/what-is-a-fab-lab/*. Retrieved June 22, 2015, from http://www.fabfoundation.org/

Facit Homes. (2015). *facit-homes.com/making-it-happen/budgets-prices-costs*. Retrieved May 30, 2015, from http://facit-homes.com/

Garas, G., Allam, M., & El Dessuky, R. (2009). Straw bale construction as an economic environmental building alternative - A case study. *ARPN Journal of Engineering and Applied Sciences, 4*(9), 54-59.

Gardiner and Theobald. (2011). *International Construction Cost Survey.* Gardiner and Theobald LLP.

Gibson, I., Stucker, B., & Rosen, D. (2010). *Additive Manufacturing Technologies.* New York: Springer.

Giles, H. (2008). Prefabricated Construction using Digitally Integrated Industrial Manufacturing. *Enquiry ARCC, Volume 5*(Issue 2), 48-65.

Gilmore, J. H., & B. Joseph Pine II. (1997, January - February). *The Four Faces of Mass Customization*. Retrieved August 15, 2016, from Harvard Buiness Review: https://hbr.org/1997/01/the-four-faces-of-mass-customization

Global property guide. (2015, October 01). *Egypt's property market surprisingly resilient*. Retrieved October 23, 2016, from www.globalpropertyguide.com: http://www.globalpropertyguide.com/Middle-East/Egypt/Price-History

Groat, L., & Wang, D. (2013). *Architectural Research Methods.* New Jersey: John Wiley & Sons, Inc.

GTZ Egypt. (2009). *Cairo's Informal Areas Between Urban Challenges and Hidden Potentials: Facts, Voices, Visions.* Cairo: Participatory Development Programme in Urban Areas (PDP).

Güler, C. (2015). Research on the Production of the Composite Panels from some agricultural residues. *Proligno Peer-Reviewed Open Access Scientific Journal*, 187-191.

Hackerspaces. (2015). *Hackerspaces*. Retrieved May 20, 2015, from http://hackerspaces.org/

Hayes, J. (2005). *Digital Fabrication in the production of affordable housing (MSc Thesis).* Ottawa: Carlton University. Retrieved from ProQuest Dissertations and Theses: http://search.proquest.com/pqdtft/docview/305006044/fulltextPDF/13B9104C45353EF3760/26?accountid=37552

Hayes, M. (1998). *Agricultural Residues: A Promising Alternative to Virgin Wood Fiber*. Retrieved October 23, 2016, from http://www.woodconsumption.org/: http://www.woodconsumption.org/alts/meghanhayes.html

Hebraken, H. J. (1999). *Supports: An alternative to mass housing.* London: Urban International Press.

Herbert, G. (1984). *The Dream of the Factory-Made House.* Massachusetts: The MIT Press.

Hounshell, D. (1985). *From the American System to Mass Production, 1800-1932: The Development of Manufacturing Technology in the United States (Studies in Industry and Society).* Maryland: Johns Hopkins University Press.

Huang, J. C., Krawczyk, R. J., & Schipporeit, G. (2006). Integrating Mass Customization with Prefabricated Housing. *Computing in Architecture: Re-Thinking the Discourse* (pp. 124 - 136). Sharjah: The Arab Society for Computer Aided Architectural Design (ASCAAD).

Imperiale, A. (2012). An American wartime dream: The packaged house system of Konrad Wachsmann and Walter Gropius. *ACSA Fall Conference* (pp. 39 - 43). Philadelphia: Temple University.

Iwamoto, L. (2009). *Digital Fabrications: Architectural and Material Techniques.* New York: Princeton Architectural Press.

Khabazi, Z. (2009). *Algorithmic modeling with Grasshopper.* Retrieved September 30, 2015, from http://blog.rhino3d.com: http://blog.rhino3d.com/2009/04/algorithmic-modelling-with-grasshopper.html

Kieran, S., & Timberlake, J. (2004). *Refabricating Architecture, How manufacturing methodologies are poised to transform building construction.* (C. Levine, Ed.) New York, United States of America: McGraw-Hill Companies.

Kierantimberlake. (2015). Retrieved June 20, 2015, from http://www.kierantimberlake.com/pages/view/14/cellophane-house/parent:3

Kiganda, A. (2015, April 24). *Boosting affordable housing in Africa using ABTs*. Retrieved from Construction Review Online: https://constructionreviewonline.com/2015/04/boosting-affordable-housing-in-africa-using-abts/

Kilian, A. (2003). Fabrication of partially double-curved surfaces out of flat sheet materials through a 3D puzzle approach. *Proceedings of the ACADIA Conference: Connecting Crossroads of Digital Discourse* (pp. 74 - 81). Muncie, Indiana: The Association for Computer Aided Design in Architecture.

Kloeser, L., Kües, U., Schöpper, C., Hosseinkhani, H., Schütze, S., Dantz, S., . . . Kharazipour, A. (2007). Panel Boards and Conventional Adhesives. In U. K. (Ed.), *Wood Production, Wood Technology, and Biotechnological Impacts* (pp. 297-349). Göttingen: Universitätsverlag Göttingen.

Kolarevic, B. (2003). *Architecture in the Digital Age: Design and Manufacturing.* New York & London: Taylor & Francis Routledge.

Kolarevic, B. (2008). The risky craft of digital making. In &. K. B. Kolarevic, *Manufacturing Material Effects, rethinking design and making in architecture* (pp. 119-128). NewYork & London: Routledge.

Lawrence, T. T. (2003, May 09). Chassis + Infill: A Consumer-Driven, Open Source Building Approach for Adaptable, Mass Customized Housing. *Master of Science in Mechanical Engineering*. Massachusetts: Massachusetts Institute of Technology.

Lefteri, C. (2007). *Making it, Manufacturing Techniques for Product Design.* London: Laurence King Publishing in association with Central Saint Martinis College.

Lintu, L. (1973). *Panels, paper and paperboard from agricultural residues.* Retrieved October 23, 2016, from FAO Corporate Document Repository: http://www.fao.org/docrep/l2015e/l2015e03.htm

Lynn, G. (1998). *Animate Form.* New York: Princeton Architectural Press.

Mansour, A., Srebric, J., & Burley, B. (2007). Development of Straw-cement Composite Sustainable Building Material for Low-cost Housing in Egypt. *Journal of Applied Sciences Research, 3*(11), 1571-1580.

Marriage, G., & Sutherland, B. (2014). New Digital Housing Typologies. *Across: Architectural Research through to Practice: 48th International Conference of the Architectural Science Association* (pp. 383–394). Genoa: F. Madeo, M. A. Schnabel.

McCullough, M. (1997). *Abstracting Craft: The Practiced Digital Hand.* Cambridge, MA: MIT Press.

Micro Compact Home. (2015). Retrieved June 15, 2015, from http://www.microcompacthome.com/

MoMA Home Delivery. (2008). Retrieved May 15, 2015, from http://www.momahomedelivery.org/

Open Building Institute. (2016). Retrieved February 13, 2017, from Open Building Institute: http://openbuildinginstitute.org/

Peinovich, E., & Fernández, J. (2012). Localised Design-Manufacture for Developing Countries. *Beyond Codes and Pixels: Proceedings of the 17th International Conference on Computer-Aided Architectural Design Research in Asia* (pp. 285-294). Hong Kong: Association for Computer-Aided Architectural Design Research in Asia (CAADRIA).

Pottmann, H., Asperl, A., Hofer, M., & Kilian, A. (2007). *Architectural Geometry.* Pennsylvania: Bentley Institute Press.

Prynne, M. (2014, June 18). *British homes are the smallest in Europe, study finds*. Retrieved October 24, 2016, from The Telegraph: http://www.telegraph.co.uk/finance/property/10909403/British-homes-are-the-smallest-in-Europe-study-finds.html

Rayo, D. A. (2015). Option One: A Model of Participatory Design to Construct a Rural Social Housing From Digital Fabrication. In B. Martens, G. Wurzer, T. Grasl, W. Lorenz, & R. Schaffranek (Ed.), *Real Time - Proceedings of the 33rd International Conference on Education and Research in Europe. Volume 2*, pp. 531-539. Vienna: eCAADe (Education and Research in Computer Aided Architectural Design in Europe) and Faculty of Architecture and Urban Planning, TU Wien.

Robeller, C., Mayencourt, P., & Weinand, Y. (2014). Snap-fit joints, CNC fabricated, Integrated Mechanical Attachment for Structural Wood Panels. *ACADIA 14: Design Agency, Proceedings of the 34th Annual Conference of the Association for Computer Aided Design in Architecture* (pp. 189-198). Los Angeles: ACADIA.

Sass, L. (2005). Wood Frame Grammar: CAD Scripting a Wood Frame House. *Proceedings of the 11th International Conference on Computer Aided Architectural Design Futures* (pp. 383-392). Vienna: Springer.

Sass, L. (2006). A wood frame grammar: A generative system for digital fabrication. *International Journal of Architectural Computing, Volume 04*(Issue 01), 51-68.

Schindler, C. (2007). *http://www.caad.arch.ethz.ch/wiki/uploads/Organisation.* Retrieved September 21, 2015, from http://www.caad.arch.ethz.ch/: http://www.caad.arch.ethz.ch/wiki/uploads/Organisation/2007_Schindler_Information-tool-technology.pdf

Schodek, D., Bechthold, M., Griggs, J. K., Kao, K., & Steinberg, M. (2004). *Digital Design and Manufacturing: CAD/CAM Applications in Architecture and Design.* Hoboken, New Jersey: John Wiley & Sons, Inc.

Sears. (2012, March 21). *Homes*. Retrieved from Sears Archives: http://www.searsarchives.com/homes/index.htm

Stevens, J., & Nelson, R. (2015). *Digital Vernacular: Architectural Principles, Tools, and Processes.* New York & London: Routledge.

Stoutjesdijk, P. (2014). *Our process*. Retrieved May 25, 2015, from ECOnnect: A house for everyone: http://www.eco-nnect.eu/

Subrizi, S. (2014, May 05). *Sergio Subrizi: how I built a MechMate CNC router on my own*. Retrieved from Open Electronics: https://www.open-electronics.org/sergio-subrizi-how-i-built-a-mechmate-cnc-router-on-my-own/

Sumiyoshi, T., & Matsui, G. (1991). *Wood Joints in Classical Japanese Architecture.* Japan: Kajima Instiute Publishing Co. Ltd.

Terzidiz, K. (2006). *Algorithmic Architecture.* Oxford: Elsevier Ltd.

The Museum of Modern Art. (2008, July 31). Home Delivery Walkthrough: Digitally Fabricated Housing for New Orleans.

Thurston, R. H. (2011). *A History of the Growth of the Steam-Engine.* New York: D. Appleton and Company.

Tsen, S., & Jumaat, M. Z. (2012). Comparison of Eurocodes EN310 and EN789 in Determining the Bending Strength and Modulus of Elasticity of Red Seraya Plywood Panel. *International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering*, 159-163.

UN. (2005). *Population Challenges and Development Goals.* Newyork: Department of Economic and Social Affairs-United Nations.

UN-Habitat. (2011). *UN-Habitat Annual Report 2010.* Kenya: United Nations Human Settlements Programme.

UNHCR. (2015). *Global Trends: Forced Displacement in 2014.* Geneva: The UN Refugee Agency.

