Homecraft

Making shelter design and construction accessible to non-experts through CNC-aided design and Makerspaces.

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Thesis report

Colophon

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Homecraft
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Abstract

Disasters, both natural and man-made, displace millions of people worldwide every year, necessitating an urgent need for shelter that should not only be safe and habitable but also adaptable to the diverse needs of displaced communities.

The design and deployment of disaster relief shelters face numerous challenges, including rapid deployment needs, environmental and cultural adaptability, sustainability, and the psychological well-being of the occupants. Traditional approaches often result in shelters that are slow to deploy, inadequately adapted to local conditions, or environmentally unsustainable. Furthermore, they frequently overlook the potential of involving affected communities in the shelter design process, missing opportunities for empowerment and better alignment with user needs.

Hence, why this thesis aimed to create an environment for people to design and manufacture their own customizable shelters with local products and culture in mind and without the need for expert intervention. Central to this approach is the design of a modular lightweight structure made with Plywood able to be set up by just two individuals without requiring large machinery. A structural analysis is conducted using the plugin Karamba 3D in Grasshopper, while verification is done through custom Python scripts within the same environment adhering to the Eurocode EN-1995.

To enhance user autonomy in shelter design, this thesis also explored the potential computational design offers as an approach to the optimization of shelter for specific environmental and contextual conditions as well as user requirements. Such as the ability to with a parametric model of the structure to iterate between numerous different options quite quickly. Giving the user the freedom to make it fit with their wishes without compromising structural integrity. In combination with digital fabrication technologies such as CNC-routing that enable the rapid production of each custom component as well as the addition to make use of the concept of Makerspaces, or similar environments where these tools like these are made available to anyone it can further democratize shelter design and production.

To further empower communities an online environment is developed to bring all of this together. Build using Viktor in combination with Grasshopper and Rhino the platform allows users to customize their shelter in both layout and materials and the rest is handled by the application, the structural analysis, optimization and generation of a digital 3D model. Which is then translated into the necessary fabrication files and information they need to set up their shelter using local materials and production. Fostering a sense of ownership while ensuring sustainability, adaptability and structural integrity.

Keywords

Transitional shelters, plywood, generation and customization, user centered design, digital fabrication, computational design, parametric design, grasshopper, python, rhino, Karamba3D.

Preface

The concept of shelter is as ancient as humanity itself. It represents safety, comfort, and a sense of belonging, a fundamental need for survival and well-being. Though everyone has different standards, different beliefs about what a shelter should be or look like. Everyone is unique so there should be a unique solution for everyone.

This thesis was born out of a personal belief that anyone should be able to design and create their own personal shelter and not be limited by a lack of expertise or tools. With advancements in digital fabrication and the rise of collaborative spaces such as Makerspaces that give access to tools you might not have at home like 3D printers or CNC machinery, I saw an opportunity to empower individuals to let them design and build their own shelter within their own community with local products. My aim was to explore how technologies like CNC machines, combined with easily accessible materials like Plywood, could democratize the construction of shelters, making it feasible for non-experts to create sustainable, functional housing solutions fitting to their own culture and community with the help of computational means. Empowering themselves and giving them a sense of autonomy to help the community recover. Giving ordinary people the tools to build extraordinary solutions. So, I hope this research contributes to a larger conversation about self-reliance, accessibility, and sustainability in the built environment by focusing on the potential of community driven spaces and open-source design.

All in all, I am deeply grateful to my mentors, Dr. S. (Serdar) Asut and Dr. S. (Simona) Bianchi as well as Prof.dr. M. (Mauro) Overend who have guided me throughout this process. As well as my partner in crime and fellow graduate Amir Ghadiri of whom I worked in close collaboration within this thesis that bloomed from our joint project in CORE.

Contents

1. Introduction

This chapter provides an overview of the key topics addressed in this thesis, beginning with an introduction to the global need for innovative shelter design and the challenges faced during the process. Delving into the proposed solutions to the challenges that arise while designing which introduces subjects like CNC-routing and Makerspaces.

1.1 The urgent need for shelter

Annually millions of people are displaced due to disasters like natural catastrophes and conflicts. According to the 2023 Global Report on Internal Displacement by the IDMC (The Internal Displacement Monitoring Centre), there were over 8.7 million IDPs (internally displaced people) in 2022 due to natural disasters, and 62.5 million because of conflict and violence. The largest increase in numbers is seen by disasters at the hand of natural disasters (a rise of 45% in comparison to the previous year), yet even numbers due to violence rose with 17% in accordance with the year before.

