Toward Reconfigurable Timber Design

Jacques Schmidt

Énoncé Théorique – January 2022

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Contents

Foreword

This thesis is written as part of my final year as an architecture student at the Swiss Federal Institute of Technology (EPFL) in Lausanne, Switzerland. It represents the first of a two-parts final work for the obtainment of the title of Master in Architecture. This thesis, also referred to as *énoncé théorique* (French for theoretical statement) has as an objective, for the student to reflect on a subject which is chosen by them.

Those theoretical reflections are being developed in a considerably short amount of time and this exercise typically does not aim at developing new theories but rather to explore existing matter in order for the student to broaden their knowledge and develop their opinion on a subject of architecture.

This thesis has been written under the supervision of Professor Corentin Fivet, with the help of doctoral assistant Petras Vestartas. I wish to thank both of them for guiding me through the research of this new topic as I was advancing. I would also like to thank my friends for the help in researching and developing this thesis and a special thanks to Malena, my girlfriend, for the help and support.

Abstract

With today's sustainability concerns and the objectives of reducing emissions of CO_2 in the construction sector for future decades, multiple approaches are taken by the actors of this industry. One big holistic idea is the design of buildings in a circular economy, with elements having longer life of service and not being automatically destroyed or disposed. For this problematic, there exist various approaches attempting to solve it. Reusing old construction material is one of them but this is not a decision for the future as it is done only retroactively. Architectural designers and engineers must think proactively and design their buildings in a way to enable the reuse of its elements once the building has served its purpose.

Such concepts exist, some constructions are developed to be both assembled and disassembled in a simple manner which is called reversible design. However this practice is still rare and not perfected. An approach to make this even more efficient and prone to reuse is the development of building elements – a kit-of-parts – that can be configured and reconfigured into multiple various designs over the years. This approach would enable the building parts to be used for longer time periods and always in a circular loop.

Looking at past, present, and future answers given to this problematic I will attempt to gather enough information in order to fully understand the design concepts involved. Furthermore, I can, based on those concepts, attempt to extract new design guidelines answering this problematic of the current reconfigurability limitations.

1

Reversible to reconfigurable: a big step

Introduction

The limitation of natural resources has gained great public awareness in the last few decades and notably after the turning point that was the 1973 energy crisis.[1] This highlighted the urgent need to reduce the emissions of CO_2 which were becoming alarmingly unbalanced (emitted vs. absorbed CO_2) and provoking the deterioration of the climate inducing the global warming situation we know today. With international agreements such as the 2015 Paris Agreement setting emission reduction targets for 2030 and 2050, the ecological transition is indispensable, and it involves all economic sectors. The construction sector is seriously concerned as it is believed to be responsible for producing approximately one third of the CO_2 emissions as well as consuming that same ratio of the world's energy for its needs.[2] The general economic growth – specifically the one of developing and evolving countries – means that there is still a great need for new constructions. At the moment, those new buildings are constructed using materials which production requires large amount of energy. In that context, there is a necessity to use renewable materials – including wood – to counterbalance the direction of events.

> *"In response to the major climatic challenges to be faced in the twenty-first century, and in light of the progress made in recent decades, both technically and in terms of regulatory standards, wood offers great potential for the development in the construction (of collective housing)."*[3]

1 www.wikipedia.com.
2 International Energy Agency (IEA), 2018.
3 Prévost et al., 2021, p.236.

Wood is a great choice of sustainable material as it has many different qualities. It can embody carbon dioxide and for each cubic meter of wood we use for construction, we save one ton of CO_2 compared to other materials such as steel and concrete. Compared to the latter, wood requires considerably less energy for its production, especially when sourcing wood locally. When using timber as the main structural material, the overall emissions related to the structural work are reduced by 60%[4] not including potential reductions of the amount of concrete necessary for the foundation, resulting from the lower density of timber. Overall, timber is probably the best option of material available to attempt solving the current issues of unsustainable construction. This material should be used in combination to new technologies, and recent advances in the construction industry in order to find more efficient solutions to the issues facing us today. It is, however, important to note that, in order to fulfill that role, timber constructions must be designed with expertise and greenwashing must be avoided.

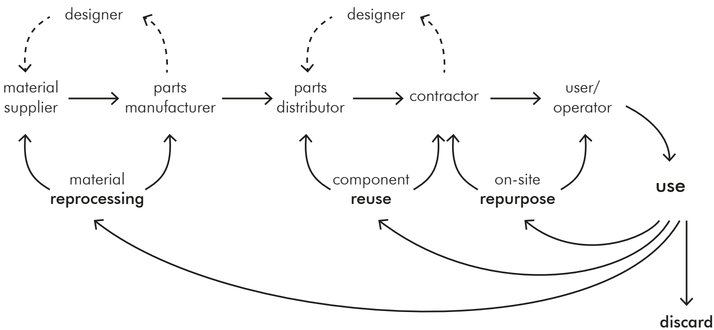
> *"Some people see the advances in artificial intelligence and the digitalisation of architecture as a threat to the singularity of architectural creation. This risk is rendered obsolete as soon as architecture realise that these new tools, far from restricting their scope for action, allow for a comprehensive approach, one capable of going well beyond the formal issues of a building by associating all the questions relating to its life cycle: sourcing and waste, the immediate context (the landscape) and what is to come (the life of the building in the next 25, 50 or 100 years)."*[5]

4 www.carbone4.com.
5 Prévost et al., 2021, p.227.

Timber construction in the circular economy

While the current economic model is mostly linear and based on models such as the simple *'take-make-dispose'* which relies on cheap, accessible energies and materials, creating enormous amounts of emissions and waste. For the construction industry, this has materialized in a linear process for the various materials. They all follow a similar flow; from raw material extraction, processing, use, demolition, and disposal with transportation present in between each step.[6]

> *"The circular economy is one that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles. This new economic model seeks to ultimately decouple global economic development from finite resource consumption. It enables key policy objectives such as generating economic growth, creating jobs, and reducing environmental impacts, including carbon emissions."*[7]



6 Gorgolewski, 2017.
7 Ellen MacArthur Foundation, 2015, p.19.

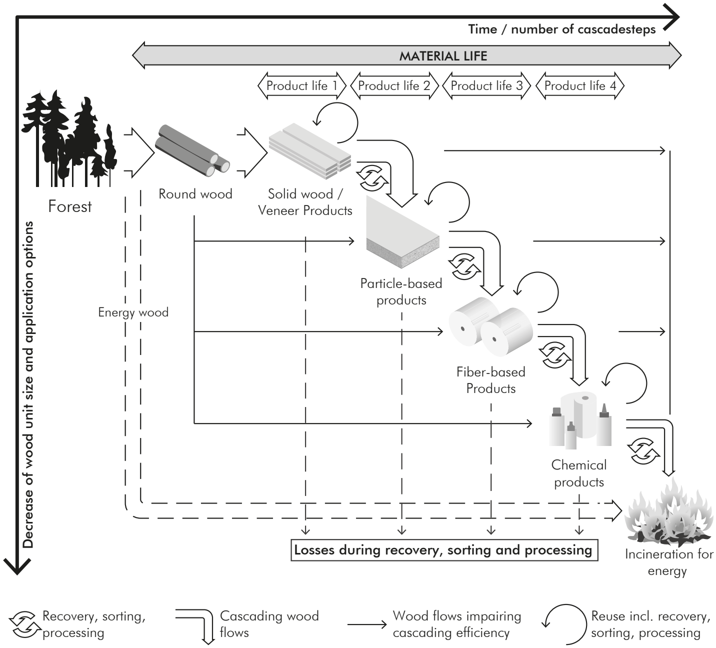
This circular economy in the building industry (see illustration on the left) is the goal for all materials and products of the world, however, this paper will focus on the use of wood (or timber) in the construction industry. Timber, just like other construction materials such as concrete, steel, bricks, and much more, must be addressed in this current era of acceleration and climate change. It is understood that timber, across its multiple forms – panels, beams, sheets, etc. – and its by-products – mass timber, glued laminated timber (GLT), cross-laminated timber (CLT), nail-laminated timber, etc. – is a big part of the construction industry. In recent years, timber buildings have become a new trend with new technological and technical progress helping to put this material back in the mind of every architect and engineer. The structural capacities of wood are well known and new engineered timber products as the ones cited previously are allowing for larger and taller constructions. It is now important develop the research around the use of timber in order to enable a smooth transition to circular economy of construction.

While there is a will from the actors of the construction industry to lower the overall emissions of CO_2, the efforts seem to be put mostly on other materials – more polluting than timber – such as concrete and steel which both produce significantly more emissions of CO_2 – Approximately 140% more than timber for a similar building type.[8] Timber is considered, in itself, part of the solution since the processes involved in the production and transformation of timber create fewer emissions than other construction materials and because timber is capable of embodying CO_2. But those capabilities and the simple use of timber are not enough and do not solve the climate issues that we face. The circular economy approach that has been explored for other materials

8 www.carbone4.com, p.4.

must also be applied to timber and its by-products. While transitioning from concrete and steel to timber-based design is a first good step, it is necessary to look further ahead of time and consider the construction of buildings as one part of a bigger whole that is the circular economy.

Timber is, because of its materiality, rather easy to use for construction. It can be easily assembled, cut, bent, and shaped in almost all of the possible ways. Thanks to its properties, it can very easily be reused downstream as there are many different ways to transform it and change its use while making smaller elements (see cascading diagram below).



While this approach of downstream reuse and transformation is one solution to optimizing the use of materials over their life span, it is not sufficient. It is understandable to use such an approach only when the material has gone through multiple uses and after its life and use as a construction element have been optimized thoroughly.

From reuse to reversible design

Antoine Picon offers an interesting take on the role of materials in architecture. Architects tend to see materials as just the image resulting from one or another material and the overall beauty of the design. Instead, the focus of the architect today should be on the process and life of the building, not as a finite piece of art but as what it really is, an assembly of elements and materials which represent only one moment in the life of those materials. The design must incorporate this circular thinking, and it begins with reuse.

> *"The real question today is to think of materials in terms of a process going from extraction to the end of the life cycle or reuse. We have to get away from an overly narrow way of thinking, that of the architectural object and its real or supposed beauty, in order to really reflect on the overall process, in which the building can be understood as only one moment. […] the building is only one of many stages in a much longer and more complex chain"*[9]

Reuse is thereby the first step toward a more circular design of buildings. The reclaiming of old construction elements or material and repurpose can be done by following two approaches: upstream reuse and downstream reuse which are presented by Fivet and Brütting in their paper from 2020, *Nothing is lost, nothing is created, everything is reused*[10].

Upstream reuse is the approach in which the materials are sourced from the existing built environment – buildings, infrastructure. This construction concept has been in place

9 Prévost et al., 2021, p.254–55.
10 Fivet and Brütting, January 2020.

for almost as long as humans have been building, but it was more common before the Industrial Revolution, in times of economic crisis, when it was complicated or too expensive to acquire new materials or simply when there was a lack of resources. It was then common to reuse elements such as wall blocks or carpentry from one older – usually abandoned – building as components for new constructions. This process has endured for centuries until the rise of mass production and the Industrial Revolution, at which time the cost of labor and materials decreased significantly. New buildings were therefore constructed with new materials sourced from all over the world and there was no more consideration toward reuse when demolishing older buildings. This practice did not evolve very much until the late 20th century when a new problematic arose: global warming. Since the late sixties, and discoveries on the matter, the problem seems to have gotten out of hand. New solutions and approaches have come forward in relation to the construction industry with the following downstream reuse being one of them.

Downstream reuse or reversible design is part of a proactive design approach, contrasting with the retroactive stance of upstream reuse. Reversible design takes place before the construction happens and implies designing elements in such a way that allows easy repairs, replacement, transport, and disassembly. This method enables greater reuse possibilities later in the life of service of elements and will be developed in the following chapter.

Reversibility: the step forward

Reversibility, or as also called earlier downstream reuse, is the first step toward better reusability and flexibility of building components. Reversible design consists in acting proactively on the development of buildings which facilitates the assembly but also specifically the disassembly. The goal is not directly to reuse reclaimed elements but to enable the reclaiming of the building elements that are part of the design in a simple manner once the life of service of the building has been consumed. The components often have the capacity to be reused or repurposed for another construction but building methods usually prevent the elements from being reclaimed as they are too well connected with each other (e.g., elements stuck in poured concrete). For this reason, the building elements are to be designed with attention to the following four specific strategies developed by Fivet[11]:

Durability: Durable components assure the conservation of both functional and technical properties of the materials throughout – and beyond – their building's life span. Design considerations include protecting the elements against possible damage, either before, during, or after their usage.

Versatility: Versatile assemblies are capable of supporting various functions and services without the need of being changed. For instance, it means that programs happening in the building can be changed without interference and therefore completely independent of the load-bearing structure. It is known that framing systems (i.e., beams and columns) are adequate for multiple types of programs, e.g., residential/offices.

11 Fivet, February 24, 2019.

Modularity: Modular assemblies are made of similar components that can be placed interchangeably at various locations. Modularity simplifies the integration of elements in the system, but also allows for easier replacement in case of incidents or damages. It is therefore connected to the concept of standardization.