UNHCR. (2017, February 28). *Syria Regional Refugee Response Inter-agency Information Sharing Portal*. Retrieved from http://data.unhcr.org/syrianrefugees/country.php?id=8

United States Census Bureau. (2010). *Median and Average Square Feet of Floor Area in New Single-Family Houses Completed by Location.* Retrieved October 24, 2016, from www.census.gov: https://www.census.gov/const/C25Ann/sftotalmedavgsqft.pdf

Vischer, L. (2015). Shaping CNC-cut plywood structures: Design principles for CNC-milled panel wood connections in a safe spanning structure. *MSc Thesis*. Delft, Netherlands: Delft University of Technology.

Watson, I. (2001, January 15). *An Introduction to Design Guidelines*. Retrieved from Planners Web: http://plannersweb.com/2001/01/an-introduction-to-design-guidelines/

Woodbury, R. (2010). *Elements of Parametric Design.* New York: Routledge.

Zarzycki, A. (2012). Component-Based Design Approach Using BIM. *Proceedings of the 30th Digital Physicality - International Conference on Education and research in Computer*

Aided Architectural Design in Europe (pp. 67-76). Prague: eCAADe (Education and research in Computer Aided Architectural Design in Europe) and ČVUT, Faculty of Architecture.

Zellner, P. (1999). *Hybrid Space: Generative Form and Digital Architecture.* New York: Rizzoli International Publications.

Appendix A | Detailed Mechanical Tests

This appendix details and documents the experiments performed by the author along with professors from the Structural and Geotechnical Engineering Department; and Material Testing Lab in La Sapienza university to determine some basic mechanical properties of the wheat straw panel (ECOboard – standard 18 mm thick boards). It reports upon the procedures, test piece preparation, loading arrangement and testing methods followed through the mechanical tests. It highlights -when important- the adjustments or limitations faced with respect to the test piece dimensions, testing equipment, loading method or procedure. It is important to emphasise that the results of these tests shall be regarded as indicative because the norm was not strictly followed due to several reasons that will be addressed in their proper locations.

8.1 Material mechanical properties

In general terms, the team decided to roughly follow the European Norm (UNI EN 789:2005) that outlines "testing methods for determining some mechanical properties of commercial wood-based panel products for use in load-bearing timber structures". These properties are intended for the calculation of characteristic values for use as material design values. According to the norm, the tests need only be carried out once for each product, unless there is a reason to suspect a significant change has occurred in the properties of the product (EN789, 2005).

The reason for following EN789 instead of EN310 for the mechanical properties is that EN789 gives safer values for Modulus of Rapture (MOR). For example, the bending test in EN789 is a 4-point test instead of 3-point test applied by EN310, this guarantees that deflection values are measured in the zone of uniform moment. The overestimation of MOR of three-point bending is due to the evaluation point of bending strength and the depth and length of test piece. The evaluation point of bending strength for three-point bending test is located pointwise at the mid-span whereas the four-point bending test is located at the weakest point between the loading noses (Tsen & Jumaat, 2012).

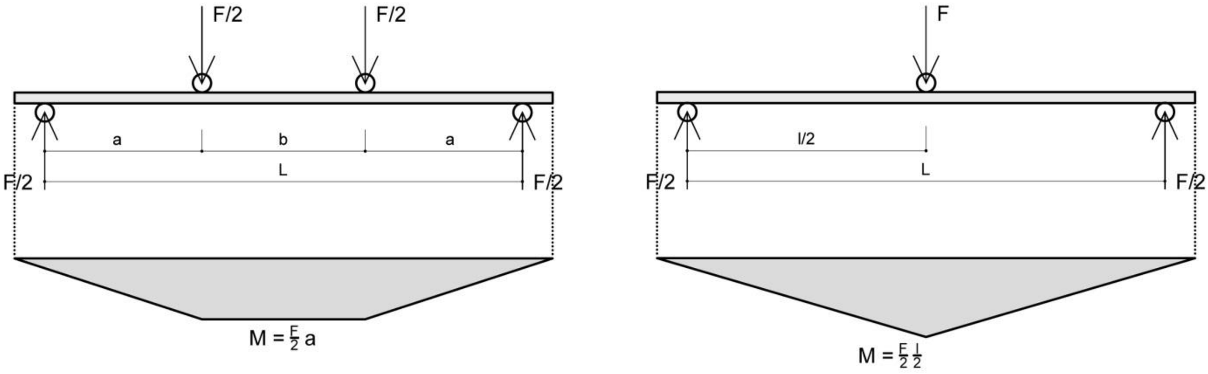


Figure 8-1: 3-point bending vs 4-point bending tests

Due to time and material availability limitations, the author decided to perform the following tests two times in opposite directions with respect to fibre -if any- to verify if the material behaves in the same manner in the two different verses:

- 4-point bending
- Axial tension
- Axial compression

The purchased panels came from the vendor already cut in half-size (1200 x 1200 mm) for ease of transportation. It was impossible to define a certain directionality of the fibres of the panels using visual examination. Given the doubts outlined before about the homogeneity of the material composition, and even if two random sheets were chosen, there would be a high probability that both sheets have the same directionality. Therefore, the team decided to always cut the test pieces for every mechanical test from the same sheet in two opposite orientations as shown in Figure 8-2. This necessitated the re-dimensioning of some test pieces to fit within the existing sheet sizes.

Three types of electric wood saws were used for the preparation of the test pieces: a hand-held circular saw, alternative saw and band saw. The cut edges were not further treated or processed unless otherwise mentioned.

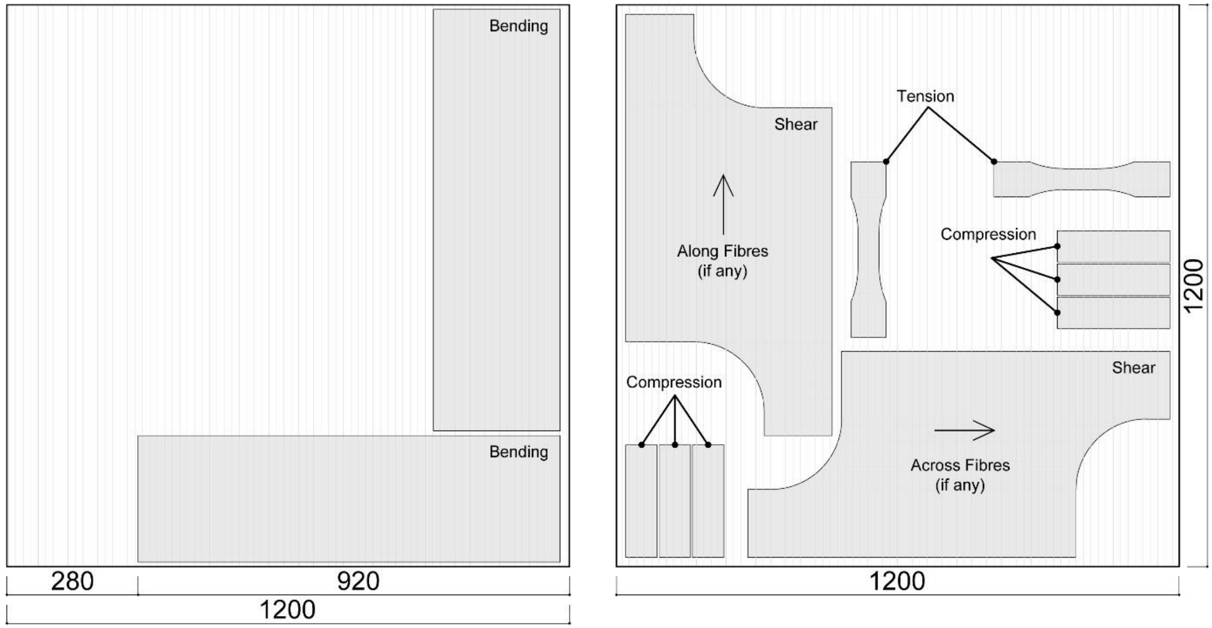


Figure 8-2: Test pieces cut-sheet layout designed so that each test has two samples taken from the same sheet in two opposite directions with respect to fibres. A border clearance of 20 mm was left on all sides to avoid material deterioration caused by handling and storage.

Figure 8-3: Test piece preparation, cutting and final edge condition

8.1.1 Bending Test

8.1.1.1 Test piece dimensions and preparation

According to the EN789 code, the test pieces shall be of rectangular cross section, in which the depth is equal to the thickness of the panel (18 mm) and the width is (300±5) mm. The length shall be calculated based on the nominal thickness of the panel following the arrangement of the loading method as shown in Figure 8-4.

Due to the previously mentioned problem of not being able to define the directionality of the panels using visual examination, the two test pieces for the bending test needed to be extracted from the same sheet. This was not possible using the dimensions provided by the European code UNI EN 789 as the two pieces would not fit into the 1200 x 1200 mm sheet. A reduction of 10% was applied to length and width dimensions of the test piece making its new overall dimensions: 890 x 270 x 18 mm.

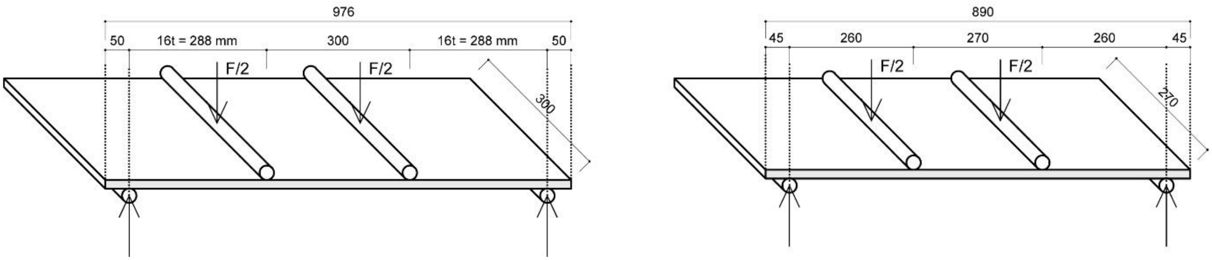


Figure 8-4: (Left): Test piece dimensions and arrangement according to UNI EN 789. (Right): Reduced test piece dimensions used in Lab test.

8.1.1.2 Test setup and loading arrangement

The same reduction was applied proportionally to all setup dimensions. The distance between the vertical load points was set to 270 mm instead of 300 mm. The distance between the load point and the support were to be 16 times the nominal thickness of the panel (16 x 18 = 288 mm) but were set to 260 mm. To give freedom for any eventual sliding of the test piece an extra 45 mm were added on both sides.

The test was setup as shown Figure 8-5 in which:

- All supports, rollers, test piece and steel bracket of the test setup were manually aligned to obtain a symmetrical system (to the best of the author's capacity).
- The steel bracket that holds the LVDT was manually cold bended to the shown shape.

- A self-aligning hinge was placed on the top of the whole setup to ensure alignment and uniform load application.
- Material Testing System (MTS) 810 Machine was used with HBM 5kN loading cell (Typ U9B – 1mV/V).

