Modular timber elements & combinatorial design:

rethinking the production chain of residential architecture

AR3A010 Research Plan

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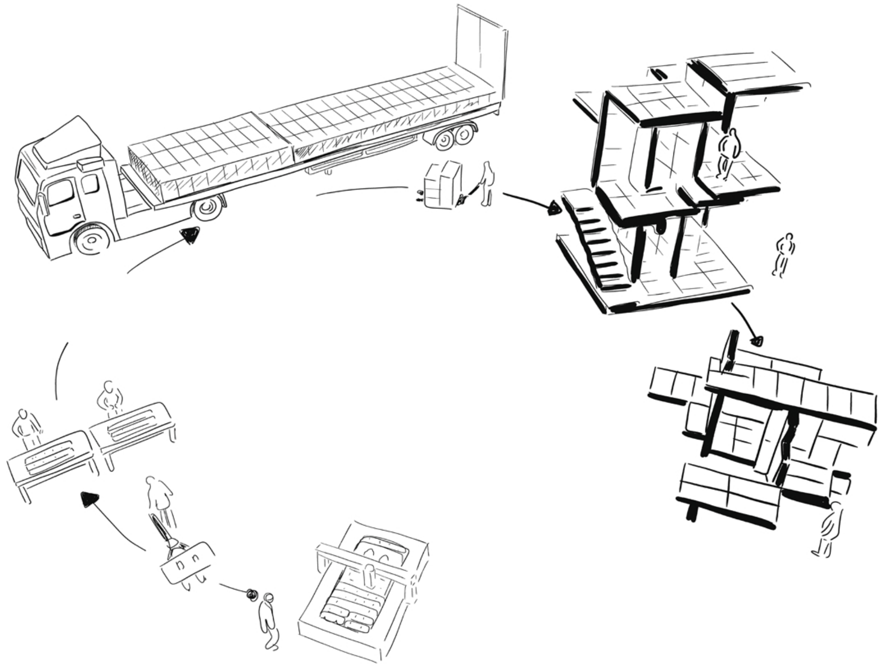


1. ABSTRACT

The standard way of building consists on average of 7000 parts and processes which in combination with the decrease in productivity within the construction sector limits the number of actors that can be involved. However, this leads to a housing shortage in many countries. The production of homes should be accessible, affordable and should offer a variety of housing solutions. In order to reach this the production chain of architecture must be rethought by considering design and production throughout the whole process. Modularity of discrete building blocks can be a way to reach efficient production processes as well as diverse housing solutions by means of combinatorial variations. This method has been used in pavilion and furniture designs, but only briefly for housing solutions. The goal of this research is to devise a methodology to design a small set of stackable timber elements to form both a structure and the inner/outer shells of a building that can be configured into versatile and affordable housing units using combinatorial design and simulation of a compression-only structure (which is designed based on equilibrium). This leads to an accessible and open-ended building system that strives to be as simple as laying out a Lego structure.

2. BACKGROUND

On average buildings consist of “more than 7000 different parts and processes which need to be assembled together into a functional whole.” (Burry et al., 2020) Additionally to the complicated system that a building is, “the construction industry has flat-lined since 1947”(Burry et al., 2020), while manufacturing has increased its productivity with the means of automation (McKinsey, 2017). With labour costs increasing and robot costs decreasing the so-called ‘Automation Gap’ (Claypool, 2019) decreases the productivity within the construction industry over time. The construction process is slow, expensive and produces a lot of waste (Eurostat, 2018) with only a few actors being able to construct, which evidently limits the supply of housing. Due to the housing shortage, there has been a wider interest in Modularity and Prefabrication. However, “this “simplified automation” (Bava 2020), and the amount of difference that can be achieved with, for example, the Modernist kit of parts (see figure 1) does not deliver the promised mass customisation and design freedom. (Retsin, 2020)

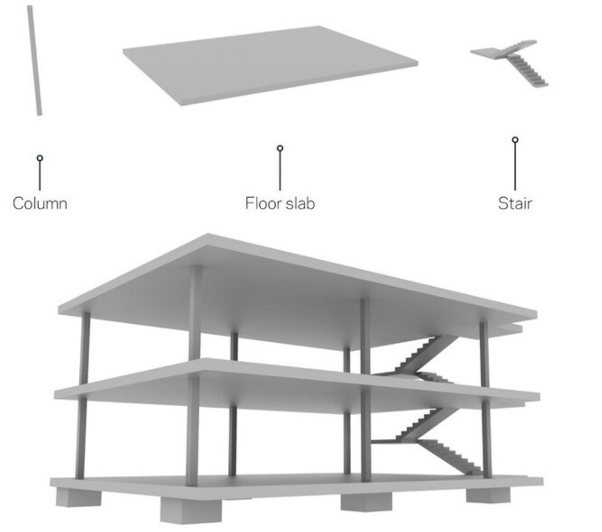


Figure 1: Maison Dom-ino. Image: Ivo Tedbury, Semblr, Unit 19/DCL, 2017.