Reversibility: Reversible assemblies allows for easy dismantling into any previous step of assembly, with zero or very little damage to the components. Reversibility is focused on connections, e.g., mechanical fasteners, interlocking assembly, or simple face-to-face joints, with considerations toward easy connecting/disconnecting.

Buildings that have been designed following those principles don't necessarily have lower emissions of CO_2 since this depends more on the choice of materials, but by implementing this approach of reversibility, it allows for the components to be easily reused once the building is fully or partly deconstructed. This extends their life of service and therefore avoids having to throw them to waste and produce new elements.

While the development of sustainable, reversible, and reconfigurable buildings is often believed to be constrained by economic factors such as a higher price of construction and materials. This has to be balanced by two things: First, reversible constructions are designed proactively and often are constituted of pre-assembled elements which considerably reduce the duration of construction and balance some of the possible deficit. Secondly, there is a long-term advantage for these structures with the components of the building able to be reused to create another building at a considerably lower cost or sold for another construction.

Reconfigurability: the objective

While reversibility is a good first step toward optimum reusability of building components, there is a crucial additional step – on which I decided to focus – that is required in order to achieve the best possible design in the circular economy – reconfigurability.

Reconfigurability is in a certain way the fifth and final principle to the previous list. It relies on reversible design while enhancing its repurposing capacities. It must be composed of adaptable assemblies, which allow some or all of its parts to be removed, added, or rearranged according to new spatial, functional, or technical needs. Principles such as transformability, extensibility, reducibility, and variability can be seen as part of adaptability. The first one is achieved if the assembly can have completely new spatial organization after the reconfiguration. The components are assembled in a new arrangement and compose a new building with different programs, spaces, and geometry. Extensibility and reducibility are specific to assemblies in or from which some parts can be added or removed, respectively. The goal here is to be able to extend or reduce the size of a building in a simple, efficient and fast manner to better suit the needs of the users while not compromising the existing elements. Variability is specific to assemblies whose parts (members or connections) have variable states (e.g., columns with adjustable height, or slidable slab-to-column connections). An adaptable system might not be reversible – e.g., non-reversible connections used for adding an overhanging balcony to a building –, and one that is reversible might not be adaptable – e.g., the removal of a block from a dry-stone arch would jeopardize the structural integrity of the system.[12]

12 Fivet, February 24, 2019.

The reconfigurability of elements requires a certain amount of modularity from those same elements and from their connections. The objective being to be able to use those designed components for multiple constructions, it is important to carefully develop those components and their connections. The way those elements are capable of getting together in multiple directions – orthogonal, parallel, or with an angle – allows for a maximum of outcomes and variations in the final design as well as optimum reuse capacities for the building components. This modular approach can be developed with the design of a kit-of-parts, which Howe et al. present that way.

> *"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 to define a finished building."*[13]

The main parts are modular, repetitive elements that can be assembled in various ways in order to create the structure of the building. If the structure is modular, the elements that will be added onto it must be modular as well to fit all the possible compositions. The objective lies then in the design of a holistic kit-of-parts including all the elements from the building, from the structure up to the cladding and partitions.

13 Howe et al., 1999.

Conclusions

Reuse and reclaiming of old construction elements have been more common recently but still very limited compared to the incredible amount of new material used for construction every day. This is in part due to the complexity of reclaiming those materials.

Reversible design proposes one approach to solve the problem of reclaiming, but the constructions using this are still very specific and their components are not assured of being reused later on.

Reconfigurability goes a step ahead here by designing components that are modular, repetitive and can be used for multiple constructions. One reconfigurable kit of part could be the basis of multiple designs and the components used can be mass-produced for cheaper and quicker construction. However, in order to develop reconfigurable concepts, it is first necessary to fully comprehend the issues with reversible construction and where it can be improved.

2

Content of the Research

Research question

By exploring the multiple projects and theories surrounding reversible design, I could notice that there is a limitation – voluntary or not – in the way that the stakeholders develop the designs. It is unfortunate to observe that most design approaches chosen by the actors of this industry don't go any further in the thinking of elements as part of a circular economy. So-called reversible designs are in fact hardly reversible and close to none are thought through to be reconfigurable.

My research question will thereby be how can we improve current construction systems in order to achieve reconfigurable timber design?

Scope and goals

This thesis is written as part of the final year of my master's studies in architecture. As a student, I intend to learn from the present conditions in order to propose a fresh look at the current state of the art in terms of reconfigurable design. While I have strong interests in the technical aspects of the question, I lack the necessary knowledge and means in order to produce a thesis of greater technological and technical depth. Instead, I focused on the constructive approach, more closely related to the field of architecture, with the objective of clearly understanding the domain of the study in addition to producing a relevant analysis of current issues. This will allow me to develop my own reconfigurable system.

Structure of the thesis

While the previous chapter was exploring the role of architecture and design in the circular economy, how to enable reuse through principles such as reversible and reconfigurable design. The following chapters of my master's thesis are built firstly around the exploration and understanding of past and present reversible timber design. With those case studies, the aim is to gather sufficient information and knowledge about the construction and design processes involved in the development of reversible structures.

After the study of cases of reversible timber design, the research can move forward into the few current reconfigurable concepts. With the aim to understand what the current directions that the industry and the academic researchers are taking toward the problematic of reconfigurability in order to assess whether one of those approaches should be followed, or a new direction should be taken.

Once all that knowledge is gathered, guidelines for further development can be extracted from the various case studies in order to fully comprehend the step that is present between a reversible and a reconfigurable design.

This will lead me toward the choice of one or multiple design directions for a kit-of-parts reconfigurable design as the theoretical and technical support for my master's project next semester.

3

Current reversible timber construction

Introduction

There exist various approaches to reversible design and they have evolved through time. I have decided to study five cases, some specific to one building, while others are exploring an entire design approach. Those cases have been chosen for their differences and their representation of the broad spectrum that is reversible design. The cases are ordered by temporality, from the oldest practice to the most recent advances in the matter. While the first two cases are more general and don't consider just one building, the first represents one of the earliest forms and practices of reversible architecture. The second was one of the most commonly used timber construction methods in the world, but specifically popular in the United States. The following three projects are much more recent. The project by Shigeru Ban for the Tamedia office building in Zurich dates back to 2013. It is an exemplary project in terms of the way timber is used as the primary structural material. The following project is representative of a new approach toward timber high-rise, modularity, and reversible design. It has been developed to be rapidly assembled and with very little variation in the structural elements, so it becomes easier to manufacture. The last project – or concept – is developed by the BAMB (Building as Material Banks), a project funded by the European Union involving multiple professionals and academics across Europe.

Traditional Japanese house construction

Balloon and Platform frame construction

Tamedia Head Office

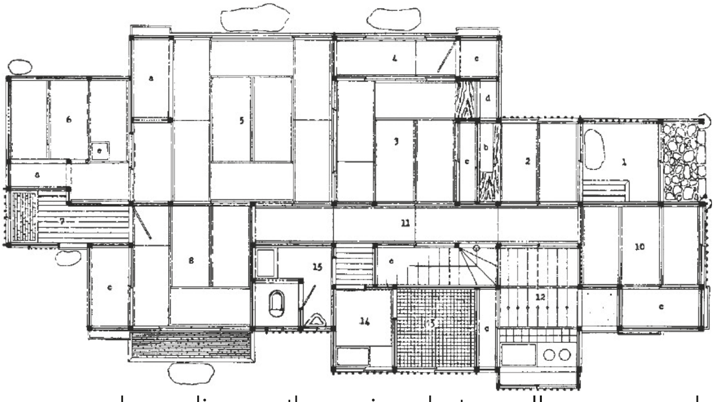
Brock Common Tallwood House

BRIC: reversible house concept

Reversible timber construction: case studies

Traditional Japanese house construction

Traditional Japanese houses have a unique position as they are all built using a timber-frame system for only one single story. It is remarkable for the fact that centuries ago, those houses would already be built with construction techniques, building elements, organization, form, and size of the spaces which were designed in a rational, modular way. The constructive system of those houses is founded on two basic units which will influence the entire design. The first one is the *shaku* which originates from China and corresponds nearly to an English foot (i.e., 30.48 cm). It sets the basic dimension that will define the layout of the structure, the size of rooms, and therefore the relationship between connected elements. The space between the columns is defined by the second unit, the *ken* (meaning "interval"), which is a multiple of the former. It



can vary depending on the regions but usually corresponds to six *shaku*.[14] Once the structure of the house assembled, the layout of the column allows for the intermediary spaces to be filled according to the individual requirements of the user. Thanks to modular partitions, translucent and opaque sliding doors, those spaces can vary upon the time of the day or the year to adapt to climate or just daily rituals.

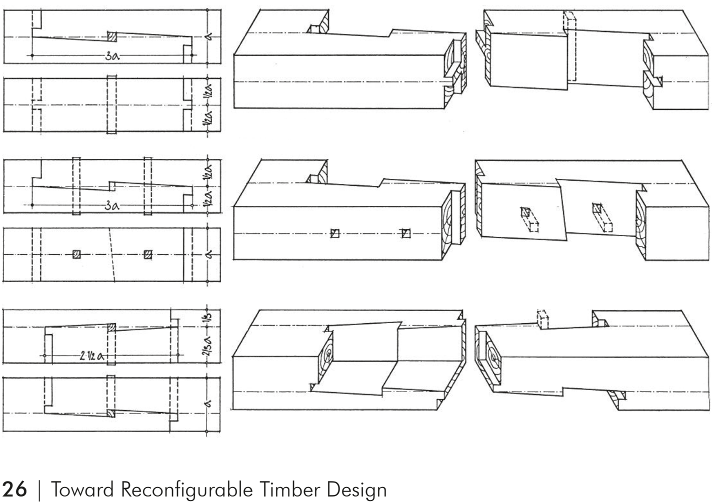
> *"Since residences of any size and room arrangement are built with identical units. The component parts are prefabricated at the carpenter's workshop. As a result, the actual building process consists of merely assembling the various units, and requires a minimum of time and labor. Removable building parts such as windows, doors, mats, and ceiling components can readily be bought on the market so that deteriorated parts can easily be replaced. With equal simplicity the house can be extended as old parts can be used for new construction."*[15]

14 Staib et al., 2008.
15 Engel, 1985, p.27.

The modular components of the traditional Japanese houses are also reversible thanks to their extremely good level of craftsmanship. Japanese craftsmen have developed ingenious wood joinery methods allowing for efficient, fast, and reversible assemblies. Structural elements were prepared by the local craftsmen in their workshop and then transported on-site where little work was needed. Elements were assembled and secured with small additional wood elements, thanks to exemplary precision of wood carving, as shown in the join drawings below.

Durability: the structural elements were very durable as they were made of carved raw wood elements. Some houses have been standing for centuries which proves the quality of work involved in these constructions. In case of disassembly, only tiny elements would be damaged while protecting the integrity of the main elements.

Versatility: It is ambiguous to talk of versatility of program while talking about house construction but it can be imagined that the same elements, being modular and following the *shaku* dimensions, could be used for other constructions.



Modularity: The timber elements are all built following the traditional Japanese *shaku* dimension which defines all the arrangements. They are therefore very modular, however, it is more complicated in relation to connections. Joints were very precise and often made for a specific location or assembly so one part would not be able to be replaced by another one.

Reversibility: Most of the elements are assembled with reversible connections of pure wood-to-wood joinery. Often, a small element of wood was placed in the middle of the joint to secure it, but also enabling an easier disassembly in the necessary case.

While traditional Japanese house construction is not an example of a system that could be applied as is nowadays, some interesting aspects of its construction method can be remembered. The way the Japanese were designing the house with modular units and components set the example for modular and adaptable construction. Furthermore, the joinery used in Japanese construction is a good example of reversible connections, however time and labor consuming.

> *"The timber elements are prefabricated with great skill and craftsmanship, without the use of additional connection materials and have flexible joints so that they cannot be damaged by tremors and earthquakes. The Japanese house is an early example of a basic modular arrangement, and of standardization and unitization in timber construction."*[16]

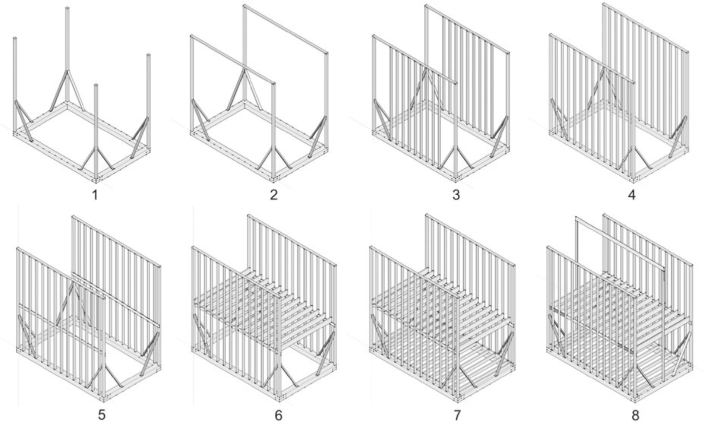
16 Staib et al., 2008, p.17.