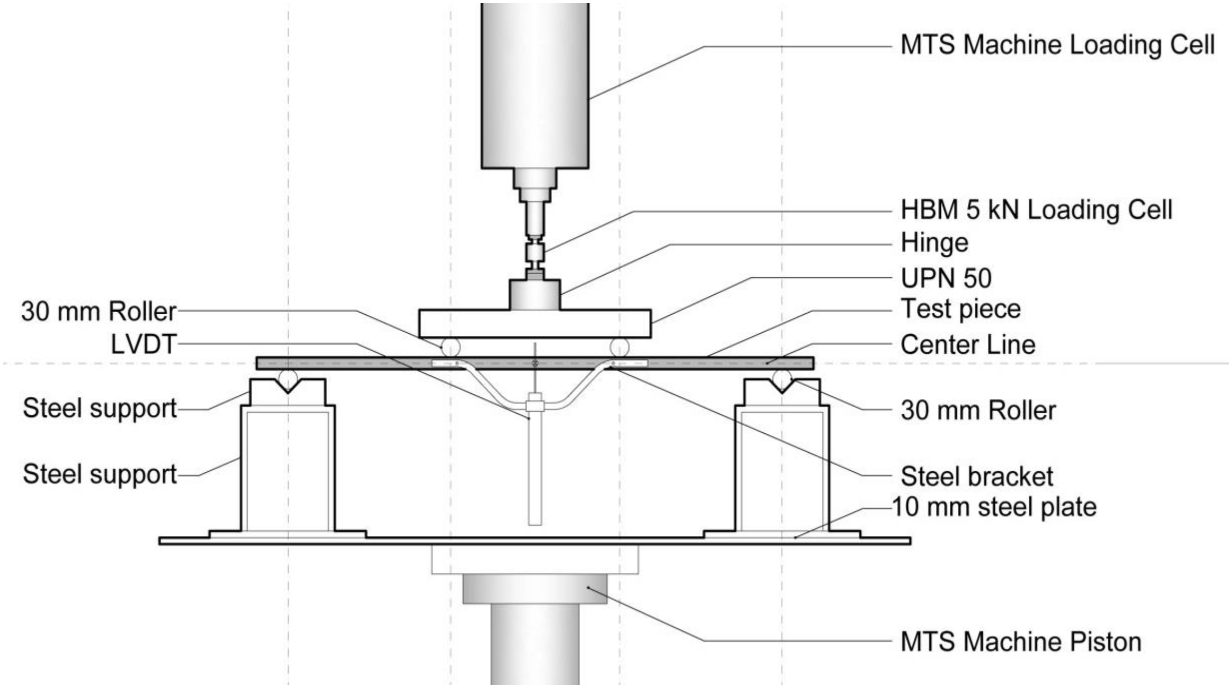


Figure 8-5: Illustration of the 4-point bending test setup

MTS Loading cell electronic thermal noise was checked and confirmed to be within 20 N. The HBM loading cell was also calibrated as shown in Figure 8-6

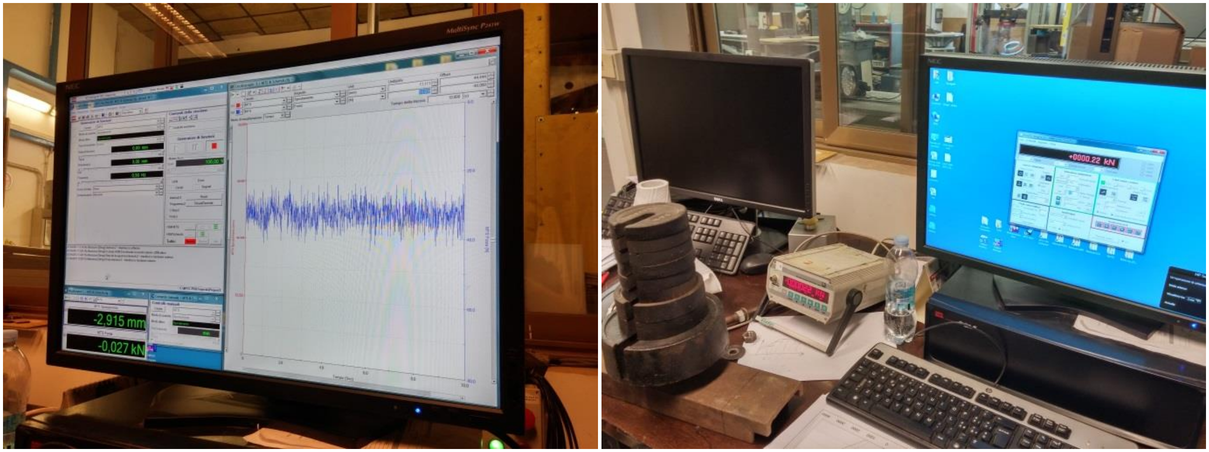


Figure 8-6: (Left) MTS Thermal electronic noise checking. (Right) Calibration of HBM loading cell

8.1.1.3 Test procedure

1- For test piece 1:
   - Preloading of 40 Newtons was applied using manual control of MTS.
   - A constant velocity of load application was set to 4 mm/min till rapture.
   - Video documentation of the whole test was performed.
2- For test piece 2:
   - Preloading of 40 Newtons was applied using manual control of MTS.
   - A constant velocity of load application was set to 8 mm/min till rapture.
   - Video documentation of the whole test was performed.

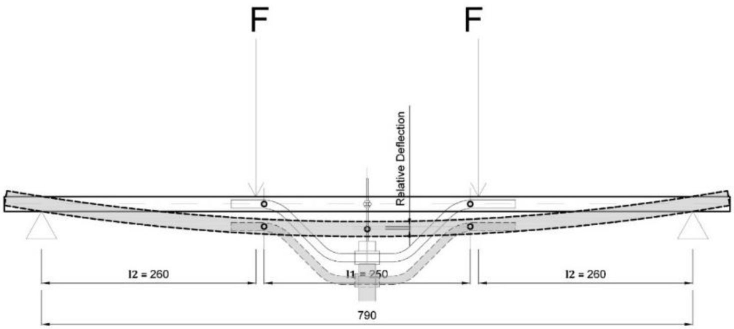


Figure 8-7: Graphical scheme of bending test based on EN789

For both tests, the weight of the two rollers (2 x 1070 gm), hinge (3470 gm), UPN beam (4420 gm), steel bracket for LVDT (500 gm) with the sum of 103 N is added to the overall loads as they represent part of the load supported by the test piece.

8.1.1.4 Results and observations

For the first test piece, rapture was reached within 780 seconds at a maximum load of (1527 N applied by the MTS machine + 103 N = 1630 N). After plotting the graph between load and deflection, it was observed that the slope of the curve changed suddenly at one point as shown in Figure 8-8. This is attributed to the fact that the test piece touched the steel base below the rollers, so the span of the test changed slightly. The author did not expect such a strong deflection to occur. However, this did not represent a particular problem for the intended purpose of this test which was the calculation of the modulus of Elasticity. The EN789 states using 0.1 and 0.4 F_{max} as reference points with their respective deformations (u_2 and u_1) which are in the elastic zone of the material and far from the point at which the change of slope took place.

For the second test piece, the two lower rollers were replaced by bigger ones (45 mm diameter instead of 30 mm). Rapture was reached within 6 minutes at a maximum load of (1460 N applied by the MTS machine + 103 N = 1563 N).

From the graph, we can see a consistent behaviour of the two test pieces in the elastic zone with an almost identical slope. Following the equations provided by EN789, the modulus of elasticity for test piece 1 and 2 is as follows:

$$E_m = \frac{(F_2 - F_1) l_1^2 l_2}{16(u_2 - u_1) I}$$

$E_m = \frac{(420-105)(250^2)(260)}{16(1.45-0.24)(131220)}$ = **2014 N/mm² or MPa**……. *Test piece 1*

$E_m = \frac{(584-146)(250^2)(260)}{16(1.92-0.44)(131220)}$ = **2290 N/mm² or MPa**……. *Test piece 2*

Bending strength of the test piece:

$$f_m = \frac{F_{max} l_2}{2W}$$

$$f_m = \frac{(1560)(260)}{2(270 * \frac{18^2}{6})} = \mathbf{13.9}\ \frac{\boldsymbol{N}}{\boldsymbol{mm^2}}\ \boldsymbol{or\ MPa}$$

The moment of capacity of the test piece:

$$M_{max} = \frac{F_{max}\ l_2}{2}$$

$$M_{max} = \frac{(1560)\ (260)}{2} = \mathbf{202800}\ \boldsymbol{N.mm}$$

Where

E_m is the modulus of elasticity in bending
F_2-F_1 is the increment of load between $0.1F_{max}$ and $0.4F_{max}$
u_2-u_1 is the increment of deflection corresponding to F_2-F_1
l_1 is the gauge length shown in Figure 8-7
I_2 is the distance between an inner load point and the nearest support as shown in Figure 8-7
I is the second moment of area of the test piece ($\frac{bt^3}{12}$ where b = panel width, t = panel thickness)
W is the section modulus ($bt^2/6$)