Overall, with the housing shortage (Groot et al, 2021), the decreasing productivity within construction and the lack of variety within the current modular and prefabricated solutions a new way of thinking about the production chain in architecture is necessary. A method needs to be established to be able to design an affordable, a customizable, and an easily automatable & constructable building system.
To find an affordable means to achieve different design solutions with a predefined set of building blocks a modular generative design framework (Azadi & Nourian, 2021) is used, that mathematically formulates the spatial configuration problem. Combinatorial design and simulation are used to evaluate, inform, and improve the variety and spatial design that the parts offer. Serialized parts have always been more affordable than custom components (Sanchez, J., 2020) due to repetition and possibility to mass-produce. Combinatorial design re-considers serial repetition of parts but under a paradigm of combinatorics. (Sanchez, J., 2020) It explores how through patterns variety can be reached whilst still achieving affordable results which allows to create versatile housing solutions yet keep them at lower costs.

3. RELEVANCE

3.1. SOCIETAL RELEVANCE

Due to a very slow and expensive process of construction the act of building is accessible only to a few actors, therefore the housing supply is limited and leads to housing shortage. Firstly, housing solutions are necessary, for example, in the Netherlands to take control of the situation, “845,000 homes need to be built by 2030” (Lalor, R. (2021)). Secondly, a home is one of the biggest investments in most people’s lives where a considerable amount of time is spent, therefore a sense of identity and variety within the housing supply is necessary for user’s to be able to customize their spaces. By redefining the spatial configuration problem through mathematics and using combinatorial design enough repetition and low costs can be reached yet also variation within the housing units can be offered. Through intertwining design, fabrication & automation a more accessible and open-ended built environment can be created.

3.2. SCIENTIFIC RELEVANCE

Research in digital design has moved beyond engaging the field not only through sophisticated forms but also through the

politics and economics of fabrication. (Sanchez, 2021) Current discourse moves beyond modularity and prefabrication and demonstrates a higher degree of variability, versatility through only a limited set of building parts. In addition, it goes a step further using these building parts and exploring the possible patterns that can be created and provide variety and differentiation at a lower cost compared to custom made elements. This idea uses combinatorial design to find affordable means for creating different designs whilst using only a few different elements. The combination of a predefined set of elements and thinking in patterns is redefining the way how architectural production chains work, however, there is still a gap between these ideas and physical housing solutions. Most work has been done either on different indoor or urban furniture (Retsin, 2019) (Figures 2) or pavilion designs (Retsin, 2017) (Figure 3), only with a few attempts to create a closed space. (Retsin, 2021) (Figure 4 & 5) Therefore it lacks the relation to physical housing solutions and existing systems.

(Left to right, top to bottom))Figure 2: Royal Academy of Arts (Retsin, 2019), Figure 3: Tallinn Architecture Biennale Pavilion (Retsin, 2017), Figure 4: House block & Figure 5: robotically assembled dwelling (AUAR, 2021)

This project, firstly, aims to use the ideas of combinatorial design and simulation to apply them to a limited set of stackable timber elements to reach a large design space and variety within the configurations that the elements offer. Secondly, the goal is to move beyond furniture and pavilions and to provide housing solutions with this logic, however, it does require rethinking the structural properties of the elements as well as how different installations and existing systems can be integrated. Thirdly, to create a set of elements that work as smoothly as Lego blocks within the context of housing the size and shape of the elements need to be related to several aspects: ergonomics, people’s movement, the size of the spaces that are used and the standard elements used in such spaces, as well as the material and production of such elements to tackle the decrease in productivity. Finally, it also needs to provide variety within the solutions offered for clients to have the possibility to customize their homes. (Bathroom, corridor, living room etc.)

4. OBJECTIVE

4.1. OBJECTIVE

It is challenging to provide affordable high quality housing solutions at a larger scale. Modularity of discrete building blocks can be a way to reach efficient production processes as well as diverse housing solutions by means of combinatorial variations. The design objective of this research is to devise a methodology to find an affordable means to create many housing variations using only a few stackable timber elements that can be mass-produced. Since customised and affordable solutions always seek a balance between variety and repetition the more specific objective is to reconsider serial repetition of stackable timber elements (that act as structure and inner & outer shells) using combinatorial design and simulation, to explore the ways these parts can be designed and reconfigured in different patterns to create spatially valid and versatile housing solutions.

4.2. RESEARCH QUESTION

How to design a small set of stackable timber elements to form both a structure and the inner/outer shells of a building that can be configured into versatile and affordable housing units using combinatorial design and simulation of a compression-only structure (which is designed based on equilibrium)?

4.3. SUB QUESTIONS

- How to design a dimension system of the elements that has a strong relation to people's movement, the used material and its production, and the internal configurational logic of a home based on ergonomics?
- How to ensure that architecturally and ergonomically valid and versatile configurations can be realized by using the proposed limited set of construction blocks?
- How to incorporate the manufacturing costs and limitations in the design of the stackable wooden blocks?