Balloon and Platform frame construction

Year:	1830s –
Location:	United States

Balloon frame construction – and later platform frame – has been first introduced in 1832 by George Washington Snow in Chicago and became the most popular timber construction system in America since the late nineteenth century.[17] It is a simple and straightforward approach to timber construction. Departing from the previous traditional framing construction, which was using large posts and beams assembled using the mortise-and-tenon connection, balloon frame construction developed itself thanks to the emergence of cheap machine-made nails as well as new water-powered sawmills. Instead of using a small number of large elements, balloon frame uses a lot of small sections, mass-produced, timber elements called studs. Thanks to their small and

17 Elliott, 1994, p.18.



standardized dimensions, the process of drying was faster, and both the storage and transportation of these elements were made easier.[18] This system also moves away from the intricate and skill-demanding joints – dovetails and tenons – of the traditional post-and-beam system, by creating a system requiring little skills. This helped democratize balloon frame design, which became very popular among the lower classes. For the first time, any farmer could build a quick and cheap house by themselves.[19]

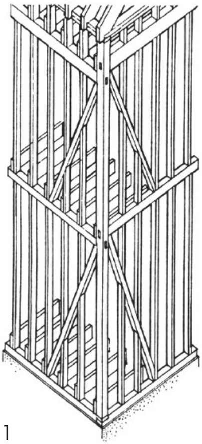
The figure above shows the process of assembly of a typical balloon frame house. It is possible to read the hierarchy of elements, starting with corner pieces, fixed by adding small bracing elements between them and the sole plates. Then, the studs can be mounted vertically one by one on the sides, extending the entire height of the building. They are fixed close to one another and compose together the load-bearing walls of the building. Those walls will then carry the joists of the floor and the roof. This structure is

18 Staib et al., 2008.
19 Robinson, March 1855.

then covered and protected by an additional cladding. The latter is commonly made of timber panels nailed on top of the studs, which also helps brace the entire structure. This entire process was fairly simple and required minimally-skilled workforce, rudimentary tools (e.g., hammer, saw), and small building crews.[20]

Platform framing (3 below) slightly differs from balloon framing (2 below) by the fact that the building is assembled floor by floor (see the figure on the right). Instead of extending the complete height of the building, the studs are assembled into wall frames of just one story high. Those walls support the floor slab, which is laid on top and which, in turn, supports the walls of the upper story and so forth up to the roof. From the beginning of the twentieth century onward, platform frame construction took over as the predominant timber framing system for small houses, specifically in America and in the UK. The construction using the balloon frame system is sometimes a faster process of assembly, especially thanks to the studs extending the complete height of the building.

20 Lanier and Herman, 1997.



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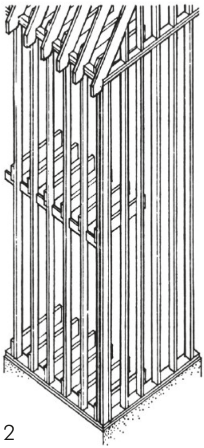

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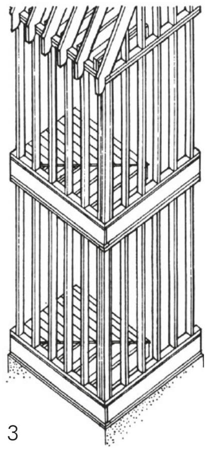

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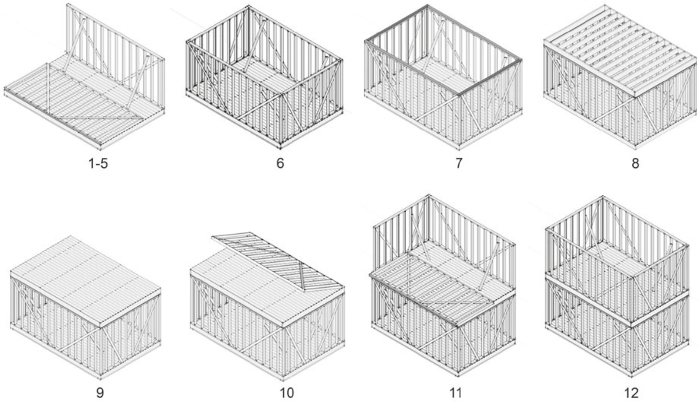


The platform frame, however, will be favored thanks to the modularity and prefabrication potential of its construction method using smaller units that are easier to handle and transport.[21]

Durability: While the elements have the advantage of being small and light, this results in less resilience to damages made during the assembly process – by the nails and tools – or the deconstruction. It is also important to note that those constructions were made 'cheaply' and it is common to have bad detailing or construction quality, creating complications with humidity resulting in elements that cannot be reused.

Versatility: This system is considerably restricted by its element length and structural capacities, thus it does not apply to other than small-scale construction of a maximum of two stories.

Modularity: while modularity in balloon framing system is limited to the multiple similar studs, it goes a bit further with platform frame. Indeed, in that system, the studs are pre-assembled into modular units for the sides and for the

21 Gorse et al., 2020.

floor using techniques that can be repeated.

Reversibility: While it is not the purpose of such design to be reversible, the systematic use of nails makes it easier to deconstruct. Generally, most of the elements of a balloon or platform frame building can be retrieved by disassembling it. The main issues are the ones stated above related to durability.

While balloon frame and platform frame constructions cannot be considered as reversible designs due to the lack of said 'voluntary design' in a reversible way, some lessons can be learned from this construction process that has been in use for more than a century. We can learn that inexpensive construction is a result of the rise of mass-produced elements – in this case, the nails and timber studs – which contribute to a process of fast assembly. This, with the straightforward construction process, helped democratize this model of construction. Similarly today, new methods – such as discrete architecture or examples like the WikiHouse (see chapter 4.2.1 and 4.3.3 respectively) – are evaluated and tested in order to make construction more affordable, simpler, and available for all thanks to new tools like computational design and automation.

Reversible construction must be made simple and straightforward by design, as is balloon frame, but without compromising the quality of the construction like in this case. Particular attention must be put toward the durability of the timber elements if further reuse of those elements is to be made possible.

Tamedia Head Office

Year:	2013
Architect:	Shigeru Ban Architects
Structural Engineer:	Creation Holz GmbH
Location:	Zurich, Switzerland

The Tamedia Head Office building is inspired by traditional timber joinery but was made possible on such a scale thanks to advances in computer fabrication and precise automated machinery. The main body of the building, which measures 38.5 m in length and 11 m in width, is organized around 8 large timber frames which are positioned every 5.45 m. Those frames, which support the 5 upper levels of office space, are composed of four columns extending the full height of 21 m as well as two transversal beams by floor. The frames

are tightened together thanks to longitudinal oval beams.

The entire building is enclosed in a glazed envelope which allows a maximum of light to enter the building and to appreciate the timber structure not only from the inside, where it creates a domestic sense, but also from the outside from where it stands strong.

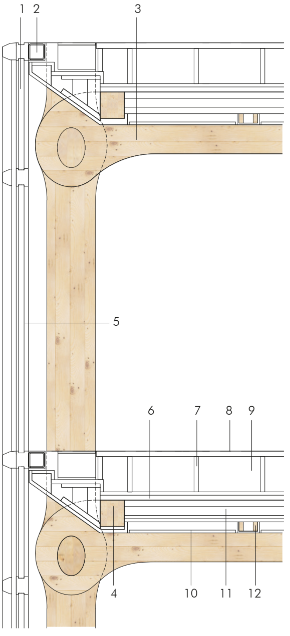
The greatest quality to this project is certainly the capacity, that its timber structure has, to support the entire building without the need for any steel or else material to secure its connections. Indeed, the structural concept of the timber frames relies on an extremely precise 'kit-of-parts' that has been manufactured by CNC machines. This precision, and the structural design involved, has allowed the system to be completely functional without the use of steel plates or nails for the connections, instead of being entirely held through tightly assembled wood-to-wood connections (see image above).

The other smart design decision for this project was the use of interlocking longitudinal oval beams which, because of their shape, can't rotate. This enables them to absorb most of the lateral forces that the building may be subjected to.

This building is not presented as a reversible project by its architect, but it definitely has some reversible attributes. As mentioned earlier, timber elements are interlocked by design and assembly without additional nails, screws, or any other metal connector. This would theoretically mean that if necessary, the frames could be easily disassembled as well as most of the glazing, flooring, and interior partitions.

> *The success of this project both aesthetically and technically is the result of a highly sophisticated and seamlessly integrated approach to design and construction. The finely articulated structure with its curvilinear elements clearly illustrates the precision and expressive potential of digital fabrication. While the structural detailing of the building is unmistakably personal and may not lend itself to widespread replication, these underlying messages are readily transferable.*[22]

22 Green and Taggart, 2020, p.115.



Detail section:

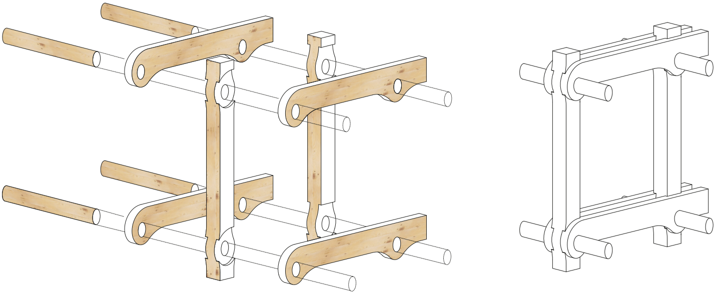
1 External shading (fabric)
2 Steel square tube 140mm × 140mm
3 Laminated timber (spruce)
4 Wood joist 200mm × 267mm
5 Triple glazing
6 Three-layer wood board 45mm and mineral wool 60–160 mm
7 Steel support for raised floor
8 Carpet and raised floor
9 Equipment space
10 Cooling/heating panel
11 Sand 80mm
12 Wood joist

Durability: the structural elements are made from sustainable timber, though it probably required a considerable amount of glue and a lot of waste wood resulted from the CNC cutting process. The structural timber frames are protected from the environment by the glazing and intelligent ventilation process has been implemented to control moisture throughout the year. Furthermore, all the timber elements have been given a 'sacrificial' extra 40 mm in thickness in all directions to avoid the need for external protection from fire. This 'extra layer' allows for the structure to remain fully efficient for at least one hour within the flames thanks to the timber's charring capacities.

Versatility: Since the project is using a framing system (i.e., columns and beams) the interior spaces are easily interchangeable. All interior spaces being free of linear structural elements it would be possible to adjust its typology if needed.

Modularity: The structural timber frames are limited in terms of variety of elements, which helps create a modular design. It is mainly composed of three repeated elements: the columns, the couple of transversal beams (same element), and the longitudinal oval beam.

Reversibility: As we saw earlier, the timber elements are assembled exclusively through wood-to-wood connections as shown in the illustration below. This allows for both easy



disassembly and good maintaining of the quality of the timber elements which have not been damaged by screwing or nailing. The rest of the elements, such as the glazing and the flooring, seem to be dismountable as well without impacting the main structure.

This is a great achievement for such a building to be limited to 3 parts structurally but in return, those timber elements are very specifically customized and therefore not easily produced limiting the reproduction of such a design for multiple buildings.

This exposes one of the issues of reversible timber buildings, the limitations in terms of production and customization. It is understood that reconfigurability was not the aim of the project, but if this design was to be made reconfigurable, it would not be efficient. The very odd and custom design of the timber elements, with its carving and specific shapes (i.e., the oval hole and the cut-out of the pillar in the shape of the beam) forbids any flexibility in the arrangement of the elements. It is hard imagining this structure being arranged in any other way than the one already defined. Furthermore, while precise and expensive machinery is not directly an issue, it does not help make the production of the timber elements fast and cheap.

Brock Commons Tallwood House

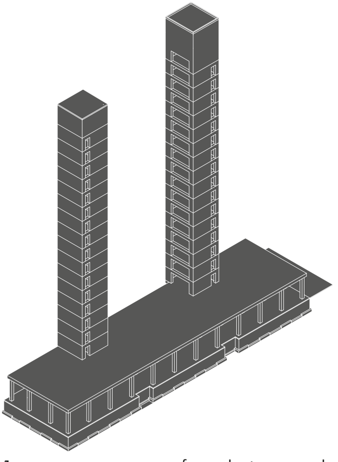
Year:	2017
Architect:	Acton Ostry Architects
Structural Engineer:	Fast + Epp
Location:	Vancouver, Canada

The Brock Commons Tallwood House project is based on the idea of a practical and efficient hybrid structure with the minimum possible number of components. Those are based on a modular floor plan which maximizes the benefits of repetition. Indeed, the typology of student housing – in this case 16 single-bedrooms per level – allows for repetitive elements that can fit well within a grid of columns. This 'keep it simple' approach resulted in the development of the two main modular structural elements of this project – the columns and the floor panels – which are repeated over hundreds of times in the entire building.