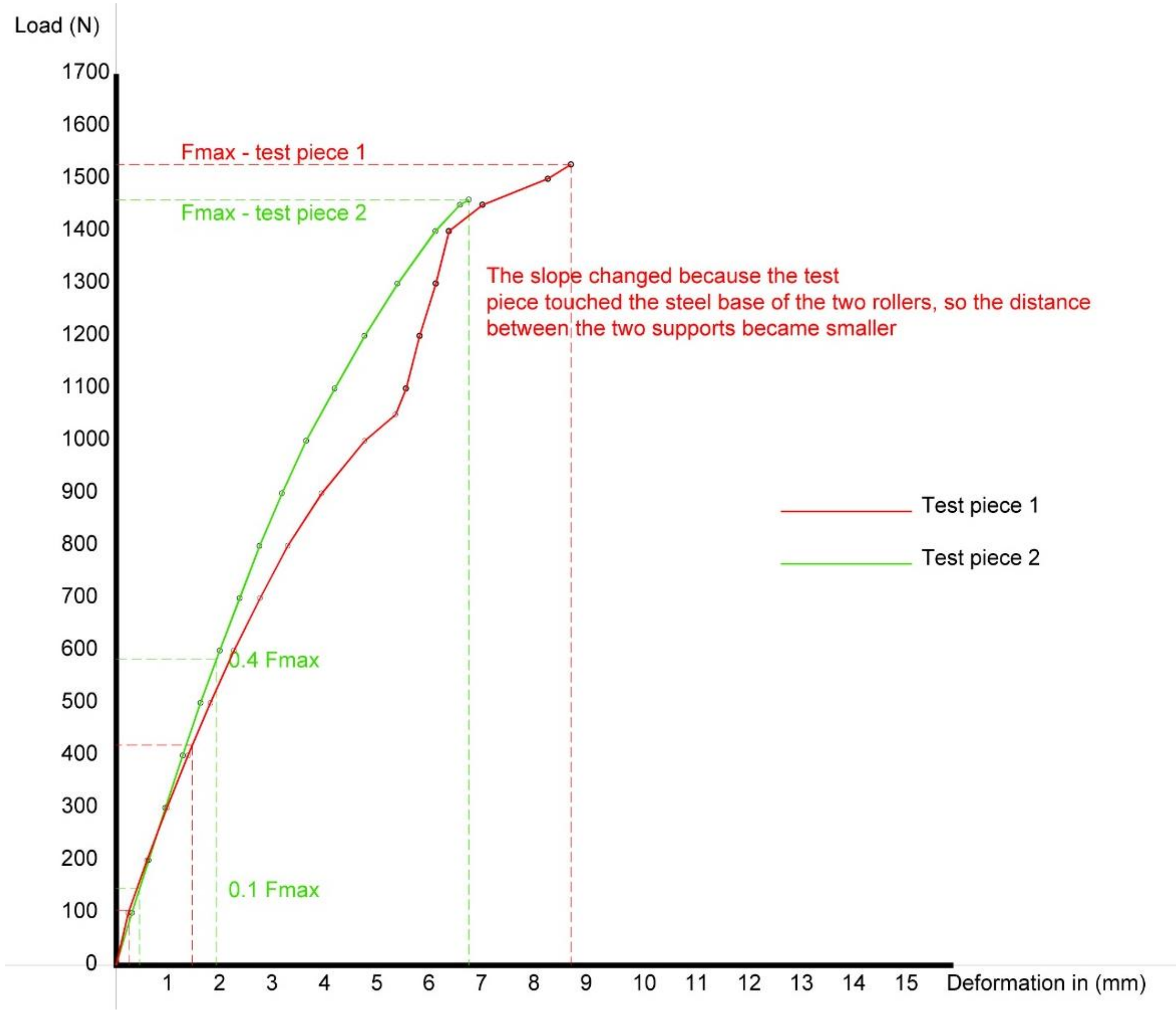


Figure 8-8: Load - Deflection for test piece 1 and 2 in bending

8.1.2 Tension Test

8.1.2.1 Test piece dimensions and preparation

Following the UNI EN 789 standards, the test piece shall have the shape shown in Figure 8-9 (Left), but due to testing machine limitation, a reduction to 30% of original size was made in order to fit the maximum width for the pulling grips of the equipment (Zwick/Roell Z250). This reduction guarantees a uniform distribution of the pulling force on the cross section of the material. The reduction was made applying a scale factor of (3/10) on the overall dimensions maintaining the proportions of the test piece as shown in Figure 8-9 (Right).

60 mm long strain gauges -produced by Tokyo Sokki Kenkyujo Co- were glued using Z70 glue which is a single component, cold curing adhesive made of cyanacrylate. The strain gauges were adhered to both sides of the test pieces at the centre of the central zone.

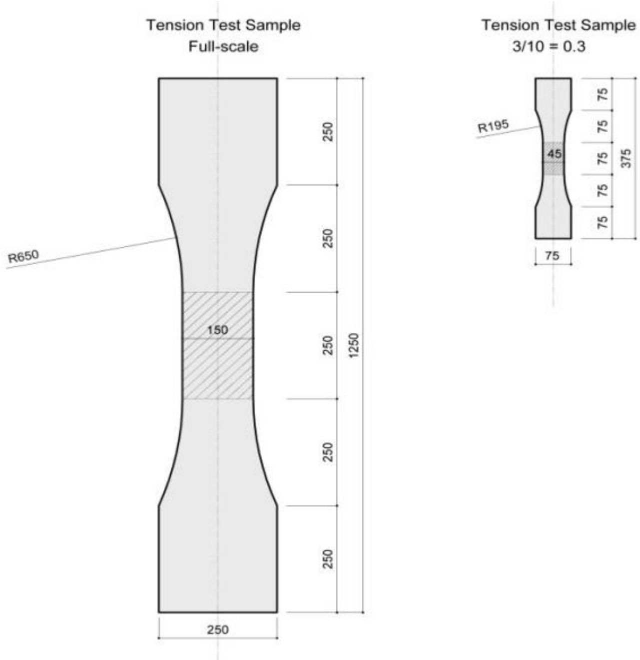


Figure 8-9: (Left): Tension test specimen according to the EN789 norm. (Right): Reduced dimensions due to testing equipment limitations (30% of original size).

8.1.2.2 Test setup and loading arrangement

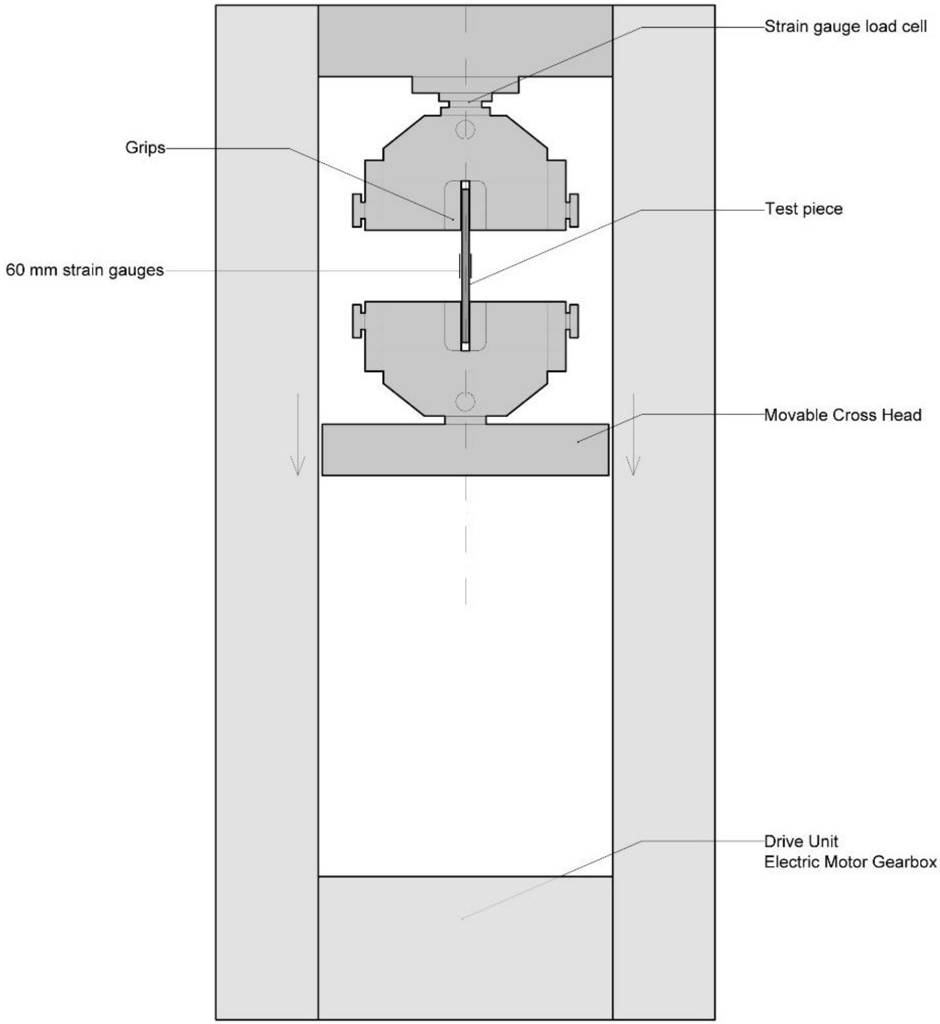


Figure 8-10: Illustration of the axial tension test setup.

8.1.2.3 Test procedure

Given that the tensile strength of ECOboards was not mentioned in the material data sheet of the supplier, various trials were made with velocities of load application in order to reach the maximum force within 300 seconds as defined by EN789. First trials were made with 0.08, followed by 0.2, 0.6 and 2 mm/min.

For test piece 1: A constant velocity of load application was set to 2 mm/min till rapture.

For test piece 2: A constant velocity of load application was set to 0.6 mm/min till rapture.

8.1.2.4 Results and observations

The data obtained from the loading test are time in (seconds), two strains gauge readings at specified time intervals (unitless) and Load in (kN), see appendix C for the raw data of the tests.

For test piece 1, rapture was reached at 6.85 kN in around 90 seconds. For test piece 2, rapture was reached at 5.55 kN in around 240 seconds. The two graphs below show the stress/strain curves of the two test pieces. The two graphs were plotted using the average value of the two strains on the X axis and the stress on the Y axis.

It was observed that the material has a brittle behaviour in tension as the failure was horizontal sudden crush. This can be attributed to the very fine fibres that the material is composed of as shown in Figure 8-11.

It was also found that the material has no specific directionality of fibres as the two samples -cut from the same sheet in opposite directions- failed at almost the same load (5.50 and 6.80 kN). The following images show the failure of both samples.

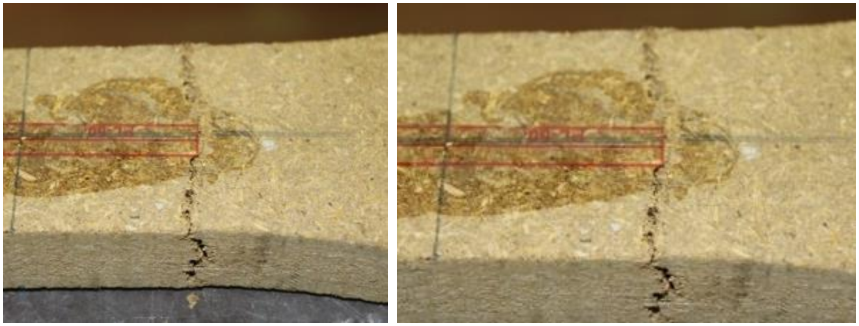
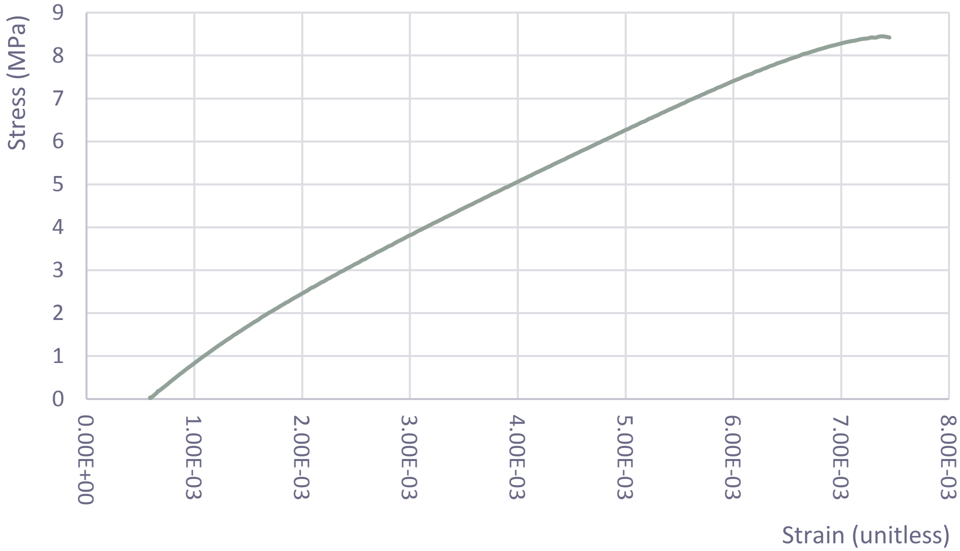


Figure 8-11: (Left) test piece 1 (Right) test piece 2; failure under axial tensile load