5. SCOPE

This research lies within the field of design computation and aims to develop a method to create a variety of affordable housing solutions with only a few stackable timber elements that can be mass-produced. The deliverable of this research is a method that is showcased in the form of a game (physical or digital – to be decided) which consists of a few stackable timber elements and a set of rules based on combinatorics and different patterns with which the players can create their desired affordable housing solution with the goal to be able to create a large variety of solutions by just using a few types of blocks.
This research addresses several areas of study: architecture, structural design, design for manufacturing and assembly and combinatorial design. Since in this research the design process is defined as a decision-making process the tools used in this research are mathematical formalisms and methods from Graph theory, Topology and Combinatorics.
This research lies within the realm of design science research (Peffers, Tuunanen, Rothenburger, Chatterjee, 2007) therefore the process is seen as research and development of a computational model and method to reconsider serial repetition of stackable timber elements (that act as structure and inner & outer shells) using combinatorial design and structural simulations based on Finite Element Method. The topics mentioned below are within the scope of this research:

- Computer aided architectural design
- Graph Theoretical Modelling of Discrete Spatial Spatial Network Models
- Geometric Design and Tessellation
- Topological Polygonization & Polyhedralization
- Gamification of Generative Design

The topics mentioned below are related to this research, however, fall outside the scope of this research:

- Computational Shape Optimization
- Computational Topology Optimization
- Participatory design

This research focuses on the serial repetition and pattern making out of stackable timber elements and its relation to housing. It ignores aspects such as technical implementation. The aim of this research is to describe a possible direction for further research and not to provide a final solution.

6. PROBLEM STATEMENT

The production of homes should be accessible, affordable and the housing units should offer a broad range of variety how the spaces can be configured and what spatial qualities they offer. This brings to the fact that the standard way of building our homes needs to be changed, instead of 7000 parts and processes a building needs a simpler production chain where the complexity of the process is decreased, and more actors can participate in constructing. The current solutions of modular and prefabricated parts do not offer variety and broad range of customization. This research aims to create a method which allows to design a limited set of stackable timber elements that can be configured into versatile affordable housing units using combinatorial design and structural simulations based on Finite Element Method.

1. Defining an underlying grid for the whole system:
   --> Relation to people's movement, material and production, and the internal configurational logic of a home based on ergonomics.
2. Defining the combinatorial and aggregation rules and necessary patterns to create a variety of housing solutions out of stackable timber elements:
   --> Combinatorial design rules of the location and direction of how elements connect to each other and what lattices they can create.

3. Defining spatial validity constraints within the context of housing:
   --> Constraints based on ergonomics and standard space sizes
4. Incorporating the limitations and costs of manufacturing within the design of the elements
   --> Trace the production of the material, for example, wood comes in standard size sheets
   --> The elements can be created through the process of CNC milling

7. METHODOLOGY

7.1. RESEARCH METHODOLOGY

This research project is a Research & Development project since it is within the realm of "Sciences of the Artificial". (Simon, 1996) The methodological approach for the framework of this research is based on design science research which is a way of "structuring research methods as a methodology in the context of developing design or "spatial decision support systems" in the more general context of developing information or decision support systems". (Nourian, 2016) (Peffers, Tuunanen, Rothenburger, Chatterjee, 2007) The more specific framework within the realm of design science research used in this research project is the "Go design" framework which is a modular generative design framework introduced by Shervin Azadi & Pirouz Nourian. (Azadi & Nourian, 2021) It is a framework for design processes in the built environment and it provides unification of participatory design and optimization to reach mass-customization and evidence-based design. This framework is articulated mathematically through 3 procedures: 1) space-planning, 2) configuring, and 3) shaping. (See figure 6) It frames typical design problems as multi-dimensional, multi-criteria, multi-actor, and multi-value decision-making problems. This framework rethinks architectural design and instead of seeing it as a representation challenge it sees it "as a chain of systematic decision-making problems in terms of given inputs and desired outputs". (Azadi & Nourian, 2021)

7.2. PROPOSED METHODOLOGY

In this research all 3 procedures of the framework introduced in the previous subchapter are seen as part of the process (See Figure 7), yet it mostly focuses on the interface of Shaping & Configuring procedures. (See Figure 8) The planning procedure is important to test through simulation and gamification whether different requirements can be reached through different configurations and whether the proposed set of elements achieve versatile solutions. The "pattern language" of the proposed model is as a game (the rule set of the game) with which people can test whether they can create what they desire and a variety of solutions. The subchapters explain the glossary and the used terminology as well as the exact steps taken within the configuring and shaping procedures.