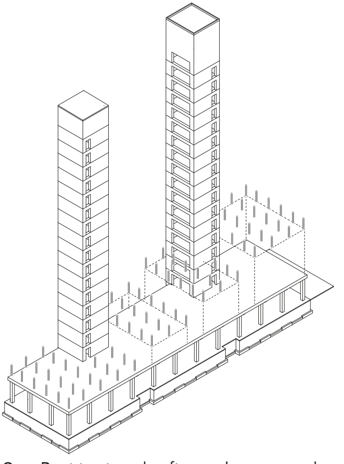
These three photographs show key moments from the assembly process of the timber elements that happened on site. The illustrations on the following page show the construction sequence that started with the foundations and ground floor which are made of concrete for a solid base. The next step was the erection of the two concrete cores located on one side of the building. After that, the assembly of the pre-manufactured timber elements could take place very rapidly. Each floor is composed of 78 timber columns supporting 29 CLT panels. Each glulam column took only between 5 and 10 minutes to install and just 6 to 12 minutes for the CLT panels which resulted in approximately 2 floors being completed per week.[23]

The relatively small size of the grid of columns – 2.85 × 4 m – allows for the floors to be made of two-way spanning CLT panels and therefore removing the need for beams. This resulted in a considerably lower floor-to-floor height, comparable to a similar concrete column and slab design, thus simplifying the installation of the building systems.

23 NaturallyWood, 2017.



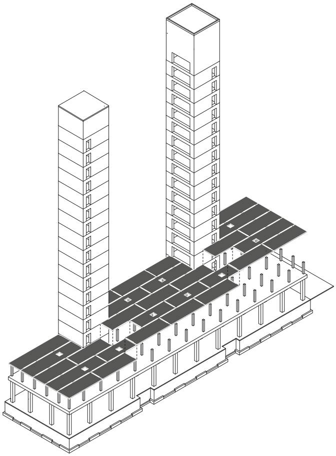
1 concrete cores, foundations and ground floor



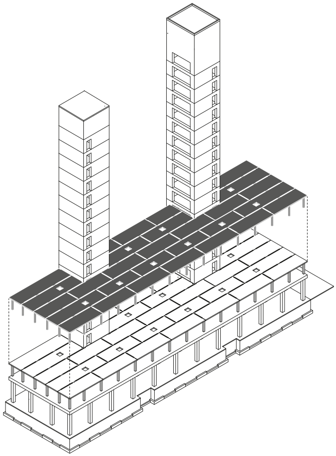
2 Positioning the first columns on the concrete slab

The facade of the building is also very modular and composed of a limited number of elements no greater than ten. Those prefabricated elements – some fully closed, some including windows, and one for the corners – are easily and rapidly installed on the structure thanks to a metallic rail that runs all around the perimeter of the CLT floors. As shown in the various photographs of the construction, this process didn't require any exterior scaffolding. The elements are carried up and mounted by workers standing directly on the structure as it is built up. This allows for an almost simultaneous erection of the structure and the facade which can then protect the timber from the weather conditions.

The structural system chosen for this project – columns and panels – has for objective the reduction of custom elements in order to attain a fast and cheap construction process. This modular system is very effective for open-plan floors and since the variation of elements is limited, the production is faster and cheaper. There was one structural issue with this sys-



3 Laying the CLT panels on top of the columns



4- Add alternatively columns and panels until the roof is reached

tem, in the fact that it is unable to withstand any lateral loads, specifically present in the context of a multi-story building along the coast of the Pacific on a terrain relatively prone to earthquakes. This problematic resulted in the decision to use a concrete ground floor and the erection of a pair of concrete cores containing stairs and elevators connecting all 17 stories. This assured the structural strength of the overall building while actually exceeding a comparable structure made exclusively of concrete thanks to the weight difference gained by the lower density of timber.

Durability: Both the structural elements – columns and panels – are made of durable materials and are well protected from the weather as well as any possible incidents, maybe too well. Indeed, when we look at the finish products, cement has been poured over the CLT panels and all the columns have been encapsulated by some fire protection. It is unsure whether the elements could be retrieved without any damages.

Versatility: Like the previous project, this one also features a vertical structure that is punctual. This allows for freedom of inhabitation and possible change of program in a rather easy manner. However, the decision to use panels instead of beams means that it would be more complicated to create double levels or vertical openings.

Modularity: The components developed for this project are very modular. They have been optimized in order to minimize the variety of the elements. Only two types of columns are used throughout all the project with the only difference being the width – from 265 mm on the first few floors to 215 mm for the upper levels. The panels are also optimized and only 4 different sizes were needed – 6, 8, 10, and 12 m in lengths by a constant width of 4 m.

Reversibility: While the building seems very reversible and its design shows improvements in the subject thanks to very efficient steels connectors – able to link vertical columns

and horizontal panels – it is hard to see those elements ever disassembled properly due in particular to the concrete covering of the panels and the various openings for shafts rendering futile the possible the reuse 'as is' of the panels. The reversibility of the columns is also doubtful due to their excessive covering in relation to fire regulation.

Reconfigurability for this project doesn't seem to be a conceivable future as we saw earlier, some of the parts are hardly retrievable. This is a pity since the construction methods put in place had great potential and modularity, but reconfigurable design requires extremely well-thought design. Furthermore, the use of concrete cores to fight the shearing forces instead of modular timber or steel bracing elements further refrains the possibility of reuse of the entire building's structural elements. It is, however, a good example for simple and fast system of assembly. The timber structure and the facade elements have been assembled on site in just a couple of months proving how efficiently the connections were designed. Recently, other projects[24] have started with a similar set of elements and it is interesting if the actors of the industry will try to enhance this already developed solution toward a system more reversible and with less concrete.

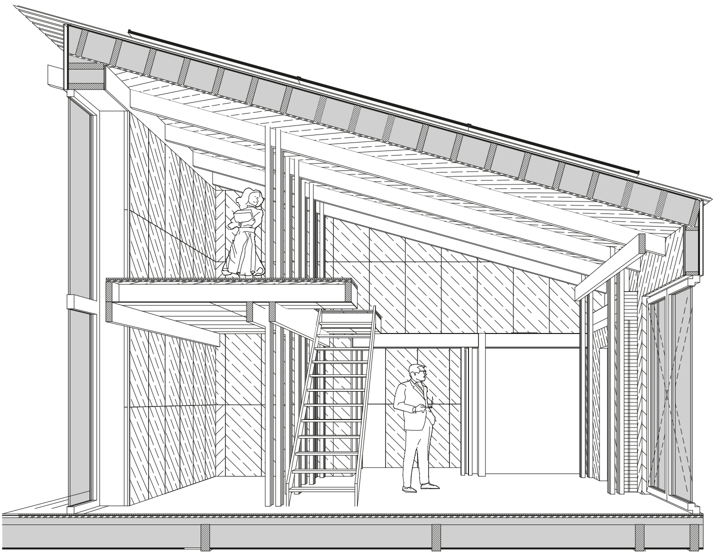
24 NaturallyWood

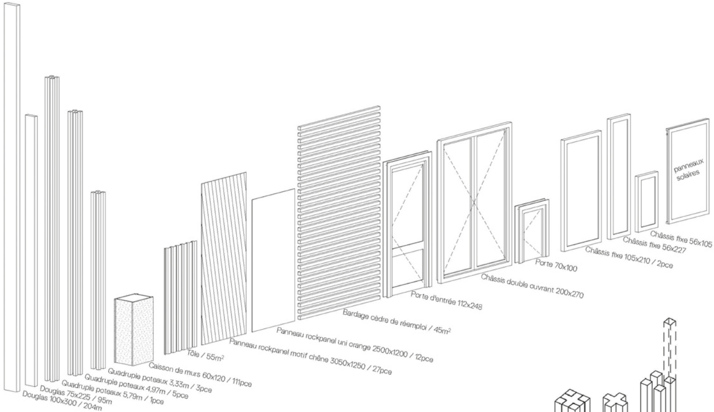
BRIC: Reversible house concept

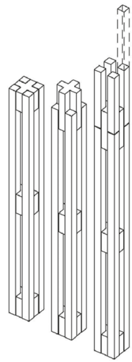
Year:	2018-
Architects:	Karbon'architecture
Structural Engineers:	–
Location:	Brussels, Belgium

This academic project explores the possibilities of creating reversible buildings that would function in a circular economy. The name 'BRIC' stands for Build Reversible In Conception, which states quite clearly the intentions of the project by the BAMB (building as material banks), a joint project by professionals and academics from all over Europe. This project combines circular building solutions for reducing waste and minimizing environmental impact. It is proclaimed as a sustainable, scalable, and reversible project.[25]

25 www.bamb2020.eu.







Timber – mostly recycled chipboard – was chosen as the main material for this project which was developed as a reversible kit of part composed of a reasonably small number of components. The little construction only required 17 different elements (see figure above) for it to be complete (facade, cladding, and partitions included)[26].

The structural system is based on three elements: load-bearing walls, columns, and beams for the floors and roof. The walls are composed of modular OSB 'cassettes' made with recycled wood waste (sixth element from the left in the figure above). Those cassettes are stacked on top of each other with interlocking elements assuring their connection. Those blocks are stacked around the perimeter of the house and are later filled with cellulose for insulation. These walls make up the primary structure of the house and will hold the side of the floor as well as the roof. The secondary vertical structure is a row of columns at the center of the house. Those columns (see figure on the top right) are designed with four

26 Capelle et al., February 28, 2019.

separate vertical elements with cross inserts every 120 cm for stability. With this arrangement, they can be stacked on top of each other quite simply by adding an intermediary insert that will lock the two columns together. This design also allows for the insertion of beams in between the four elements of the column. Those beams will support the floors and the inclined roof.

Durability: The materials chosen are low quality and as the project was not intended to last, it was smarter to use reclaimed or recycled elements, but if the goal was to develop elements with a long life of service, higher quality timber should be used. Additionally, many elements like cladding are screwed on the walls which creates little damage to the cassettes. Furthermore, the use of cellulose, however, interesting for this case, creates a mess after the disassembly.

Versatility: The building and its (small) space is designed for one purpose, in this case, a small house. However, it could theoretically be possible to build another space with more or less the same kit of parts. The structural elements like the cassettes and the columns could be placed in different layouts, and with more of them, a larger scale construction could take place.

Modularity: A lot of elements of the building are modular, especially the wall cassettes and also the columns, but everything else – the beams, cladding, roof, etc. – are not designed in a thorough modular way. The choice of an inclined roof doesn't help in this case as it creates unnecessary strangely shaped elements on the facades as well as odd connections with columns.

Reversibility: The building was designed for reversibility and in a lot of ways it achieved it, but not entirely and not sufficiently. The building has been dismounted as part of the exercise. A lot of elements have been screwed and this is reversible but leaves small damages on the surfaces. Some surfaces had been sprayed with clay for the finish and airtightness which rendered the process of deconstruction more complicated. The system chosen for the construction, presented as reversible, is lacking efficiency as it seems complicated both to assemble and to disassemble. Indeed, a lot of additional steps are needed on site and the level of prefabrication was too low to reach a satisfying result.

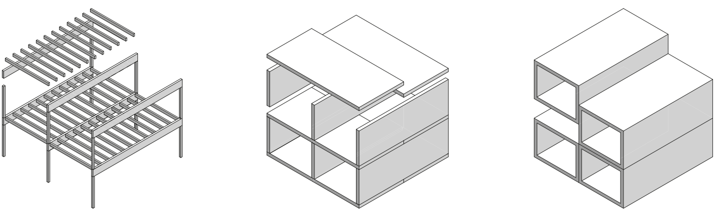
This project is close to a reconfigurable one as the same kit of parts could be used in many ways, however, as we have seen, it is not as reversible as it pretends to be. The project was surely educational for the students from various fields of the construction who participated in this project but it would be interesting to continue exploring this direction further and to make new propositions of assemblies while reducing the issues of durability and reversibility.

Conclusion: extracting new guidelines

These five case studies can teach us that timber design has multiple possible approaches, which have evolved through time. We have come from highly skilled craftsmen to highly precise automated machines while the simplicity of the system allows for greater democratization of the design.

It can be deduced from the analysis of those projects that reversible design is not as easy as it seems and even the projects that proudly consider themselves reversible are, in fact, not entirely reaching a true reversible quality. Of the four principles of reversibility, often one or another was not fulfilled, considerably reducing the chances of reuse as it is the objective of reversible design.

The idea of designing all the elements according to a modular dimension or unit is the first step to a construction that is straightforward but reversibility relies much more on the connections than on the elements themselves. The links, joints, fasteners, or connectors are the key to reversibility. They enable the possibility of assembling and disassembling the components of the building therefore it is understandable to put great efforts at designing those connection elements. It is, however, important to not ruin the efforts put in the connectors by compromising those joints with additional material such as poured concrete (i.e., the case of Brock Commons Tallwood House).



As for the constructive methods, there are three approaches, with all having their advantages and disadvantages. First, a construction of linear modules. Columns and beams are the most basic structural components of a building. As they are only linear elements, the freedom of accommodating the intermediary spaces is high but in counterparts, the beams are an obstacle to ceiling systems and create higher floor-to-ceiling heights. Second, a system of panels is favored if the goal is to reduce that height and fit more levels in the same built volume. Indeed, the panels are thin and create a regular flat surface to put the finishing layers. They also allow the various systems to more freely in horizontal directions. They, however, are often compromised when holes have to be made for shafts and other conducts to go through multiple levels. A hybrid system mixing columns and horizontal panels can also be a good solution as explored in the project of the Brock Commons Tallwood House. The third approach is of modular volumes. It is considerably efficient in the way of fast assembly and prefabrication, but lacks variety as the modular elements are too big. They reduce the freedom of design and the only way to reuse those large modular elements is simply to move them to another location and assemble them similarly.