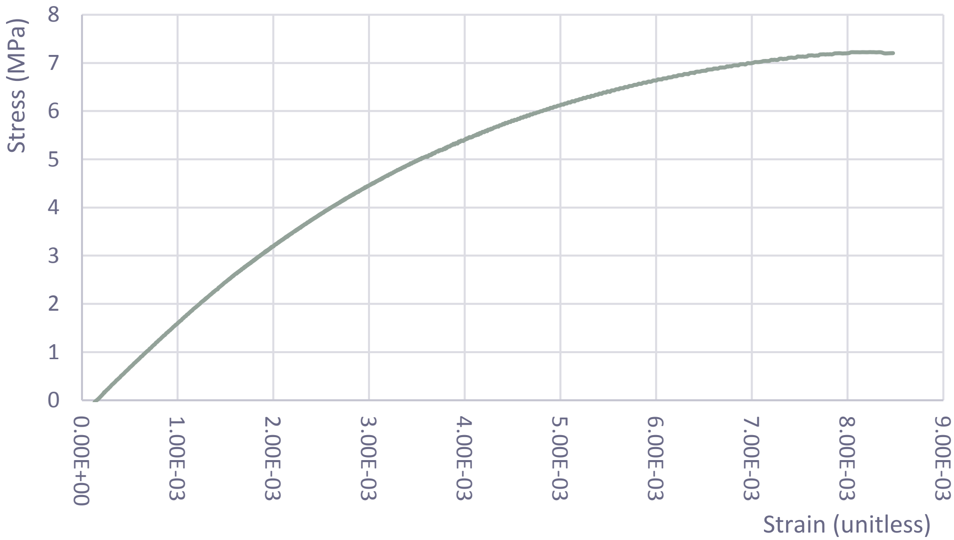


Figure 8-12: (Upper) Stress - Strain curve for tension test piece 1
(Lower) Stress - Strain curve for tension test piece 2

The tension modulus of elasticity of the test piece was calculated according to the formula:

$$E_t = \frac{\Delta Stress}{\Delta Strain}$$

$$E_t = \frac{(\sigma_2 - \sigma_1)}{(\varepsilon_2 - \varepsilon_1)}$$

$E_t = \frac{(3.368-0.842)}{2.67*10^{-3}-1.01*10^{-3}}$ **=1521 MPa (N/mm²)** ....*Test piece 1*

$E_t = \frac{(2.888-0.772)}{1.78*10^{-3}-5.28*10^{-4}}$ **=1730 MPa (N/mm²)** ....*Test piece 2*

The tension strength f_t of the test piece calculated from the following formula:

$$f_t = \frac{F_{max}}{A} = 6840/810$$

= 8.44 N/mm²

Where

A is the cross-sectional area of the test piece at mid-section

σ_2- σ_1 is the increment of stress between $0.1S_{max}$ and $0.4S_{max}$

ε_2- ε_1 is the increment of strain corresponding to S_2-S_1

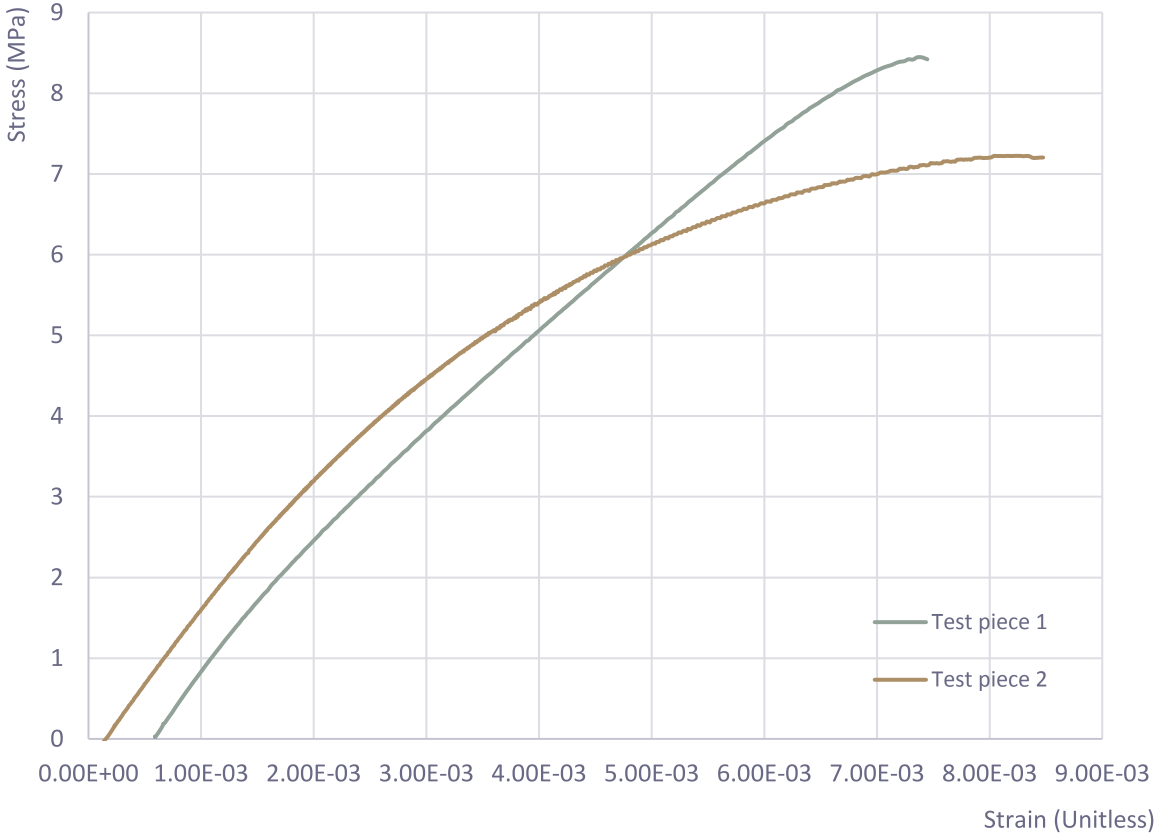


Figure 8-13: Stress - Strain Curves of test piece 1 and 2. The elastic zone can be seen almost identical in both tests.

8.1.3 Compression Test

8.1.3.1 Test piece dimensions and preparation

Following the EN-789 standard, the test piece shall have a rectangular cross section whose dimensions depend on the nominal thickness of the panel. In case of 18 mm panels, three pieces cut from adjacent locations of the panel should be bonded and machined to the dimensions of 220 x 70 x 54 mm. Six pieces (3 for each panel orientation) were cut from adjacent locations in the panel and had the following dimensions: 240 x 70 x 18 mm. They were bonded (glued) using Pattex Vinil universal glue manufactured by Henkel. The glue was applied uniformly on a clean surface in ambient temperature. Small clamps were used to hold the three pieces together. They were left to dry for more than 48 hours. They were later trimmed using a cropper circular bench saw to the overall dimensions of 225 x 70 x 54 mm.

60 mm long strain gauges -produced by Tokyo Sokki Kenkyujo Co- were glued using Z70 glue. The strain gauges were adhered to opposite sides of the test pieces at the centre of the face.

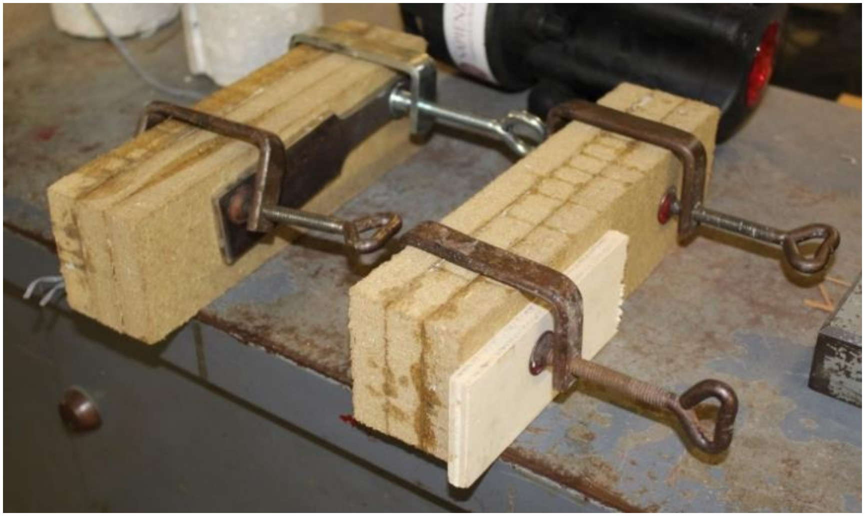


Figure 8-14: (Left) Compression test piece preparation. (Right) Compression loading arrangement using spherical head on the top. A micrometer was used to center the test piece to the center of the circular platform.

8.1.3.2 Test setup and loading arrangement

The loading arrangement of the compression test followed the standard method of EN789 which states that the load shall be applied to the test piece through a spherical connection at the top. As for the rate of load application, a constant rate through which maximum loading can be reached within 300 seconds (±120 seconds).

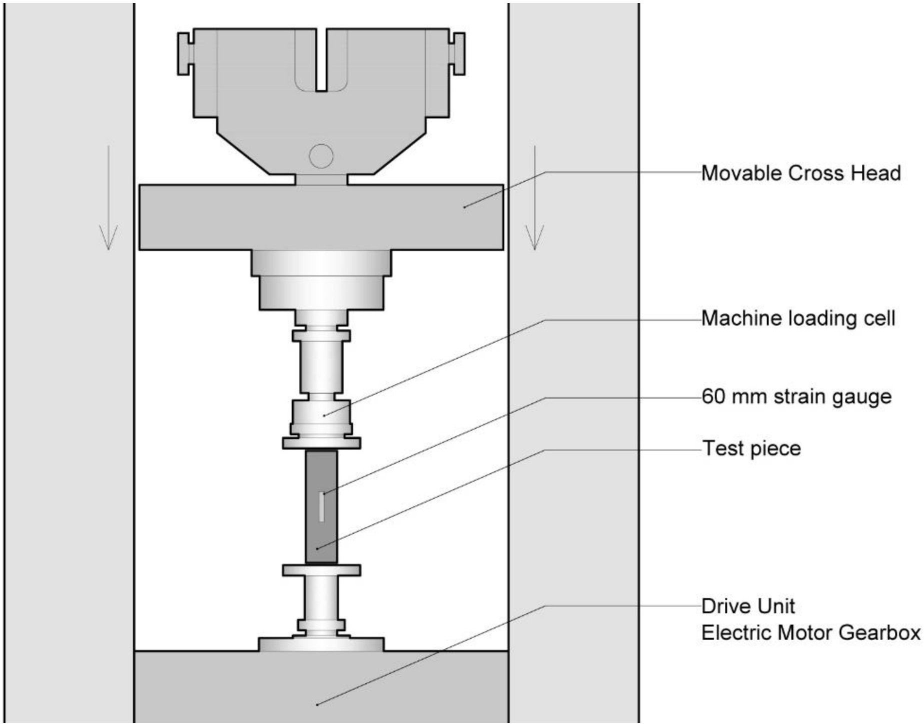


Figure 8-15: Illustration of the axial compression test setup

8.1.3.3 Test procedure

The material supplier data sheet gives only modulus of rapture and modulus of elasticity in bending. The author had limited expectations of the maximum load that the material can bear in compression. A decision was made to start with the same velocity applied in the second tension test which was 0.6 mm/min to primarily explore the response of the material in compression. For test piece 1 and 2, a constant velocity of load application was set to 0.6 mm/min till rapture.