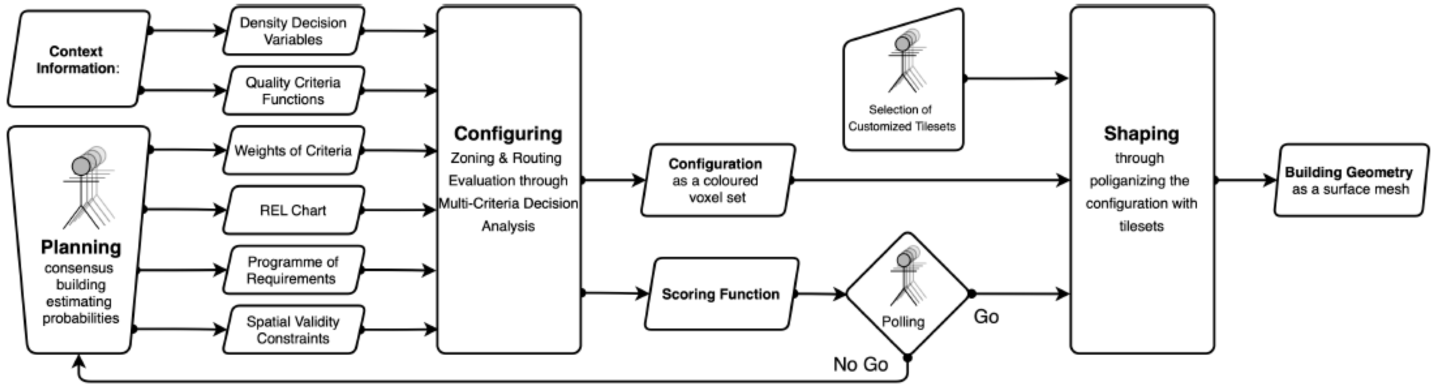


Figure 6: Main flowchart of the Go design framework (Azadi & Nourian, 2021)