More generally all elements must be designed in a manner to make them compatible with reversible connections. Structure elements are the most significant, but learning from traditional Japanese houses, it is also important to design the additional elements (e.g., facade elements, partitions, doors, flooring, etc.) as modular elements that can be inserted onto the structure of the building.

4

Reconfigurable timber design

Introduction

Reconfigurable and flexible designs are still rare nowadays, but some actors of the construction – academics and members of the industry – have begun to explore new approaches to enable such projects to happen. Most projects are still conceptual or simply at a prototypal level, still it is important to understand where the industry is heading to. The following cases – due to the rareness of reconfigurable projects – are not limited to timber construction, but they share this idea that architecture can be reconfigurable, and they set interesting examples and inspiration for a possible innovative approach developed in the last chapter of this thesis.

The following projects and concepts that will be studied can be divided into two categories, the first being more theoretical and the second more practical, either with prototypes, product development, or physical projects. The study of both those categories of approaches aims at offering a new perspective as to how can architecture be designed in a reversible and reconfigurable way.

Theoretical approach and literature

Reconfigurability has long been known as a concept in multiple fields and industries (e.g., industrial design, automakers, and more) but more often rather as a theoretical and conceptual approach than a physical one. In architecture, reconfigurable projects which have been built are very rare. This led me to also explore theories and concepts related to reconfigurability in architecture as a support for the research while I attempt to find recurrent ideas in those following theories which could translate in guidelines for my proposals.

Discrete architecture

With the advances in computer-assisted design and more recently robotic and automated assemblies, a new approach has emerged from multiple researchers. This discrete architecture is an emerging body of work that aims to redefine both the production and construction methods of architecture by putting forward the notion of discreteness in the digital design as well as in the physical assembly of buildings.

> *"'Discreteness' is a notion that comes from the sciences, referring to what is individual and separate. It is the opposite of the continuous, that which is uninterrupted and seamless."*[27]

27 Retsin, March 2019, p.8.

Discrete architecture detaches itself from the more conventional continuous approach toward architecture which is part of the issue that the industry faces with the current global warming crisis. It aims to understand and manage the design of the built environment through the use of modular defined 'parts'. Discrete architecture relates to the notion of mereology, which is a term derived from the Greek *meros*, meaning 'part', and it refers to the study of a whole – a building – through the relationship between its constituting parts – the building components.[28]

All buildings are made of smaller-scale components that are assembled together throughout the process of construction. A building is constituted, on average, of more than 7,000 different elements[29], it would be unproductive to attempt to automate these many different operations. However, if the syntax of a building – meaning what is composing the building – can be reduced to just a few, well-designed, elements, automating their assembly becomes more feasible.

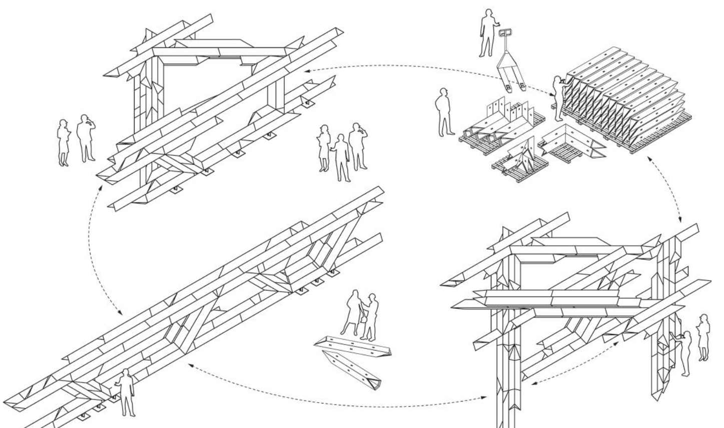
This syntax works around the idea that elements are understood as hierarchically equal, generic units – or modules – that, unlike the modernist assembly, have no predefined, geometric type or function as can be seen in the photograph of the pavilion for the 2017 Tallinn Architecture Biennale by Gilles Retsin. This is a departure from conventional elements with a predetermined function (e.g., column, beam, wall, floor, roof, etc.) which only operate for one specific function, toward the design of generic elements having the capacity to adapt and become either a beam, a column, a floor or any other structural, or partitional component depending on the position, orientation, and connection of the said unit in relation to the others. Their combination into specific assemblies

28 Koehler, March 2019.
29 Retsin, March 2019.

can, then, enable the functional conditions for inhabitation and use according to the desired program. Architecture is no longer about the overall form but instead becomes about the relations between its individual, independent parts.

This process of thought and design enables rapid, efficient, reversible, and reconfigurable construction. Since the elements are generic and fairly simple, they can be mass-produced which lowers their cost. The available quantity is therefore high, and possibilities of assemblies are varied and numerous. The illustration below shows that it has become possible to create different buildings from the same kit of elements and the process of transformation is more accessible and straightforward. The modular design of the components allows easy extension by connecting new elements following the same technique. Deconstruction is made simpler thanks to reversible assembly joints between the components which can be reused on another project and reconfigured in almost unlimited ways.

Advanced digital fabrication and manufacturing tech-



nologies such as industrial robots and 3D printers have, nowadays, become more commonly used in construction. But this has been done mainly as replacements for human labor (mimicking actions of the human body) and rarely as a tool to enhance fast modular assembly.[30]

Discrete architecture seems promising about reconfigurability, but it still has to stand out from the status of conceptual and sculptural. For this it will need to produce real, programmatic and inhabitable architecture. One of their attempts will be explored further in the chapter 4.3.4.

> *"Discrete architecture develops design strategies for serially repeating, recombinable sets of generic discrete elements that can be assembled into fully functional and complex buildings."*[31]

30 Claypool, March 2019.
31 Retsin, March 2019, p.41.

Reconfigurable design concepts: case studies

While most of the following case studies are still concepts, research or prototypes, they are representing the stage of current reconfigurable construction across the globe. The cases that I chose to study are of various origins, The first being an academic research which resulted in the creation of a prototype. The second is also originally an academic research but it turned into the creation of a product, a reconfigurable flooring system. The third is the result of a group of independent researchers which resulted in the construction of many prototypes and actual small-scale projects based on the idea of 'democratic' architecture where people could create their house by using components from a kit of parts and an assembly guide. The next one is the attempt by the researchers at the Bartlett School of Architecture – who developed theories about discrete architecture – to translate their theoretical approach into an architectural project. The last project which I will explore is from a Danish architecture firm who developed an ideal village based on the circular economy with reversible and reconfigurable properties.

Once again, the cases chosen are varied, and by making this decision, the aim is to broaden the view of possible approaches to the problematic that is reconfigurable design as well as other related topics such as automation, democratization of architecture, or the design in a circular economy. These projects will be explored in order to extract precise guidelines as how to design for reconfigurability.

Reusable kit of parts for diverse structures

Aeternum reconfigurable system

WikiHouse

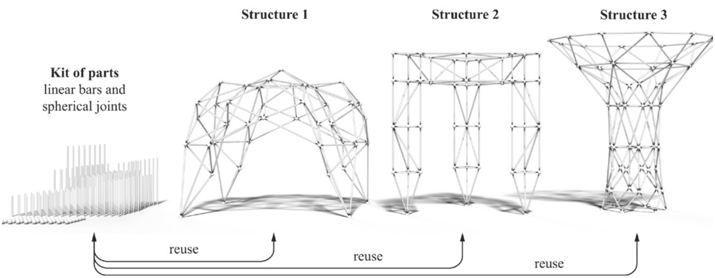
AUAR – Block Type A

Urban village project

Reusable kit of parts for diverse structures

Year:	2021-
Researchers:	Brütting, Senatore, Fivet
University:	EPFL
Location:	Lausanne/Fribourg, CH

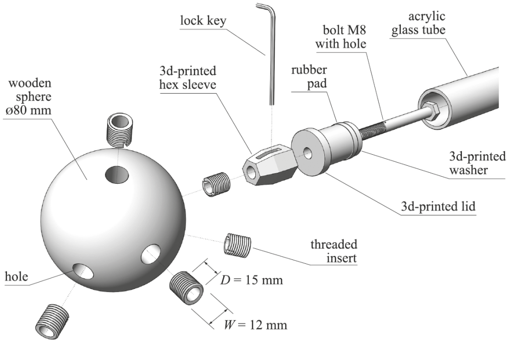
This academic project has the goal of developing a reconfigurable kit-of-part as an approach toward more reusable structures.[32] Two problematic were tackled by this project. First, the ability of reconfiguration of a bespoke kit-of-parts, and second, the capacity for the elements to be assembled in various ways as to not limit the design to a unique combination. That last step required designing new connective elements that can be used in various assemblies. This design is more focused on structural trusses, gridshells, and space frames as the image below shows, but it is also an approach to consider for what reconfigurable timber structures could be based on.



The approach explored by this project is one of linear bars and spherical connectors which enable the construction of multiple space structures (as shown in the figure above). The method for the development of such a kit of parts comprises two steps. First is the optimization of the overall geometry

32 Brütting et al., May 2021.

and the structural elements – length and cross-section of the bars – in order to minimize the variety of parts and favor the reuse of identical elements. The second part consists in optimizing the spherical joint – or connector – by finding the best arrangement of the receptive holes to allow for a variety of connections as shown in the illustration below.



The elements needed to build those three structures independently would have been 351 bars and 140 nodes. With the optimization process, a resulting final kit-of-parts can be composed of only 170 bars and 54 connectors. This is less than half the number of components originally required.

This concept is very compelling in the approach it has toward the combination of reconfigurability and optimization of structures. The development and potential of the spherical connector are remarkable and some similar approaches with timber have been explored by other people.[33] However, it is hard to imagine this process being applied to a full load-bearing timber structure at the scale of an entire building. Indeed, all the examples – digital and physical – of this approach seem to be limited to pavilions, roof structures or non-loaded designs.

33 Build with Hubs Ltd.

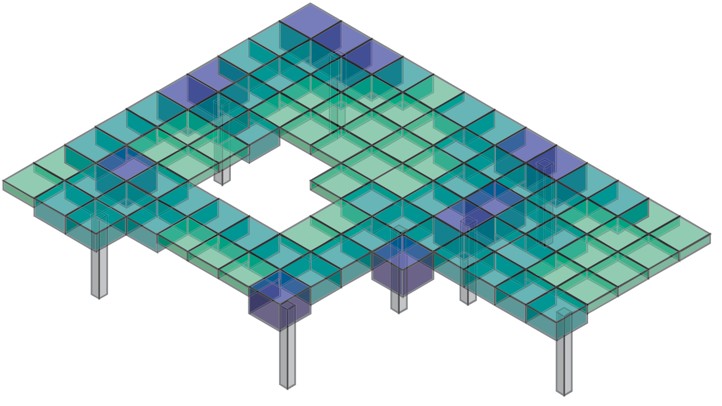
Aeternum reconfigurable system

Year:	2018-
Researchers:	Muresan et al.
University:	EPFL, HEIA-FR
Location:	Fribourg, Switzerland

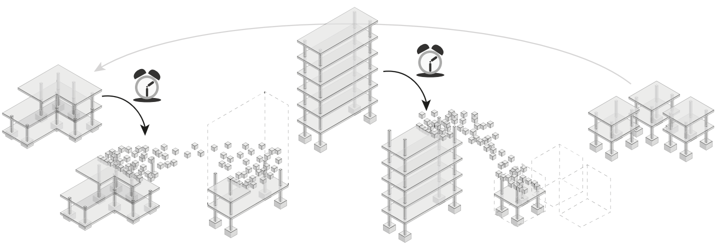
This is a concept of repetitive modular construction system developed by Alex Muresan et al. in Switzerland which started as an academic research and developed into a product called Aeternum.[34]

The concept is the following: a modular slab system, adaptable and reversible that enables reconfigurable design of buildings in the circular economy. This design extends the life of service of structural elements, in this case, the slabs. The Aeternum product is based on previous research papers by Muresan et al. on the design of modular slab system (see image below) and on a reconfigurable structural system for both residential and office typologies which will both be explored in this chapter.

34 www.aeternum-tech.com.



The first paper[35] explores modular structural slab systems and the complex challenge of avoiding oversizing while allowing maximum flexibility of configuration as well as the capacity of such a system to be functioning with an irregular column layout. Throughout digital modelization and randomization, it has been possible to define the capacity of the modular slab to adapt to various column arrangements. Furthermore, a discrete approach to the design of the slab component allows for better optimization of the material according to the related load while assuring serviceability requirements.