8.1.3.4 Results and observations

The data obtained from the loading test are time in (seconds), two strains gauge readings at specified time intervals (unitless) and Load in (kN), see appendix B for the raw data of the tests.

The two graphs were plotted using the average value of the two strains on the X axis and the stress on the Y axis.

For test piece 1, rapture was reached at 34.40 kN in around 350 seconds. For test piece 2, rapture was reached at 41.20 kN in around 410 seconds. The two graphs below show the stress/strain curves of the two test pieces.

It was observed that the failure behaviour was consistent with natural wood failure modes. The first test piece failed with shearing. The second test piece failed with a combined mode consistent with crushing and splitting.

The material showed a consistent behaviour for the two test pieces with no observable difference between panel orientations. Given the artificial nature of the material being a composite with its characteristics depending primarily on the bonding material (resin) therefore, a coherent result was expected with no major deviations. It came as no surprise that the material performance in compression was better than the performance in tension.

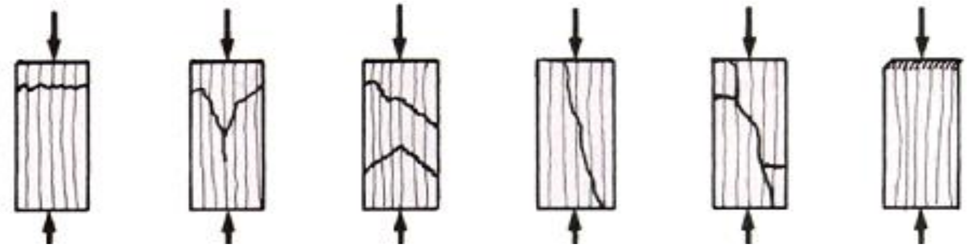


Figure 8-16: Failure types of non-buckling clear wood in compression parallel to grain: (a) crushing, (b) wedge splitting, (c) shearing, (d) splitting, (e) crushing and splitting, (f) brooming or end rolling. **Source:** http://classes.mst.edu/civeng120/lessons/wood/failure/index.html

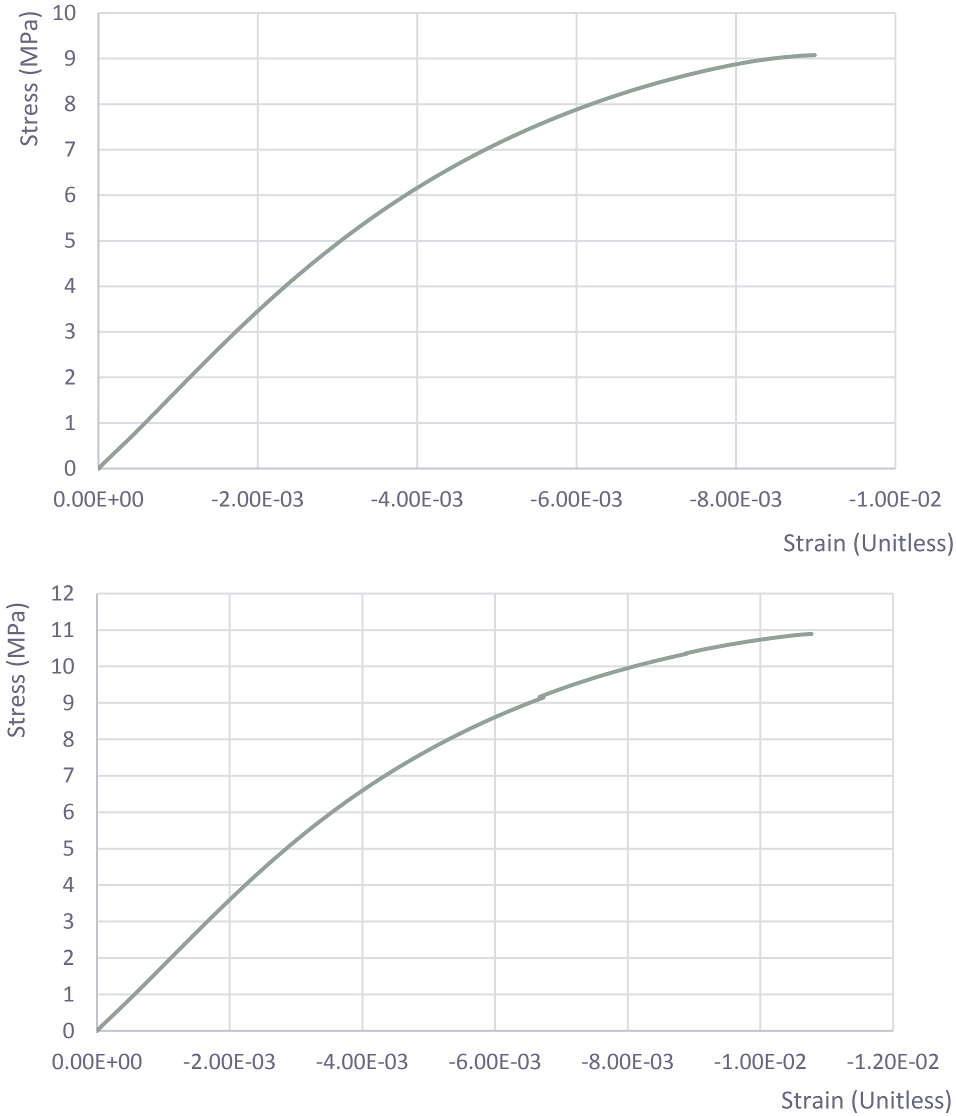


Figure 8-17: (Upper) Stress - Strain curve of compression test piece 1
(Lower) Stress - Strain curve of compression test piece 2

The compression modulus of elasticity of the test piece was calculated according to the formula:

$$E_c = \frac{\Delta Stress}{\Delta Strain}$$

$$E_c = \frac{(\sigma_2 - \sigma_1)}{(\varepsilon_2 - \varepsilon_1)}$$

$E_c = \frac{(3.628-0.907)}{2.10*10^{-3}- 5.32*10^{-4}}$ **=1735 MPa (N/mm²)** ....*Test piece 1*

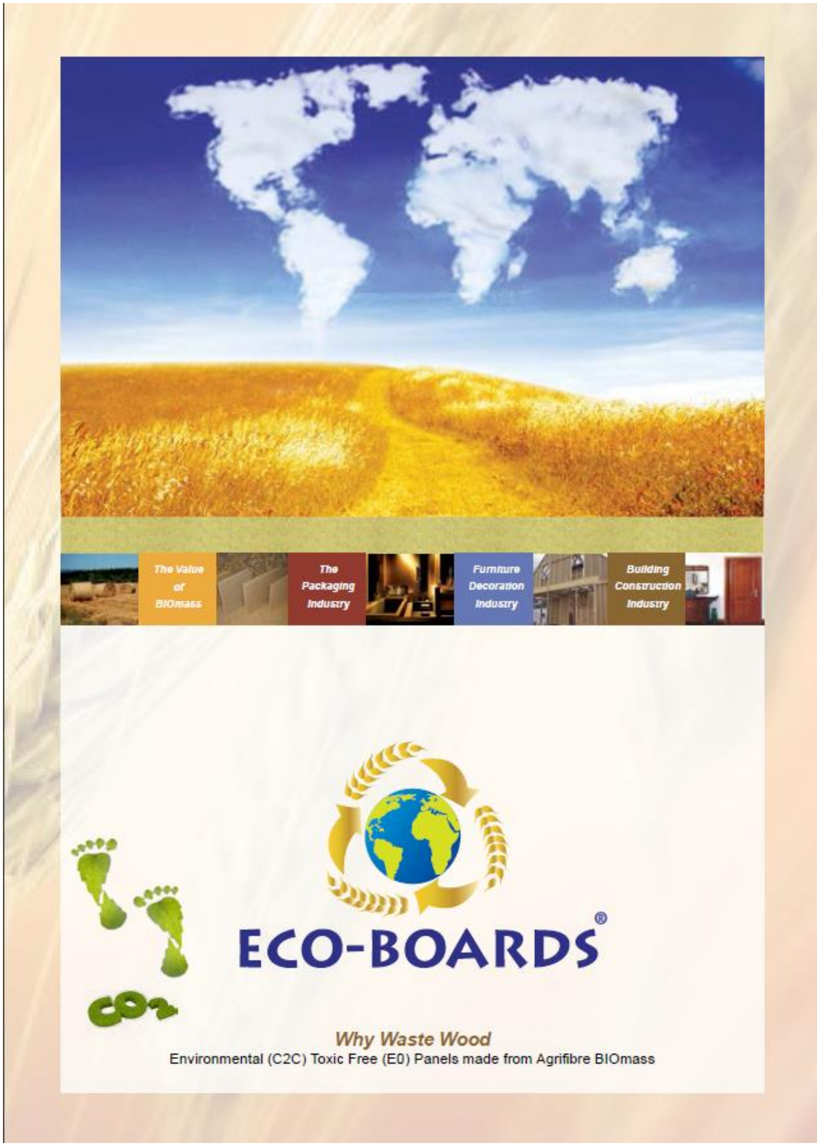
$E_c = \frac{(4.352-1.088)}{2.45*10^{-3}- 6.11*10^{-4}}$ **=1774 MPa (N/mm²)** ....*Test piece 2*

Where

$\sigma_2 - \sigma_1$ is the increment of stress between $0.1\sigma_{max}$ and $0.4\sigma_{max}$

$\varepsilon_2 - \varepsilon_1$ is the increment of strain corresponding to $\sigma_2 - \sigma_1$

Appendix B | ECOboard Commercial Data sheet



Mission Statement

"ECOBoard is committed to a role of environmental, sustainable and socially responsible leadership in all facets of our business. Changing the world one board at a time.

Goal

To create a Blue Biobased Economy by combining Environmentally-friendly innovations and having a large impact on our Carbon Footprint by storing CO2 in Healthy Biobased Buildings & Furniture

Our Values

"We will conduct our business with the highest ethical standards, strive for excellence in all we do, and measure success by the relationships we build in the communities where we live and work."

1 piece of ECOBoard (1220 x 2440 x 18 mm)
Can store and avoid the emission of **150** kg CO2 !
Can reduce the harmfull effects of **4** kg formaldehyde !
One tree with a diameter of **25** cm and 2 m high will NOT be cut !
while the emission quantity is equal to the release of **100** kg Oxygen,
or the total amount of absorbed oxygen by **1** man per year.
Can change **40** kg of waste straw into treasure

ECO-BOARDS®

ECOBoards

ECOBoard Bio based Panels are made from agricultural residues such as straw or reeds and are bonded together with the natural lignine of the cellulose fibres with only 3% additive without any formaldehyde nore other VOCs.

ECOBoards are a healthy and ecological alternative for chipboards, MDF, OSB or Plywood and can be used for a wide range of applications They surpass the structural properties of wood based panels and can be cross-referenced to any relevant international standard such as BSEN 312 / EN 300 / ANSI A208 / etc..

ECOBoards have a NEGATIVE Carbon Footprint of MINUS - 0.98 kg so they actually store or sequestrate CO2 about their own weight! ECOBoards can be used in virtually all applications where conventional boards are used, like the furniture & interior decoration industries, building & construction industries and for industrial packaging. Due to the fact that formaldehyde-free added resin (NAF) is used, ECOBoards have emission levels far below the strict European formaldehyde regulations (E0) and the USA (HUD 24) standards. ECOBoards are suitable for use in environmentally sensitive areas such as schools, nurseries, children's furniture, hospitals, public buildings, laboratories and nursing homes or any eco-friendly domestic application.