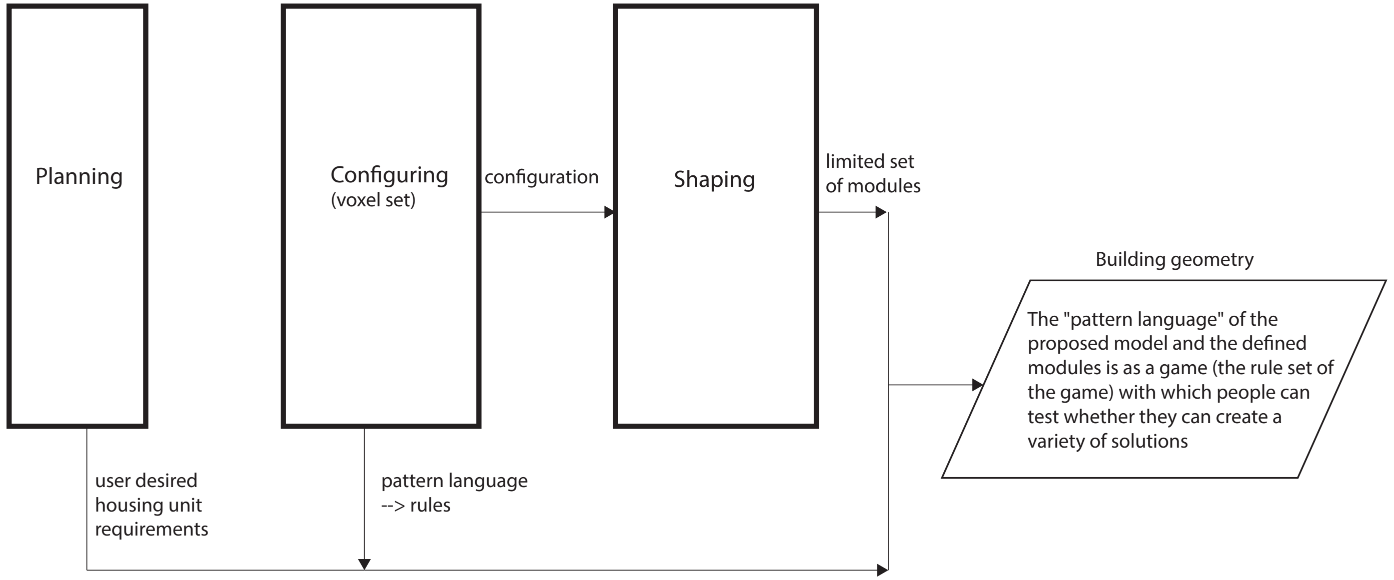


Figure 7: General flowchart for the roles of the 3 procedures in this research

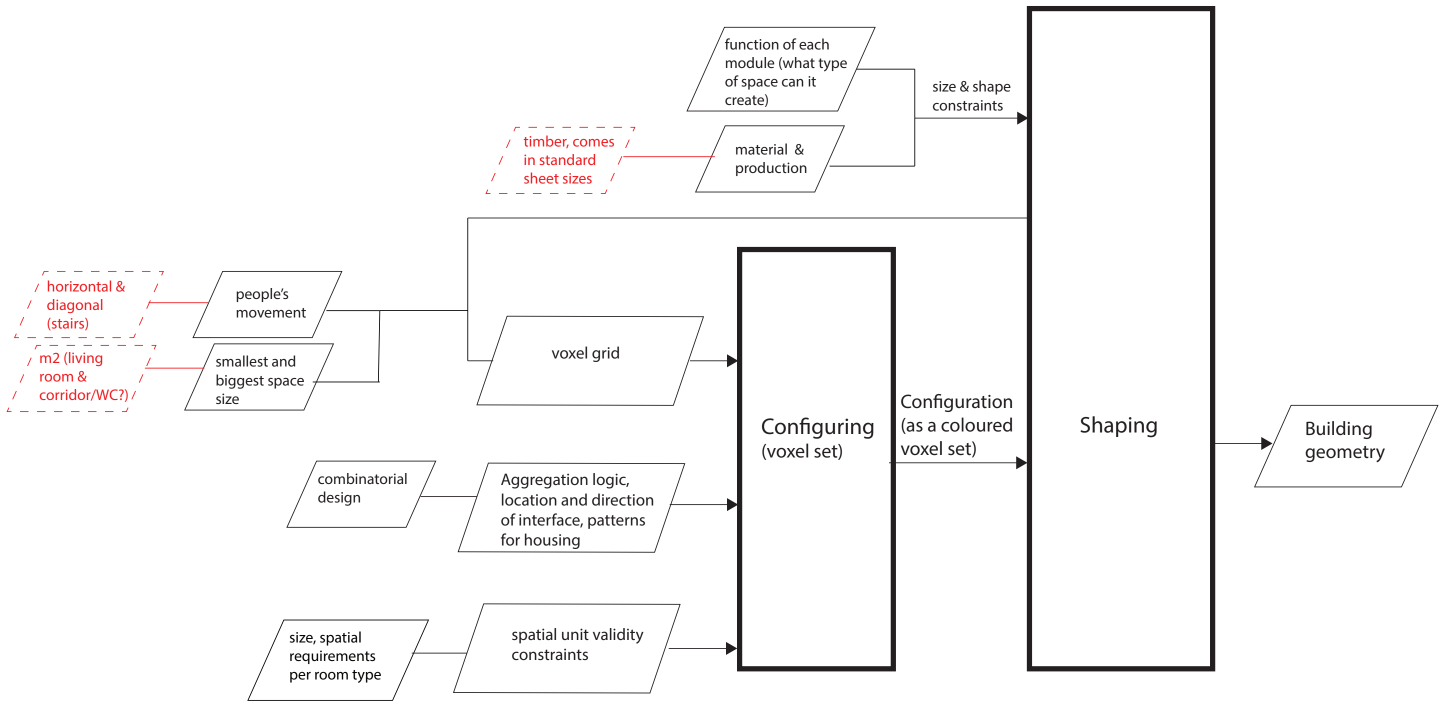


Figure 8: Configuring and Shaping procedure flowchart.

7.3. PROPOSED GLOSSARY

- **module** – predefined element (building block with the information of how and where it connects to the other building block types)
- **lattice** - connection of the predefined elements to each other, possible patterns that they create
- **spatial units** - connection of several lattices into valid spaces (limited set of building blocks creating valid spaces, for example, a bathroom
- **components** - housing configurations, connected spatial units (for example, a housing unit with 1 bedroom, bathroom, kitchen, living room which are connected in a specific way – think of apartment floorplan)

7.4. CONFIGURING PROCEDURE

Step 1: Definition of a voxel grid

Firstly, a dimensional, voxel grid is defined for the smallest element in the proposed glossary – the module – as well as for the universal logic of the system based on several constraints:

- people's movement – horizontal, vertical (diagonally – for example, stairs)
- the dimensions of the spaces that can be found in a (Living room, bathroom, stairs, corridor etc)

Step 2: Combinatorial rules to create patterns for housing

Once the voxel grid is created certain rules must be defined for the voxels to create meaningful patterns for housing solutions within the grid. Combinatorial rules are defined to create patterns - lattices - that can create versatile yet at the same time valid spaces. To explain the connections the location and the direction of how modules are connected is described. The way the modules are connected is related to the function of the modules – stackable timber components that create the structure, the inner and the outer shell of a building. Therefore, stacking is one of the restrictions of the pattern making. See an example in Figure 10 of aggregation rules where the modules, their faces and their connections are defined and then an aggregation library is achieved. (Hadjimitova, 2020)