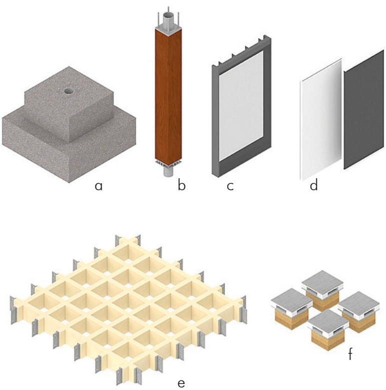


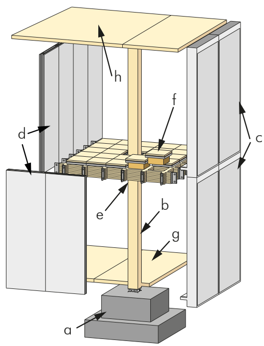
The second paper[36] widens the problematic to the construction system of the entire building structure, focusing on reconfigurability between residential and office building typologies. As an answer to the current problematic of obsolescence of buildings, this paper offers a reconfigurable construction system that allows for its elements to be combined into various designs. This combined with a reversible construction enables the buildings to enter a circular economy where buildings and their elements can be repurposed, rearranged, and reused in a continuous loop (see image above), thus reducing considerably construction efforts, costs, and CO_2 emissions over the long term.

35 Muresan et al., 2018.
36 Muresan et al., November 1, 2020.

The overall system developed through those two papers and turned into the Aeternum product takes shape primarily as a flooring system combined with modular components such as columns, panels, and tiles. This modular slab system is composed of intercrossing orthogonal beams of constant dimensions. Square modules composed of six beams in each direction can be connected together laterally thanks to bolted steel plates, but those slab elements can also be stacked on top of each other in order to locally increase the static height, thus resisting bigger loads were required (often near columns, similar to a mushroom column, or along other specific load lines). This system could be functioning with any type of column, but the preferred type is a modular column that can be connected vertically with metallic connectors (similar to the ones present in the Brock Commons Tallwood House[37], see chapter 3.2.4). The spaces in between the beams of the modular slab allow for the columns to go through the levels. This requires adding another element on the column in order

37 NaturallyWood, 2017.





a. foundation b. column
c. facade d. part. wall
e. slab module f. floor tiles
g. flooring h. ceiling

to support the slab module through which it is passing. The slab modules can afterward be covered with modular floor tiles which fit perfectly onto the slab elements. The design is completed with the use of additional modular elements such as facade panels and glazing, but also modular partitioning and insulation components able to fit within the design of the floor. The columns can be placed on strategically located concrete foundations supporting the entire construction.

This approach to reconfigurable design is not only interesting but also seems conceivable on a large-scale construction. The considerably small scale of its module and the extreme modularity of the elements enables a reconfigurable design. Its capacity to adapt to the column layout and to varying loads is compelling. Additionally, the way it combines columns into a slab system allowing great flexibility for both design of spaces and systems (water, air, electricity, etc.) is remarkable. However, it seems in hindsight that this system, as stated in the second paper[38] is efficient only for building typologies such as residential and offices as it is very constrained geometrically to in orthogonal design. Obviously, the great majority of constructions are orthogonal, so this should not be too much of a problem.

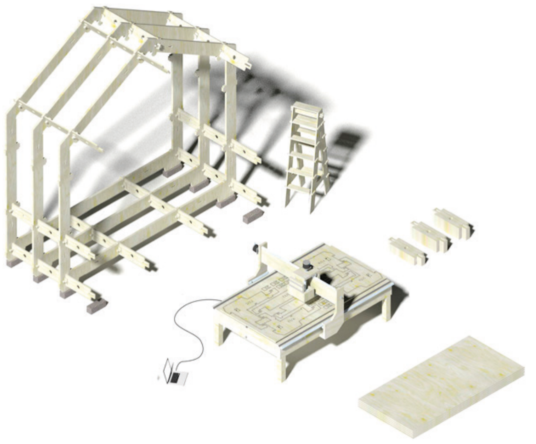
38 Muresan et al., November 1, 2020.

WikiHouse

Year:	2011-
Researchers:	Parvin et al.
Architects	00 Architects
Location:	Great Britain

WikiHouse is a digitally manufactured building system. It aims to make it simple for anyone to design, manufacture and assemble beautiful, high-performance homes that are customized to their needs.[39] The concept is based on a kit-of-parts that has been digitally designed. The various components of the WikiHouse are functioning as discrete elements which can be assembled into walls, frames, beams, or floors. Those elements are conceived first digitally in order to get an optimum kit of parts. Thin panels of cross-laminated plywood are then cut precisely by CNC machines before being assembled either in the factory or directly on-site.

39 www.wikihouse.cc.



The joining of the panels is simple wood-wood connections and requires no additional connector element except locally inserted screws. (see image above)

The extremely simplified process of assembly from the kit of parts to the building is inspired by the approach taken by popular assembly companies such as Ikea and Lego[40] which, as we all know, basically sell kits of parts for constructing respectively furniture and toys.

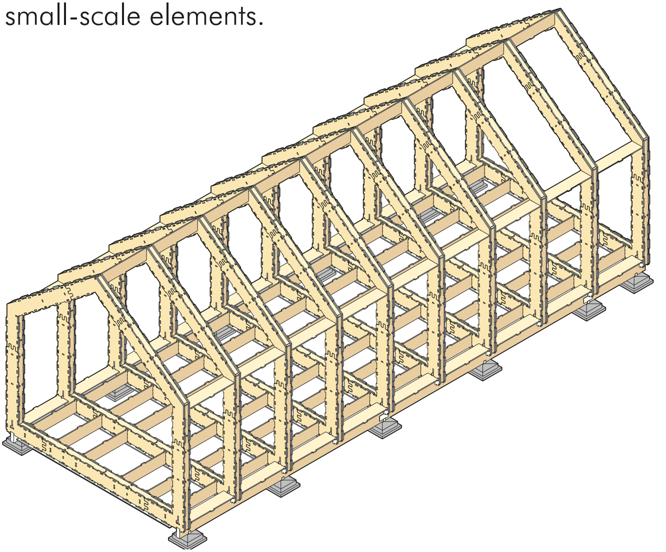
The approach taken by the WikiHouse is the result of a different goal than reversibility or reconfigurability. It is aiming at offering affordable, fast, simple, and sustainable dwellings for the common person. However, this project still is a relevant example for this research as it involves a newly designed reconfigurable and modular kit of parts.

Two approaches to the construction method can be taken with this project. First, a process similar to balloon frame can be followed and frames can be erected and linked together by transversal elements. (See image on the left.) The skeleton can then be covered with any finishing panels. The

40 Izquierdo Esteban, 2019.

second approach is similar to the B.R.I.C. project previously explored. (See chapter 3.2.5) The small modular panels are assembled into brick-like elements composing walls into which the beams and the roof are inserted.

While this approach toward reconfigurable design is interesting to explore for small-scale architecture, it is not applicable to larger scales and therefore limited in the scope of possible design outcomes. Furthermore, the complexity of the shapes makes their potential reuse and reconfiguration less likely. This system, although compelling in regard to the popularization of architecture through digitalization and automation, does not seem universal enough to be used as the new standard timber construction system. It is, however, important to point out the very clear way in which both production and assembly are presented. The joining technique used to assemble timber panels is also to be considered for further explorations even if it looks limited to small-scale elements.



AUAR – Block Type A

Year:	2020-
Researchers:	Claypool et al. (AUAR)
University:	UCL
Location:	London, Great Britain

Automated Architecture Ltd (AUAR) is a spinoff of the AUAR Labs at the Bartlett School of Architecture (UCL). The team at AUAR, composed by some of the same people theorizing about the discrete architecture which I studied earlier (see chapter 4.2.1). Their approach, similarly to the previous project (WikiHouse), aims at increasing participation and engagement in local communities by turning the assembly process into an accessible and democratized part of the construction, by everyone, for everyone.

For Block Type A (see image above), AUAR based itself on earlier works about discrete architecture from Daniel Koehler[41], Gilles Retsin[42][43], and Jose Sanchez[44], among others. AUAR developed a building system based on a kit-of-parts model composed of self-similar (i.e., the sub-elements resemble each other and the whole) without designated functions. Those parts are all the same dimensions (120x60x-20cm) and connected together one by one using reversible post-tensioned steel rods. Each block has 54 connection points spread equally on all six sides in order to create a great variety of possible compositions. The blocks can be assembled manually but also easily and quickly automated with robotic assembly.

Thanks to its modular and reconfigurable characters, Block Type A can respond to both short-term needs and long-term 'life of service' optimization through reuse. One other main advantage – as presented in the corresponding paper – of that approach, which uses only one discrete timber block, is that it can be theoretically scaled indefinitely. It seems, however, that those blocks, even when assembled in a smart

41 Koehler, March 2019.
42 Retsin, 2016.
43 Retsin, February 2019.
44 Sanchez, July 2017.

way, always produce odd details of architecture as well as non-functional spaces. Furthermore, even if proclaimed scalable, it seems that it would not be optimized for very large structures (e.g., multi-story). The first image shows a proposed concept of a little studio that requires additional modular elements such as doors, windows, and cladding in order to become more functional and inhabitable.[45]

The system is simple and extremely modular, thus enhancing the reconfigurability of the design over time and also resulting in more freedom of architectural design. The simplicity of the elements and their rigidity to change implies limitations regarding topics such as insulation and systems integration. Although the discrete approach is efficient for modularity, the overall concept still requires the development of additional pieces for specified purposes which cannot be discrete, e.g., windows, doors, systems, insulation, finishing layers, etc.

45 Claypool et al., October 2020.

Urban Village Project

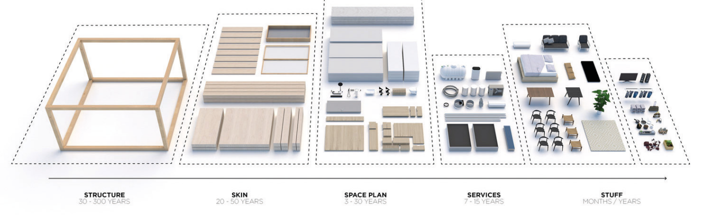
Year:	2018-
Architects:	Effekt Arkitekter
Designers:	SPACE10
Location:	Copenhagen, Denmark

The Urban Village project is a visionary and holistic approach to sustainable, affordable, and livable dwellings[46] from Danish architects Effekt Arkitekter and research lab SPACE10. The concept is developed to answer social, economical, and technical problematics of the current age. Although the first two aspects are not negligible in the real context, I will focus on the technical aspect of the concept.

The architectural design of the project is based on the repetition and multiplication of a reversible modular timber frame. Components are prefabricated and quickly assembled on site. The system is fully reconfigurable as well. The timber frames allow for a variety of occupations or inoc-

46 Effekt Arkitekter.

cupation that can vary over time. While the project offers interesting insights into the economic and social aspects of the project, the technical side is kept just on the surface and it is unclear how exactly everything functions together. It is, however, interesting from the point of view of the overall approach to explore this project in its technical aspect. In that regard, the structural system in place is the following. The primary structure is based on a six-by-six meters framing system constituting a 'wireframe-like' load-bearing system of glued-laminated timber columns and beams. Those frames are then forming the base 'layer' onto which the other modular elements come to attach themselves. In an attempt to develop this modular approach holistically, much of the design elements are turned into modular, repetitive components. The image below shows those elements arranged in order of service life span – simultaneously of size and structural importance – from the load-bearing timber frames on the left which can last more than a century if well maintained to the little appliances on the right which have only a few months of service.



The elements are then assembled onto the frames, first with additional timber beams and CLT panels to create the floor, roof, and the external closed walls. It is followed by the glazing and then the interior partitions and internal systems before being ready to furnish the new home. The great majority of components and sub-components are seemingly modular up to an unknown degree which creates an ambiguous balance between technical constraint and freedom of design. Indeed, the decision of using such a scale for the timber frame limits the possibilities of design to the spaces of those frames which results in very pixelated design. This will, however, be efficient enough for most residential as well as office typologies which are not directly mentioned in this project.

While this approach has many advantages like the possibility of scaling its system up to large complex modular buildings as the illustrations show. The technical details are still lacking and I am unsure of the real reversibility of all the components. They seem easy to assemble but will it be as easy to remove and reuse?

Conclusions and additional guidelines

With this case study, it s possible to conclude that there are various possible ways to answer the problematic of reconfigurable design with each approach having different advantages. While the design from AUAR seems to be the one that is the most reconfigurable and modular, it is also the one with the less precise architecture. The balance must be found between the development of a modular component and the design of the architecture that will result from it. The Aeternum flooring system seems like a good alternative choice to classical beam or panel floors as it sort of takes the quality of both while eliminating their issues. The Urban Village project has a better development of the general modularity which is an important part of the design as all elements must be developed in a modular way to fit within each other. A spherical joint system like in the first case study could allow for very different connections between elements but this comes with the inconvenience of being weaker. Additionally, the use of too many different angles is not necessarily needed in the majority of constructions and it would require to create more specific shaped elements to fit those angles. This would therefore go against the modular thinking.

Reconfigurability is broad but it is not the goal to satisfy all the possible constructions. Obviously, the same kit-of-part is not expected to build both a square house and a dome, but it has to be convenient for the majority of typologies (e.g., residential, offices, educational, institutional, industrial, etc.)

↘ All elements of the construction (i.e., the structure, the partition walls, the facade, the floor, and the roof) must be developed following the same modular thinking in order for those to fit all together.