Moisture Resistance: ECOBoards are extremely moisture resistant and are specified for use in the most strenuous humid domestic interior conditions where dimensional stability and retained structural intregraty are of great importance.

Fire Resistance: Standard ECOBoards are fire retardant for 30min , since they scorch rather than burn, and we also offer a full range of fire ratings up to 120 min, NEN 13501-1 class B.

High Strength, Lighter Weight: The excellent strength to weight ratio makes handling the product on-site easy.

Screw Tightness: Superior screw holding ability means that a wide choice of fittings can be used.

Machinable: ECOBoards are made in a single layer process giving homogenous consistency througout its thickness, similar to MDF. Its superior internal bond (cross tensile) allows smooth strong profiling and sharp machined edges.

Finishing: When sanded, ECOBoards create an excellent finish and readily accept melamine, formica, paper foil laminates, and biobased or wood veneers. Painting after priming gives excellent results.

Thickness and Sizes: Standard thicknesses ranges from 3 to 28 mm with a density of 750 kg/m³ and to 42 mm with a density of 500 kg/m³

ABC BOARD COMPANY VIBE BIOBASED ECO-BOARDS®

Benefits

ECOBoard Benefits

- 100% Biodegradable
- 100% Formaldehyde-free, E0
- 3% formaldehyde-free RESIN instead of 25% GLUE as in regular particleboards
- 100% Durable - Sustainable Source
- 100% Recyclable to equal product (Cradle 2 Cradle)
- Superior moisture resistant
- Amazing Fire Resistance
- Superior Screw strength and Elasticity
- Less Weight for same strength characteristics as industrial grades of particle board
- Homogeneous single layer can be finished with many effects including, painted, veneered, melamine, micro foils, etc..
- Machineable profiling
- Healthy working environment and less dust
- Conforms to all relevant Standards NEN / ANSI A208 / BSEN 312 / HUB / etc..
- Densities available from 200 kg/m3 soft board to 800 kg/m3 HD
- DUBO-keur certified, NaturePlus certification pending
- No fumigation necessary for container transport, is insect repellent
- Insulating & Constructif Properties 400 kg/m3 x 40 mm : R = 0.62 m^2 K/W
- Life Cycle Analysis : NEGATIVE CARBON FOOTPRINT [- 0.98 Co^2 eqv/kg"] CARB 2"

Specifications ECO-Board 12 mm

Property	BSEN 312 P4	ANSI 208 M2	ECO-Board Panel (Wheat Straw)	ECO-Board Panel (Bagasse)
Density (kg/m3) *	No Requirement	640-800	650	710
MOR (N/mm2)	17	14,5	19	23
MOE (N/mm2)	2.300	2.250	2 650	2.500
Internal Bond (N/mm2)	0,4	0,45	0,7	0,9

Testrapport ECO-Board 18 mm

Test	Unit	Condition	ECO-Boar	MDF-E1
Bending renght	Mpa	Min 1	38,3	29
Elasticity	Mpa	Min 1600	3810	2980
Screw Pull	Surface	Min 1100	1520	1000
Internal Bond	Mpa	Min 0.35	0,80	0,51
Swelling in Thickness	%	max 8%	3,40%	10%
Moisture Content	%	max 13%	6%	9%
Formaldehyde	mg/100g	E1 max 0.9	0	0.5-0.9

"NIBE Research voted ECO-Boards best DUBO-choice particleboards for environment and health"

ECO-BOARDS®

ABC BOARD COMPANY

Environment

Carbon Sequestration

Straw and other biomass from agriculture and/or horticulture will absorb about 1.78 kg CO2 per kg Agriculture absorbs even more CO2 than most forests or trees.
Straw is actually like a little tree that is already cut and that will grow back in a year or 6 months depending on the country. By using this straw to produce bio based materials like ECOBoards 1.78 kg of Carbon will be stored for every kg produced.

Impact

The Life Cycle Analysis shows that the impact to the environment after producing ECOBoards including all energy, additives and transport is MINUS 0.96 kg CO2 LESS per kg because they start at MIN 1.78 kg of CO2 .
At end of life the old ECOBoards are reused as raw material for new ECOBoards and thus the Carbon remains saved > cradle2cradle .

Health

Traditionally woodchips are used for production of standard board material and are mixed with approximately 25% urea glue (10% for MDF). This urea glue contains formaldehyde, a toxic gas that is emitted during the material's lifetime. According to the Environmental Protection Agency; formaldehyde is a pungent gas that can cause cancer, nausea, asthma, irritations and severe allergic reactions. ECOBoards however are mainly bonded with the natural lignin from the cellulose fibres and use just 3% resin containing NO Formaldehyde and produce NO emissions.

Recycling

Traditional boards make environmentally safe recycling or processing for compost almost impossible without the release of toxic gasses and other related issues.
At end of life the old ECOBoard and leftovers are reused as raw material for new ECOBoards and this the recycling Carbon remains saved stored.This is even better than the Cradle 2 Cradle cycle.

Sustainable development

The factories which produce ECOBoards comply with the strictest international standards fo CARB. ISO 9001.Every factory is responsible for >200.000.000 kg CO2 LESS in the atmosphere!

ABCBOARD COMPANY

End of 2014, beginning of 2015 production of ECOBoards is starting in cooperation with ABC BOARD COMPANY International.

ECO-BOARDS®


ECO-Boards are the alternative
The current situation needs to be changed...
Harvest residue is mostly burned
Harvest
Residue is left on the field
To be burned causing CO2 pollution and wasting valuable resources
Trees are cut and processed to create boards
Deforestation provides wood
Processed with toxic glue
To make MDF and other panels. At end of life recycling is an issue and panels are mostly burned.
Worst case scenario >20% recycle wood is used and replanted but 50% of the world forest is already gone
ECO-BOARDS
The Wrong Choice
Harvest
Residue (from harvest)
ECO-Boards Factory
Bonded with healthy resin
Healthy construction
Waterproof Furniture
Fire-Proof Doors
Waste (for recycling)
ECO-BOARDS®
The Natural Choice
ECO-BOARDS

Building & Construction industries

ECOBoards are widely used in the construction industry in North America and are accredited by TECO as fully compliant within the industry. The excellent strength to weight ratio of the ECOBoard panels further eases handling on the construction site. ECOBoards were benchmarked against all relevant international standards such as BSEN 312 P4 to P1, ANSI A208.1, EN 300, etc...
ECOBoards can replace plywood, chipboard, OSB or multiplex for a wide range of applications.
ECOBoards are also DUBOKEUR by NIBE Research in the Netherlands as best choice for particleboards in environmental and health point of view, advised in sensitive areas where the end user has concern for their living environment, such as: schools, nurseries, hospitals, public buildings, laboratories, museums, nursing homes, etc...

Industrial packaging & Packaging

The excellent strength to light weight ratio make ECOBoards an ideal choice for re-useable shipping crates. ECOBoards material has been tested and approved by Trada for use in tea chests. Since it is formaldehyde free it is used for fresh food and vegetable transportation. ECOBoards are insect-free and insect-repellent so no fumigation is necessary for container transport.

ECO-BOARDS®

Applications

Furniture and Interior Decorating industries

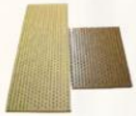
ECOBoards can be used in virtually all applications where conventional boards are used. Their excellent strength to weight ratio, and screw hold properties mean that a variety of hardware can be used, including, hinges and brackets. Painting after priming gives excellent results.

Insulation with Constructive properties

ECOBoard Softboard is produced under lower pressure in order to keep the voids of the straws, therefore the thermal conductivity is close to that of foamed plastic and less than 0.65 W/(m*K). The thermal capacity is higher than that of inorganic materials. Meaning ECOBoards can be used both as Constructive and Insulating panel with a higher permeability than OSB.

Sound Absorption

With ECOBoards we can make a special sound absorbtion board which fills a need of the decoration industry. At present, current sound absorption boards in the market are made of medium density board. In contrast sound absorption ECOBoard is made of equal quality ECOBoard, which has well-proportioned grain apertures. Sound mechanical process capabilities ease the process of installation.



Moisture resistant

Unlike traditional wood based boards, ECOBoards are extremely moisture resistant and are specified for use in the most strenuous humid domestic interior conditions where dimensional stability and retained strength are of great importance such as Kitchen & Bathroom furniture, skirting boards, moldings, compared to MDF structural integrity is preserved after contact with water.

ABC BOARD COMPANY VIBE BIOBASED cradle to cradle ECO-BOARDS®

Special Doors

ECOBoard Door Cores and Doors

Low density ECOBoards are ideally suited for quality low cost technical door cores and doors with extreem fire-retardant properties, solid compound doors and flush doors. Finished doors can be delivered to customers' specifications.

Features

- Green and environmentally friendly.
- Formaldehyde free.
- Many styles and thicknesses are available
- Easily processed, improving yield and reducing losses.
- Can be pasted directly with wood skin which reduces the quantity of surface decoration.
- Moisture resistant
- Standard Fire retardant - 30 min up to 120 min
- Anti-termite characteristics
- Much lighter (strength – weight ratio) than normal doors

Finished door examples

ECO-BOARDS®

ABC BOARD COMPANY

Fire Doors

Fire retardant ECOBoard

The special fire retardant ECOBoard easily exceeds the new European standards for fire and smoke development NEN 13501-1 class B. The fire retardant ECOBoard has excellent product processing properties and a burning behavior reaching flame resistance of level B1, as well as various higher physical chemical properties.

ECOBoard fire retardant doors and door cores

The standard ECOBoards are already untreated for 30 minutes fire retardant. They scorch rather than burn, therefore, ECOBoards are the perfect 'green' material to produce fire retardant doors and fire retardant door cores. ECOBoards offer a full range of fire rated panels and door cores to fit most applications. Our fire rated product line includes, fire retardant capabilities up to 120 minutes rated.

Example of Totally Biobased Door with Bamboo frame and Sugarcane Pulp Finish

ECO-BOARDS®

ECOnnect

Ultimate Challenges

This project combines the potential for a predicted New Industrial Revolution with one of the greatest challenges the world faces: to build a 1-million-inhabitant city per week for the next 20 years for $10,000 per family (Aravena, 2011). By opening up design to collaboration in a structured way we can arm ourselves with the greatest knowledge and creativity available, required to take up challenges of such scale. Where the first industrial revolution democratized consumption, the next one is expected to design and democratise production – through digital networks of shared knowledge and digital fabrication devices.

Performative Evolving Design

The developed process uses digital technologies to allow broadly defined building performance to become the main guiding design principle. The system of adjustment and advice does more than merely optimizing quantitative parameters. Moreover, it fully supports the designer in creatively and effectively balancing the many - sometimes conflicting - performance related aspects. Both the building system itself and the intelligence behind the online information- and simulation driven design context have great potential to be developed collaboratively and thus evolve over time.

From digital to physical directly

The proven principle of CNC cut elements with integrated friction fit connections for full-scale building has been developed to reach new levels of adaptability, simplicity, material efficiency, aesthetics and structural performance.