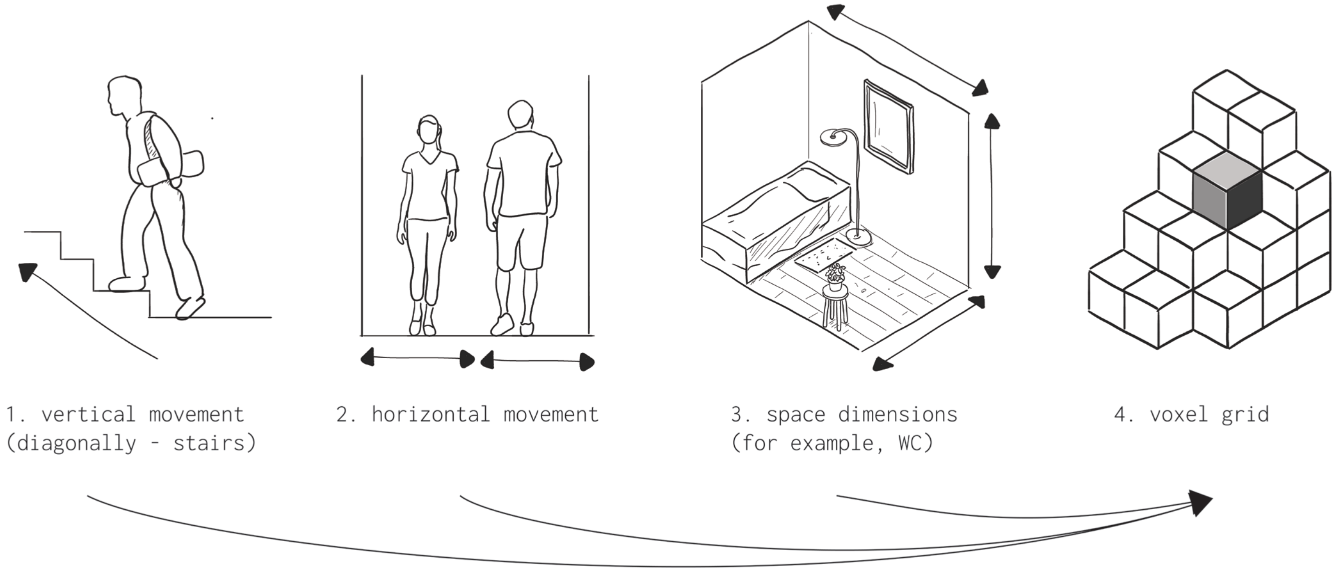


Figure 9: Configuring – Step 1: voxel grid, based on vertical, horizontal movement and space dimensions

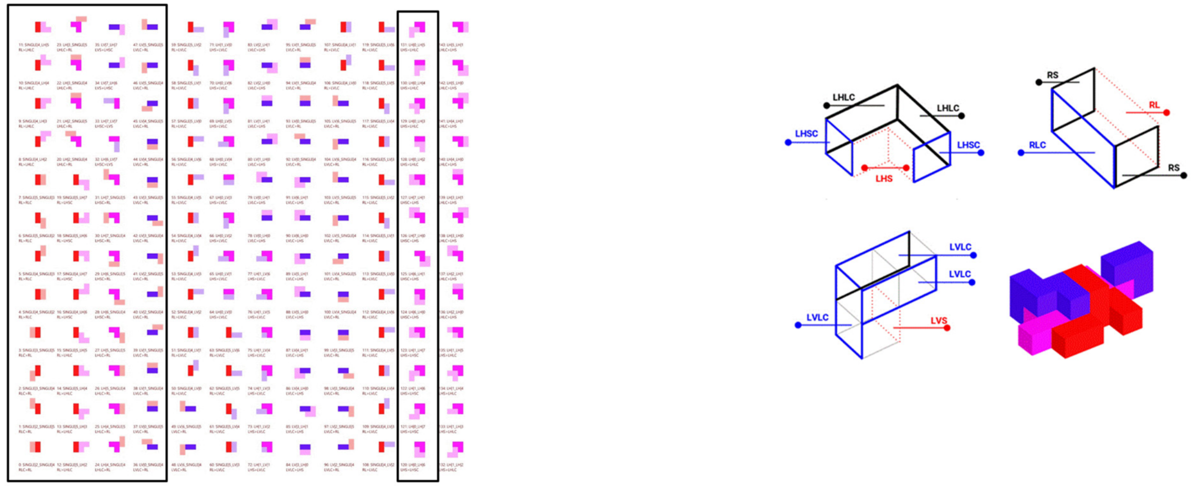
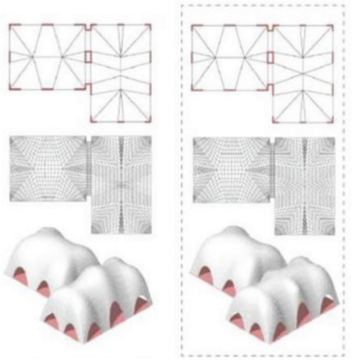


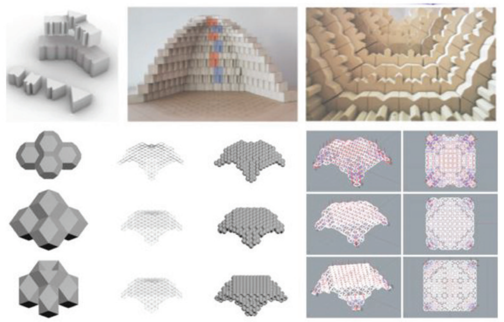
Figure 10: Aggregation rules. (Hadjimitova, 2020)