↘ Modules must be of small scale in order to get more freedom of assemblies resulting in more various designs.

↘ Connections can be made of different materials than timber if this enables faster assembly and better reversibility.

↘ Those connections must offer various possibilities of assembly in order to be applied in different designs.

↘ Minimizing the number of elements in the kit-of-parts is not necessarily the best option as it will result in restricted design proposals. The variety and number of elements must be balanced between efficiency of production and freedom of design.

5

New reconfigurable timber design

Introduction

For this last chapter, I attempted to put together the guidelines and the concepts that I just studied in order to create a new reconfigurable timber design. The various concepts which I have studied previously, have given me insights into how to build reversible and what are the main issues with it. The objective of the new proposal will be to be as reconfigurable, modular and straightforward as possible while also keeping a good level of constructive reality. It is still an architectural design and must not be taken as a finite and completely developed model. Many new issues have come up while developing this model and it will be a task for the next semester to fix them and aim for a more complete and defined system.

Proposals for improvement of current methods

As it has been said during the case studies, most of the approaches have decided to focus on one part and are lacking another side of the reconfigurable design. This issue is understandable since reconfigurable design is very complex and must take into account a lot of variables and constraints. I see more potential in some approaches than others.

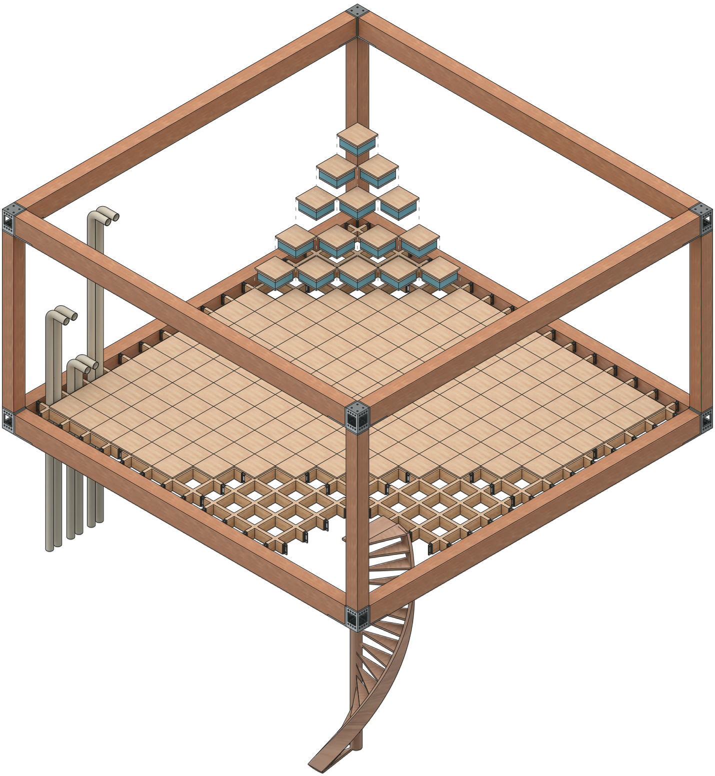
The floor system Aeternum, for instance, has the great capacity of allowing free passage of technical elements vertically while also staying considerably thin and allowing other technical components to run below it. It is, however, just a floor system and it must be used with other additional modular elements while designing all those elements in a rigorous modular way.

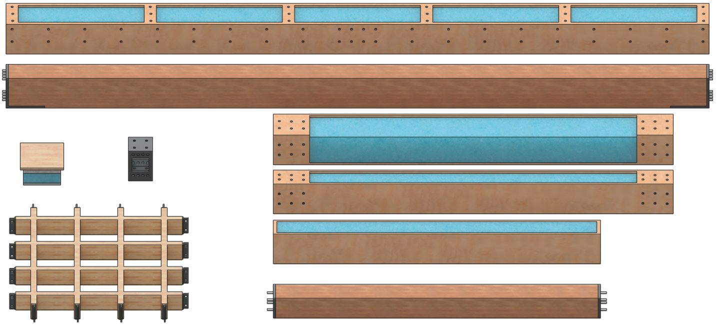
The Urban Village Project by Effekt Architects is another very interesting approach as it is more thinking in terms of modular interchangeable elements that could create various design proposals. This project is, however, lacking detailing. The images shown by the architects never talk about constructive system and how elements are functioning together. The potential is great but the reality of construction must be faced and constructive solutions must be found.

Thirdly, the Block Type A discrete system also has some good potential, maybe not so much architecturally but more technically. The possibility for elements to have many options for assembly and connections is remarkable and this system could be used with other modular components as in this case the discrete parts are just blocks with little architectural outcome.

Reconfigurable design proposal

These last concepts could be modified, upgraded and combined to create a new proposal of reconfigurable system. For this thesis, I attempted to combine the approach of the Urban Village with the Aeternum flooring system while developing the detail level of the former. This resulted in the design below. It is very interesting to see the high level of modularity coupled with great freedom of design thanks to the flooring elements.

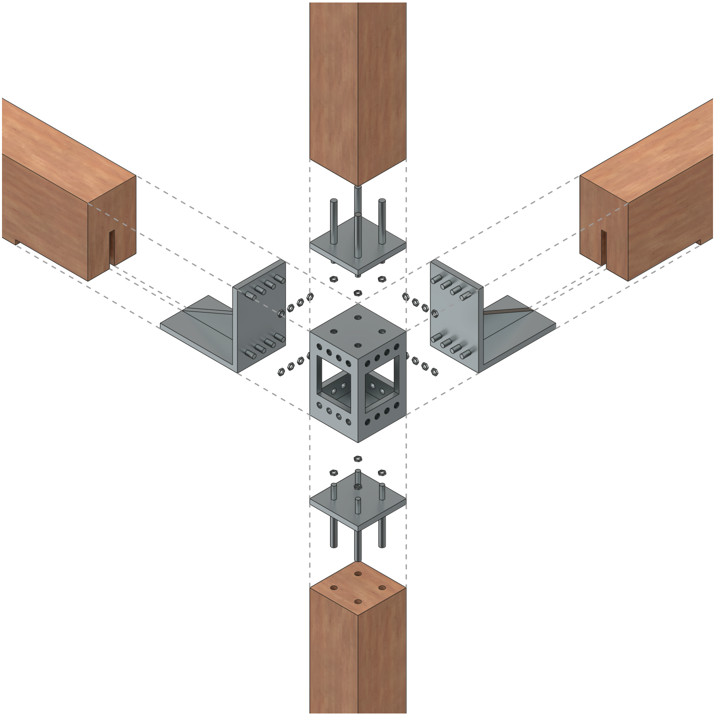


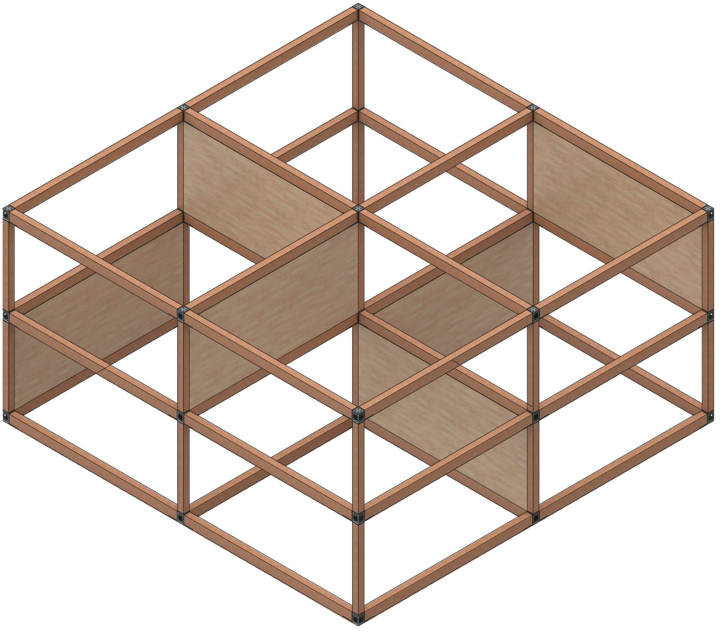


The idea of the framed modular units from the Urban Village Project is kept as the basis of the system. The 6 × 6 m grid is a good measure for the construction of residential or office projects. The frames are filled an adapted version of the Aeternum floor system which allows good freedom of design with the plans of the interior. Sixteen floor elements are required to fill an entire unit while some of them can be removed to allow vertical circulation within superimposed units. The composition of the floor system allows an easy passage of vertical tubes and other technical elements. The floor components are attached to the timber frames with reversible bolted connectors making sure that both the frame elements and the floor components can be disassembled without damaging one another.

The image above shows the kit-of-parts required to build the frame units, the floor as well as the exterior framing covers. The frame itself is assembled with only 3 elements. The columns, the beams and the connectors. The latter allows the connection of up to six elements onto it. Those assemblies create the framing of the system which creates the inhabited part of the design.

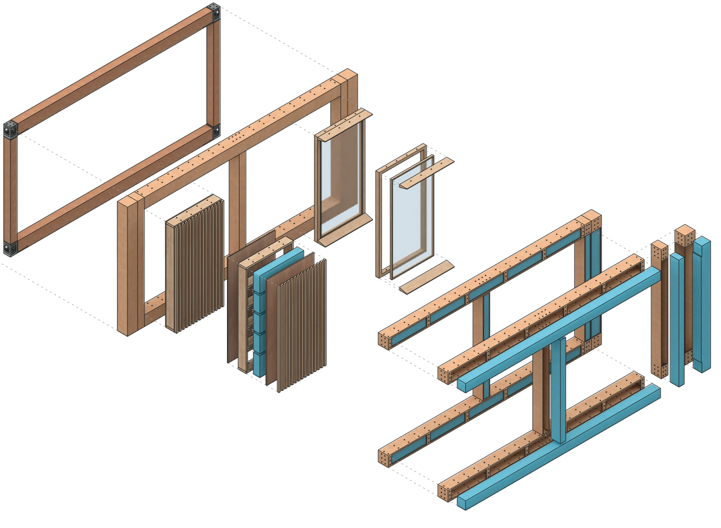
Those beams and columns are assembled together thanks to a metallic connector. While the design aims at using a maximum of wood, those steel connectors allow for more efficiency regarding reversible connections as the elements can precisely fit within the allocated holes in order to be tightly bolted together in a more secure way than a wood-to-wood connection. The image below shows a typical assembly of the frame elements onto the steel connector. In a similar manner to the Brock Commons Tallwood House, the metallic ends are attached into the columns. In this case the system does not support panels but beams so the connector must have dedicated spots for the beams to attach.

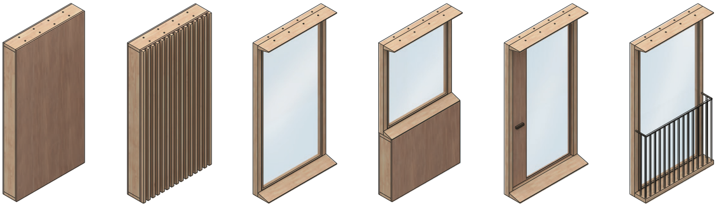




With the aim to have a minimum of concrete used in the project, the problematic of lateral loads can be raised. For this matter, the project respond with the use of large CLT panels which fit within the frames sides and act as bracing elements capable of withstanding the shearing effect of lateral loads. Those panels can be placed strategically, especially in the interior of the frames where no opening is needed. They can be oriented in the two directions and act together against loads coming from all directions. The entire structure would therefore be more resistant and rigid allowing for the design to grow bigger and taller with little to no concrete.

The frames would become the support for the entire secondary structure, as well as for the facade elements. Those facades are also made in a modular way. In order to insulate the interior from the exterior, additional elements are attached onto the frames. Those elements cover the frames and the columns with sufficient insulation while also being the support for the facade elements (i.e., windows, doors, enclosed panels) which can offer a skin to the skeleton. Those long elements are constructed with inspiration from the Block Type A discrete blocks. They are made of 'CNC-cut' cross-laminated plywood with a large number of possible assembly points. Once attached onto the frames, they become the support for the facade elements who have the similar pattern of connection which enables them to securely attach themselves onto those elements. The illustration below shows the assembly and system created by those modular elements, from the frame up to the facade.

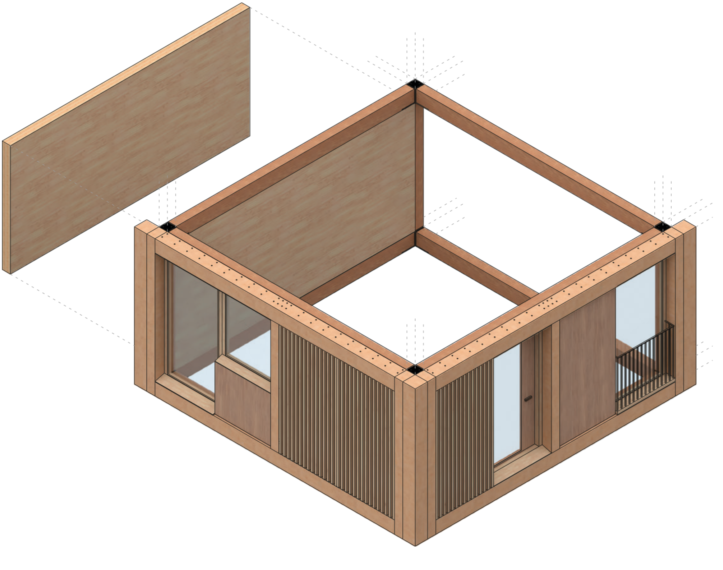




With those supports allowing for modular attachments, the possibilities of enclosure are becoming almost unlimited. For this proposal, and with inspiration taken from the Urban Village Project, I designed a set of modular facade elements. The illustration above shows 6 various possible enclosure modules who can all fit next to one another. Various facade finishes can be chosen. In this case, a flat panel and a louvers version are put forward while four styles of openings are imagined. The third drawing shows a fixed full-sized window while the fourth imagines a window that sits above a panel (i.e., for instance in a kitchen zone). The fifth and sixth proposed facade elements are openings. First a door and last an opening glass door on an inset balcony.