A 21st century reinterpretation

The digital design process is tested and specified via a realistic case study related to the expected increase in demand for quickly realisable post-disaster housing for the mid-to long term. A transitional shelter is designed for Villa Rosa; an informal settlement south east of Port-Au-Prince, Haiti.
Based on the mass-customisation principles of the new industrial revolution, the concept perfectly fits its climatic, cultural, technological and historical context. A concentrated solar power system integrated in the parabolic roof provides three basic needs: protection, electricity and clean drinking water. The ornamentation made possible by the building system is a modern re-interpretation Haitian vernacular architecture of highly decorated gingerbread houses.

The value proposition

The growing middle class in developing countries all over the world wants better housing; more comfortable, more reliable and simply more spacious. However they are on a budget. We leverage digital fabrication to create affordable housing which is locally produced and fully biobased.See below

ECO-BOARDS®

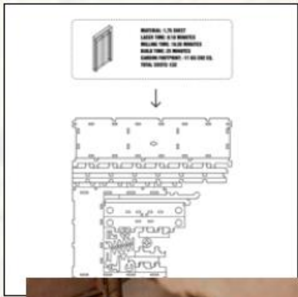
A digital fabrication product

Digital fabrication in ECOnnect translates into designing housing on the computer and have a robot - a CNC router - cut out the components. These components are like 3D puzzle pieces, together they make up an actual house. (picture)

ECOnnect
A HOUSE FOR EVERYONE

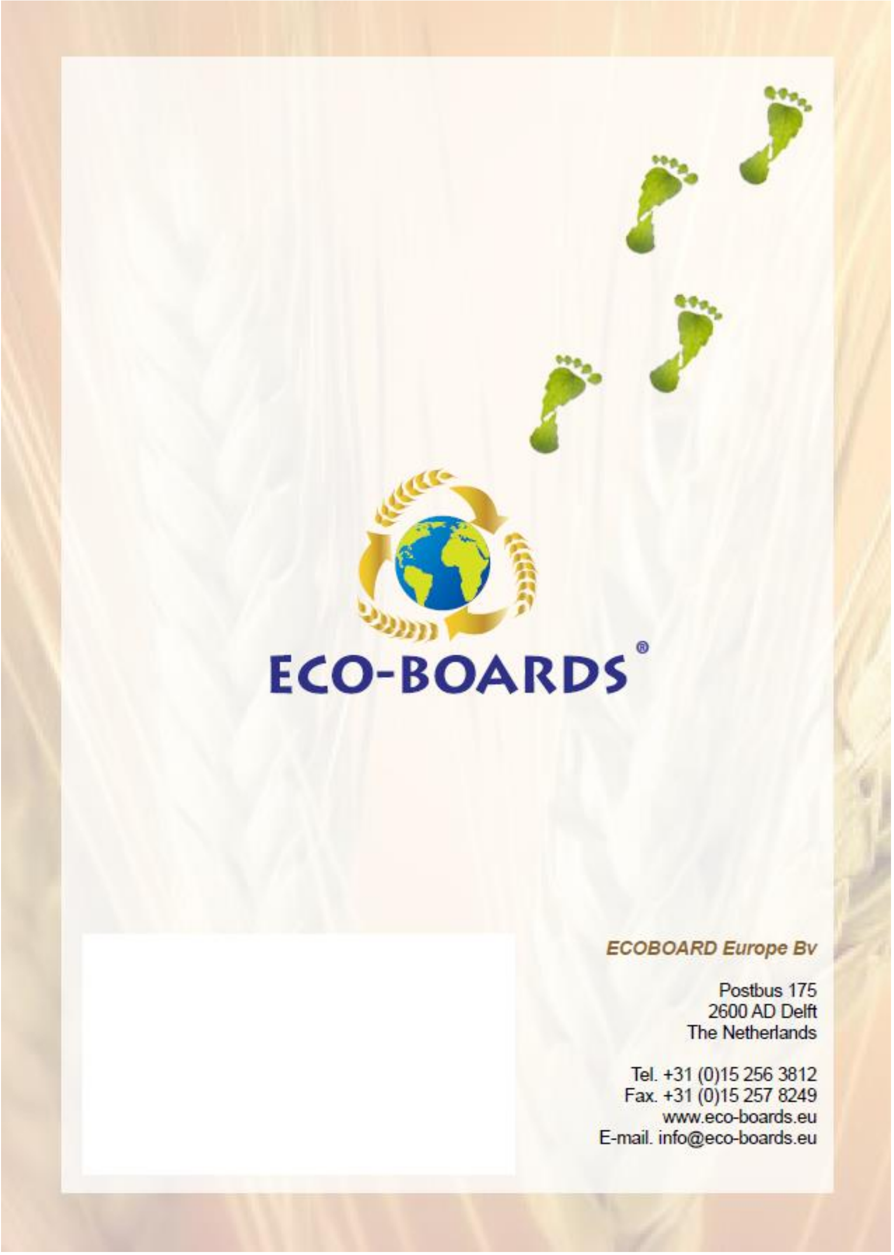
Friction Fit

The design of such a building is made up of multiple layers. First layer : architectural design - What does the house look like and how does it functions ? Second layer contains the elements , for example, a truss or a door frame with door.
The elements are in turn made ??up of smaller parts which are cut by the CNC cutter and that ultimately form the house together. If it is a type of building design , it can be endlessly produced . It is even possible to modularly to offer the two rooms or four bedrooms , a veranda or extra floor ? The client may say , we are pressing the button. And can be predicted in detail how sheet is needed and how long does the production process . " By the digital way of producing. "Another advantage of eConnect is the dimensional accuracy. The parts you produce a margin of 0.01 millimeter , all connections therefore fit perfectly . You can ' friction - fit' make connections . Homes assemble without screws or glue joint !



ABC BOARD COMPANY VIBE BIOBASED cradletocradle ECO-BOARDS®


Products
World Expo
Shangai
Structural
Insulating
Panel
ECO-BOARDS
HALAL
ABC BOARD
COMPANY
ECOBoards
ECOBoard 15mm Standard
Density 750 kg/m³
ECOBoard 8mm Standard
Density 750 kg/m³
ECOBoard Paint High Gloss
ECOBoard 40/35mm Soft
Density 500 kg/m3
ECOBoard Deco
Density 650 kg/m³
ECOBoard Deco
Density 650 kg/m³
ECO-BOARDS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Fax. +31 (0)15 257 8249
www.eco-boards.eu
E-mail. info@eco-boards.eu

ECO-BOARDS

DECLARATION OF MATERIALS : ECOBOARD

We certify that our high and low density fiberboard (ECOBoard) is made from 96 to 97 % cellulose-based Fibreresidue from agriculture and 3 to 4 % NON ADDED FORMALDEHYDE binder.
The rest of the binder comes from released lignine from the agrifibres.
ECOBoards have no formaldehyde emmission and remain far below E0 norm.

No wood was used to produce ECOBoards.
All forests remain.

Waldo Chotkoe

C.E.O.
ECOBOARD EUROPE B.V

ECOBoard Europe BV
Teslaweg 5
2627 AV Delft , The netherlands
TEL : +31 (0)15 2563812
www..eco-boards.eu

SUCCESS BY QUALITY
Entwicklungs- und Prüflabor Holztechnologie GmbH
Zellescher Weg 24 · 01217 Dresden · Germany
www.eph-dresden.de

accredited by Deutsche Akkreditierungsstelle GmbH (DAkkS)

European Notified Body for construction products 0766
Recognized body of DIBt SAC03

CERTIFICATE OF CONFORMITY OF THE FACTORY PRODUCTION CONTROL

0766 - CPR - 338

In compliance with Regulation 305/2011/EU of the European Parliament and of the Council of 9 March 2011 (the Construction Products Regulation or CPR), this certificate applies to the construction product

Particle board (straw board)

P4 particle boards acc. to EN 312: 2010
for internal use as a structural component in dry conditions
Thickness range >13 to 20 mm
(Product code 2615046-001)

produced by

Ecoboard Co., Ltd.

Placed in the market by

ECO-BOARDS®

This certificate attests that all provisions concerning the assessment and verification of constancy of performance described in Annex ZA of the standard

EN 13 986: 2004

under system 2+ for the performance set out in this certificate are applied and that

the factory production control fulfils all the prescribed requirements for these performances.

This certificate was first issued on 04 June 2015 and will remain valid as long as the test methods and/or factory production control requirements included in the harmonised standard, used to assess the performances of the declared essential characteristics, do not change, and the construction product, and the manufacturing conditions in the plant are not modified significantly, unless suspended or withdrawn by the factory production control certification body.

Dresden, 04 June 2015

Date

Institut für Holztechnologie Dresden gemeinnützige GmbH – Überwachung der WPK

Dr.-Ing. Bernd Devantier
Notified Certification Body

ECO-BOARDS

MDF-Testboard 16 mm		Unit	Condition	MDF-E1	ECO board	Conclusion
Bending Stength	Buigsterkte	Mpa	x > 13	29	38.3	Accord
Modulus of Elasticity	Elasticiteitsmodulus	Mpa	> 1600	2980	3810	Accord
Internal Bond	Binding	Mpa	x > 0,35	0.8	0.51	Accord
Surface Soundness	Oppervlakte Hardheid	Mpa	x > 0,8		> 1,16	Accord
Swelling in Thickness (2hrs)	Zwelling in dikte	%	< 8,0 %	10%	3.4%	Accord
Moisture Content	Vochtgehalte	%	4 -13%	9%	6%	Accord
Density	Densiteit	g/cm3	0,4 - 0,9	0.72	0.72	Accord
		Vlak	> 1100	1000	1520	Accord
Screwpull	Treksterkte	Kant	> 700	900	970	Accord
Formaldehyde Emission	Formaldéhyde Emissie	mg/100g	E1 < 9,0	0,5-0,9	E 0 0,0	Accord

PARTICLE BOARD	SPAANPLATEN	P2	P3	P4-P6	P5-P7	ECOBoard
Bending Stength	Buigsterkte (EN 310)	+	+	+	+	+
Modulus of Elasticity	E-modulus bij buiging (EN 310)		+	+	+	+
Screwpull	Treksterkte loodrecht op de vlakken (EN 319)	+	+	+	+	+
Screwpull	Oppervlaktetrekkracht (EN 311)		+			+
Swelling in Thickness (24hrs)	Zwelling in 24 u (EN 317)			+	+	+
Moisture Resistance	Weerstand tegen vocht (EN 321/EN 1087-1)				+	+

MDF		MDF	MDF-H	MDF-HLS	ECOBoard
Swelling in Thickness (24hrs)	Zwelling bij 24 u (EN 317)	+	+	+	+
Screwpull	Treksterkte loodrecht op de vlakken (EN 319)	+	+	+	+
Bending Stength	Buigingsterkte (EN 310)	+	+	+	+
E-modulus	E-modulus in buiging (EN 310)	(+)	+	+	+
Moisture Resistance	Vochtweerstand (EN 317/EN 321)[2]		+	+	+
Moisture Resistance	Vochtweerstand (EN 319/EN 321)[2]		+	+	+
Moisture Resistance	Vochtweerstand (EN 319/EN 1087-1)[3]		+	+	+

ECO-BOARDS

ECOBOARD EUROPE bv - Teslaweg 5 2627AV Delft NL - www.eco-boards.eu

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