Step 3: Spatial unit validity

For the elements to create spaces that are valid and versatile housing solutions certain rules must be set to create a spatial unit out of lattices. Certain relation to ergonomics must be met (See figure 11) as well as to the function and the minimum size of such a space must be met (toilet – minimum m2). Finally, the spatial units and the component (housing unit) that they create together must be structurally stable, therefore a simulation of a compression-only structure (which is designed based on equilibrium) is undergone. (See figure 12))



1. Computational Shape Optimization for Designing Compression-Only Buildings



2. Topological Shell Design for Modular Approximation of Optimal Catenary Shells.Overlaying the previous steps output shell with the predefined voxel grid to find an overlapping modular structure.

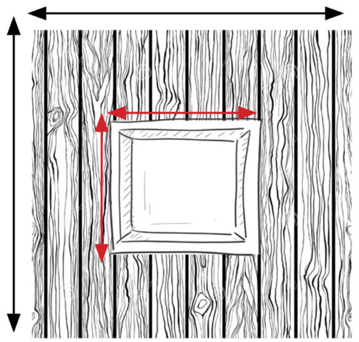


Figure 11: Spatial validity of spatial units – example of an open/closed surface rule.

Figure 12: Compression only structure simulation, shell -> modular element structure (Left: EARTHY 2019-2020, Yarai Zenteno, Fahriba Mustafa, Patrattakorn Wannasawang, Akash Changlani, Elisa Vintimilla, Shasan Choksi; Right: Karim Daw, Shervin Azadi, Pirouz Nourian, Hans Hoogenboom)

7.5. SHAPING PROCEDURE

The procedure of shaping takes the configuration of the configuring procedure and tries to create a geometrical representation of the tile set. (See figure 13)

Additionally, to the voxel grid constraints from the configuration procedure the shaping procedure considers a few other aspects to create a geometrical & physical representation.

Step 1: Manufacturing costs and limitations:

For example, the shaping procedure faces the constraint of the manufacturing process, more specifically the costs and the limitations of this process. The limitations include the material and its production, meaning the shape of the module must be related to the size of, for example, standard wooden sheets as well as the possible shapes that can be reached with such a material. (see figure 14)

Step 2: the types of different geometrical blocks necessary to create a variety of spaces/structures

Shaping also specifies more specifically what each type of module offers within the context of creating a home and what properties do the several modules need to cover to be able to create several patterns. All these constraints create limitations for the possible shapes and sizes of the elements.

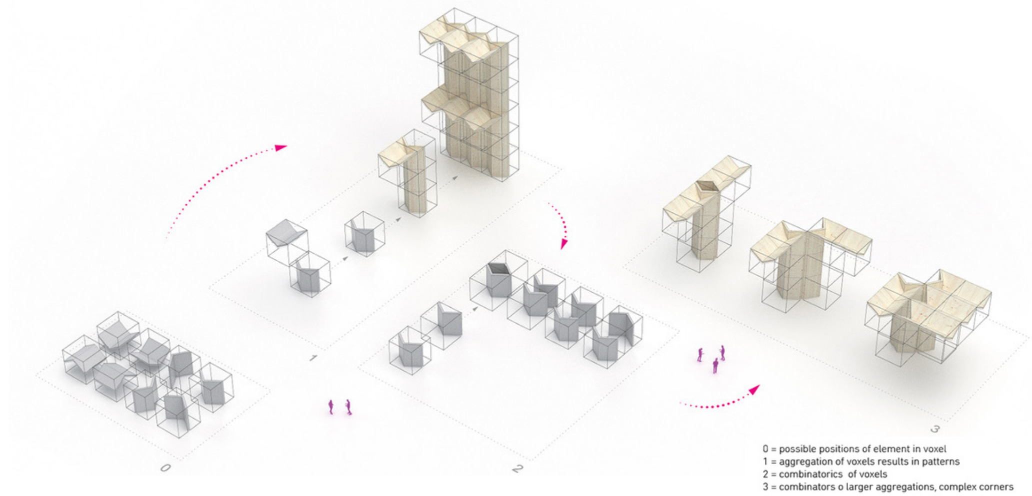


Figure 13: Nuremberg Concert Hall; voxel -> module -> patterns -> combinatorics -> aggregations (Retsin, 2018)