This approach enables a good level of freedom and customization of the design while keeping the modular efficiency. The majority of elements could be prefabricated in factory conditions and assembled on site very fast like it has been done for the Brock Commons Tallwood House which required only a couple of months to get erected.

This reconfigurable system is a first proposal and still has many issues that will require special attention during the development of the Master's project next semester if this approach is the one that will be followed. Some of the main issues that have appeared during this research is for instance the connection of the frames in the center of the construction, when 6 elements come to attach to the connector, it seems impossible to attach the last one as all the spaces to access the bolts would be closed by other members of the frame. A system similar to the one of the Brock Commons Tallwood House (i.e., where the column simply slides into the connector without securing it with a bolt) could be imagined but the tightness of the construction might be impacted. Additionally, the modular facade elements function very well on all the external convex parts but the concave angles are creating overlapping issues with the use of regular modular elements. Specific elements would have to be developed which reduces the efficiency of the overall system. Furthermore, the position of the frames as part of the inside space might need the creation of specifically adapted corner elements for the flooring to fit around the frames.



Conclusion

This proposed system is an upgraded version of previously studied Urban Village Project and incorporate elements from other cases like an adapted version of the Aeternum flooring system as well as the discrete connections from Automated Architecture Ltd. As stated before, the concept is not complete and reconfigurable design is not an easy task. The goal of a holistic modularization of the constructive system is not an idea that is new but while it has been present for a very long time (e.g., the traditional Japanese houses), this is an approach that requires long-term development and focus to achieve.

Fully reconfigurable timber construction has not yet become a reality. However, the development made by the various actors is promising and with the Master's Project coming up next semester, I intend to continue developing this idea through further stages of construction, realism and efficiency. This research and the later development of the corresponding thematic will require me to shift my architectural thinking toward reconfigurable timber design.

Definitions

Discreteness refers to elements that are individual and separate. It is the opposite of the continuous, that which is uninterrupted and seamless. The discrete elements are independent and are not defined by their purpose.

Reversible design describes how a building is designed to be readily taken apart at the end of its useful life so that the components can have a second use.

Reconfigurable design describes how a building is designed in such a way that, in the case of deconstruction, all – or most of – its elements can, not only be reused, but, moreover, be reassembled together in various ways to form a new building.

Durability is the capacity of a building element to be resilient through space and time. A durable element will typically have either a long life of service or the capacity to be sustainably recycled.

Modular design refers to the design of buildings and their components in a way that is repetitive. The module is an element or a unit that can be replicated and assembled to create something bigger.

Kit-of-parts are a set of various building components that are engineered, designed, and prefabricated to be assembled together in multiple possible ways.

Reuse is the act of using a component for a second time, either for the same role or for a different purpose.

Recycling is the process of turning an element back to its state before its fabrication or into another type of element by cascading it down the product line.

Life of service is the duration of life of a building or one of its elements for which it can still be used for its original purpose or for any other equivalent role.

Democratized architecture refers to an architecture that aims at being available to the most people. This often goes to the process of making architecture affordable and not skill-demanding.

Linear Economy is the model in which the raw elements are sourced or produced, transformed, used, and finally accumulated as waste. This model follows a singular, uni-directional way.

Circular economy refers to a closed-loop model of an economy where waste is eliminated and products are sold, consumed, collected, and then reused, remade into new products, returned as nutrients to the environment or incorporated into global energy flows. (Gorgolewski, 2017)

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4 Jacques Schmidt (based on illustration by C. Fivet)

6 Jacques Schmidt (Hudert and Pfeiffer, *Rethinking wood*. Basel, 2019, p. 42)

24 ©David A. LaSpina

25 Tetsuro, Yoshida. *Das Japanische Wohnhaus*. Tübingen, 1969, p. 71

26 Engel, Heino. *Measures and Construction of the Japanese House*. Rutland, 1985, p. 92

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29 O'Brien, Michael J. *Hybrids on the Way to the Western Platform Frame*. 2010, p. 41

30 Elliott, Cecil D. *Technics and Architecture: The Development of Materials and Systems*. 1994, p. 18

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63 Brütting et al. *Design and fabrication of a reusable kit of parts for diverse structures*. 2021, p. 10

64 Muresan et al. *Design Space of Modular Slab Systems with Discrete Stiffness Distribution and Irregular Column Layout*. 2018, p. 2

65 Muresan et al. *Sustainability through reuse: a reconfigurable structural system for residential and office buildings*. 2020, p. 5

66 left: www.aeternum-tech.com; right: Jacques Schmidt (based on Muresan et al. *Sustainability through reuse: a reconfigurable structural system for residential and office buildings*. 2020, p. 5)

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Bibliography (all mediums combined)

Brütting, Jan, Gennaro Senatore, and Corentin Fivet. "Design and Fabrication of a Reusable Kit of Parts for Diverse Structures." *Automation in Construction* 125 (May 2021). https://doi.org/10.1016/j.autcon.2021.103614.

Build with Hubs Ltd. "Hubs: Geodesic Domes Made Simple." Accessed December 29, 2021. https://buildwithhubs.co.uk/index.html.

Capelle, Teodora, Flavie Lowres, Kiruthiga Balson, and Mirko Farnetani. "Testing Bamb Results Through Prototyping and Pilot Projetcs." Buildings as Material Banks, February 28, 2019.

Claypool, Mollie. "Our Automated Future: A Discrete Framework for the Production of Housing." *Architectural Design* 89, no. 2 (March 2019): 46–53. https://doi.org/10.1002/ad.2411.

Claypool, Mollie, Manuel Jimenez Garcia, Gilles Retsin, Clara Jashke, and Kevin Saey. "Discrete Automation: Community-Led Housing Platforms." In *Distributed Proximities: Proceedings of the 40th Annual Conference of the Association for Computer Aided Design in Architecture. Volume 1: Technical Papers, Keynote Conversations*, Association for Computer Aided Design in Architecture (ACADIA)., 638–47, 2020.

Effekt Arkitekter. "Urban Village Project." Effekt Arkiteker. Accessed December 30, 2021. https://www.effekt.dk/urbanvillage.

Ellen MacArthur Foundation. *Delivering the Circular Economy: A Toolkit for Policymakers*. Ellen MacArthur Foundation. Cowes, UK, 2015.

Elliott, Cecil D. *Technics and Architecture: The Development of Materials and Systems for Building*. The MIT Press, 1994. https://doi.org/10.7551/mitpress/6674.001.0001.

Engel, Heino. *Measure and Construction of the Japanese House*. 1st ed. Books to Span the East & West. Rutland, Vt: C.E. Tuttle Co, 1985.

Fivet, Corentin. "Design of Load-Bearing Systems for Open-Ended Downstream Reuse." *IOP Conference Series: Earth and Environmental Science* 225 (February 24, 2019): 012031. https://doi.org/10.1088/1755-1315/225/1/012031.

Fivet, Corentin, and Jan Brütting. "Nothing Is Lost, Nothing Is Created, Everything Is Reused: Structural Design Circular Economy." *Structural Engineer* 98 (January 2020): 74–81.

Gorgolewski, Mark. *Resource Salvation: The Architecture of Reuse*. Hoboken, NJ: Wiley, 2017.

Gorse, Christopher A., David Johnston, and Martin Pritchard. *A Dictionary of Construction, Surveying, and Civil Engineering*. 2e ed. Oqr: Ncs. New York: Oxford University Press, 2020.

Green, Michael, and Jim Taggart. *Tall Wood Buildings: Design, Construction and Performance*. Second and Expanded edition. Basel: Birkhäuser, 2020.

Howe, A. Scott, Isamu Ishii, and Tomohiro Yoshida. "Kit-of-Parts: A Review of Object-Oriented Construction Techniques." In *Proceedings of the ISARC'99 - International Symposium on Automation and Robotics in Construction*, 165–71. Madrid, 1999.

International Energy Agency (IEA). "Toward a Zero-Emission, Efficient and Resilient Buildings and Construction Sector." Global Status Report, 2018.

Izquierdo Esteban, Sonia. "Self-Assembling Architecture. User Graphic Manuals." In *Graphic Imprints*, edited by Carlos L. Marcos, 1108–16. Cham: Springer International Publishing, 2019. https://doi.org/10.1007/978-3-319-93749-6_91.

Koehler, Daniel. "Mereological Thinking: Figuring Realities within Urban Form." *Architectural Design* 89, no. 2 (March 2019): 30–37. https://doi.org/10.1002/ad.2409.

Lanier, Gabrielle M., and Bernard L. Herman. *Everyday Architecture of the Mid-Atlantic: Looking at Buildings and Landscapes*. Creating the North American Landscape. Baltimore: Johns Hopkins University Press, 1997.

Muresan, Alex, Jan Brütting, Javier Cañada, Dario Redaelli, and Corentin Fivet. "Design Space of Modular Slab Systems with Discrete Stiffness Distribution and Irregular Column Layout," 2018, 8.

Muresan, Alex, Jan Brütting, Dario Redaelli, and Corentin Fivet. "Sustainability through Reuse: A Reconfigurable Structural System for Residential and Office Buildings." *IOP Conference Series: Earth and Environmental Science* 588, no. 4 (November 1, 2020): 042066. https://doi.org/10.1088/1755-1315/588/4/042066.

NaturallyWood. "Brock Commons Tallwood House Factsheet," 2017. https://www.naturallywood.com/resource/brock-commons-tallwood-house/.

NaturallyWood. "Tallwood 1 at District 56." Naturally Wood. Accessed January 13, 2022. https://www.naturallywood.com/project/tallwood-1-at-district-56/.

Prévost, Violaine, Isabel Concheiro, Antoine Picon, Yves Weinand, Yann Rocher, Christophe Catsaros, and Jean-Pierre Neff. *Les cahiers de l'Ibois 2: Ibois Notebooks 2*, 2021.

Retsin, Gilles. "Bits and Pieces: Digital Assemblies: From Craft to Automation." *Architectural Design* 89, no. 2 (March 2019): 38–45. https://doi.org/10.1002/ad.2410.

Retsin, Gilles. "Discrete and Digital." TxA 2016 (unpublished), 2016. https://discovery.ucl.ac.uk/id/eprint/10070957/7/Retsin_Discrete%20and%20Digital_AAM.pdf.

Retsin, Gilles. “Discrete Architecture in the Age of Automation.” *Architectural Design* 89, no. 2 (March 2019): 6–13. https://doi.org/10.1002/ad.2406.

Retsin, Gilles, ed. *Discrete: Reappraising the Digital in Architecture*. Architectural Design Profile, no 258. Oxford: John Wiley & Sons, 2019.

Robinson, Salon. “How to Build Balloon Frames.” In *Transactions of the American INstiture of the City of New-York for the Year 1854*, 405–7. Albany, USA: C. Van Benthuysen, 1855. https://books.google.ch/books?id=MyU2AQAAIAAJ&pg=&redir_esc=y.

Sanchez, Jose. “Combinatorial Commons: Social Remixing in a Sharing Economy.” *Architectural Design* 87, no. 4 (July 2017): 16–21. https://doi.org/10.1002/ad.2190.

Staib, Gerald, Andreas Dörrhöfer, and Markus J. Rosenthal. *Components and Systems: Modular Construction: Design, Structure, New Technologies*. 1st ed. München : Basel [Switzerland]; Boston: Edition Detail, Institut für internationale Architektur-Dokumentation ; Birkhäuser, 2008.

www.aeternum-tech.com. “Aeternum - Enabling Circular Buildings. ” Aeternum. Accessed December 29, 2021. https://www.aeternum-tech.com.

www.bamb2020.eu. “Build Reversible In Conception (B.R.I.C.).” BAMB. Accessed December 23, 2021. https://www.bamb2020.eu/topics/pilot-cases-in-bamb/bric/.

www.carbone4.com. “Sauver le climat avec nos forêts ? La construction touche du bois ! | Carbone 4.” Accessed December 21, 2021. https://carbone4.com/.

www.wikihouse.cc. “WikiHouse.” Accessed December 30, 2021. https://www.wikihouse.cc.

www.wikipedia.com. “1973 Oil Crisis.” In *Wikipedia*. Accessed December 21, 2021. https://en.wikipedia.org/w/index.php?title=1973_oil_crisis&oldid=1054960230.