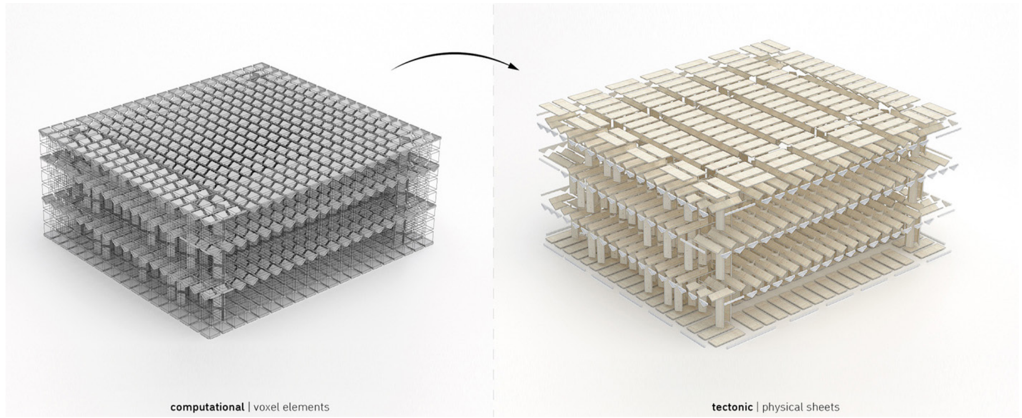


Figure 14: Nuremberg Concert Hall; transition from voxel elements to physical timber sheets (Retsin, 2018)

8. EXPECTED RESULTS

This research aims to create a methodology to approach the design of a limited set of stackable timber elements (that create a structure and inner/outer shell of the building) which can be configured and assembled into versatile housing solutions that can be mass-customized and produced. Therefore, a systematic approach through the procedures of configuring, and shaping are undergone (described in the proposed methodology section) to achieve a rule-based configurator and a few timber elements that can create many options of valid housing spaces providing variety and affordability. The result is either a physical or digital game where players can try to create desired configurations following a few simple rules.

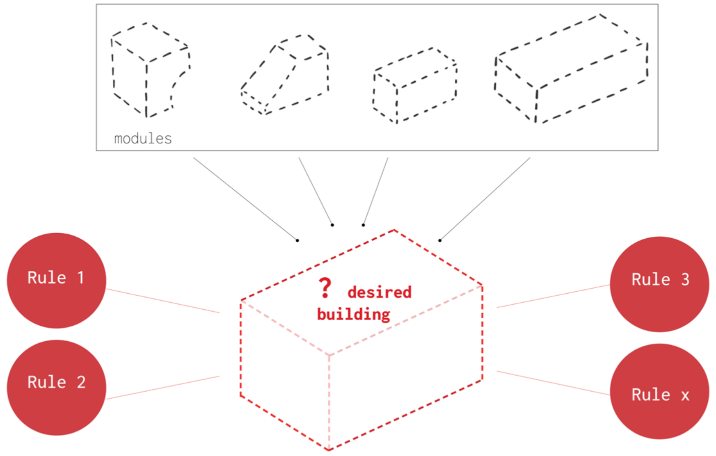


Figure 15: Potential game outcome: predefined module, rules -> creation of desired building

Figure 16: Lego models by architects (Keskeys, 2016)

Figure 17: Sweet medium between automation & human labor; drawign base: Shearing Layers of Change (Brand, 1994)

9. RELATION TO DESIGN IDEAS

This research serves as a base for the design in which a few stackable timber components are used to design the structure and the inner outer shell for a specific housing solution related to the context and user's needs. Because of the size of the building blocks the building system does not predefine how the spaces might look. Similarly, to the granularity and scale of a Lego piece it has a large design space. (See figure 16) Through the gamified approach (See figure 15) the creation of the design also tests the created method and whether the desired outcome for the certain context can be reached using a limited set of the created building blocks and logic behind them. This system reduces the chaos within the architectural world by providing a system that only has a few pieces and rules, yet it acknowledges that there are always many systems involved in an architectural project and it intends to be generous to the existing systems in the way they can be connected.

The system within a design project also finds a sweet medium between increasing the productivity of the construction by having a fully automated process until the prefabricated elements are brought to the site where local craftsmen can create meaningful and context-related final touches for the project such as cladding, specific elements etc. (See figure 17) Finally, the system allows for an open ended and accessible housing solution.

The context during the design process is chosen doing case studies and questioning what is context within this project? 2 potential locations are chosen based on the produced or imported wood and high density residential areas. Therefore, Netherlands and Japan are chosen, for which studies will be done and a brief will be determined. Studies are based on determining what the characteristics of the residential areas and their issues. For example, whether it is a residential area with limited ground space or also limited height? (See figure 18)

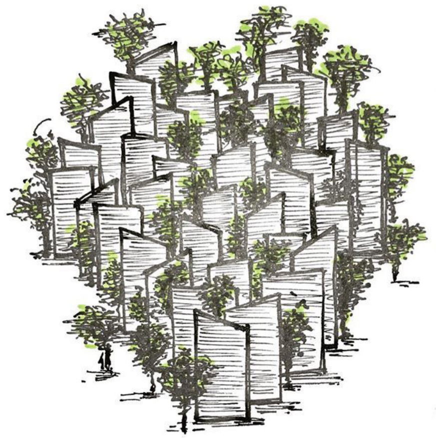


Figure 18: High density single family residential area (Studio precht, 2020)

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