The IDMC also warns that these numbers are likely to continue to rise as in the last nine years the number of IDPs has risen from 33.3 million to a staggering 71.1 million. They noted that this is due to various reasons, including: escalating conflicts and violence in areas like Ukraine and Russia as well as the DRC (Democratic Republic of Congo), along with the increase of natural disasters, like the severe flooding in Pakistan, the earthquakes in Türkiye and other large natural disasters that have led to the displacement of millions. These individuals are added to the already large number of people facing extended displacement due to ongoing conflict, frequent disasters, and the absence of lasting resettlement solutions which results in an ever-growing number.

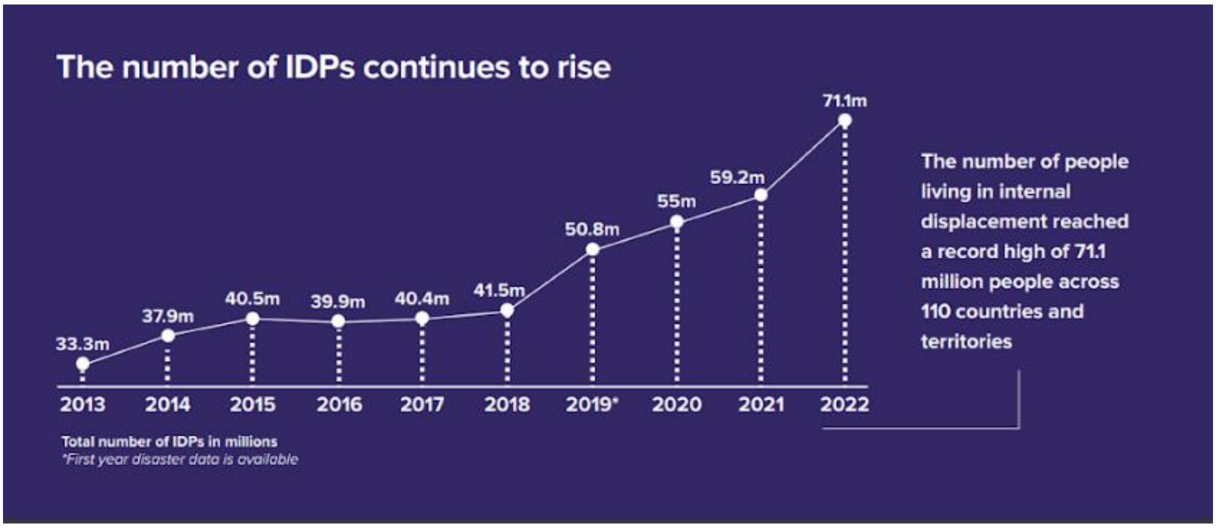


Figure 1: Increase of internal displacements from 2013 to 2022
Source: IDMC (2023)

So, what are the opportunities to reduce these numbers? According to the (IDMC, 2023), one of the opportunities lay in assisting IDPs with options to return home, integrate into new localities, or resettle within their own nation. Shelter provision is one of the main concepts of disaster management after all. Primarily in the phases right after disaster, response and recovery (Erdelj et al., 2017). When done properly it can help stabilize communities, allowing people to focus on rebuilding their lives, work, and social structures (IFRC & RCS, 2013; Sphere, 2018). It can contribute to faster, more sustainable recovery for affected populations and can reduce the risk of secondary health and safety issues, like exposure to the elements or overcrowding and additional conflicts between the displaced (Alshawawreh et al., 2020; Kim et al., 2021).

Figure 2: Disaster management phases
Source: Own diagram, based on Erdelj et al. (2017)

1.2 Shelter terminology

Before we delve into what makes a shelter 'proper', first we should take a look at what we understand as being a 'shelter' as within literature there is no real consensus on what terminology to use which can lead to some confusing situations.

Quarantelli (1995) differentiated shelters in 4 categories: Emergency shelter, temporary shelter, temporary housing and permanent housing. Highlighting the difference between emergency and temporary structures, by people's behavior and period of stay. Defining emergency shelter as the initial place people seek shelter right after the disaster, often for just a few hours or, at most, overnight. Temporary shelter as assigned accommodations, established in specific locations where things such as food and water distribution are taken into consideration, typically safe spaces like large public buildings, a friend's house, hotels etc. The difference between 'housing' and 'shelter' he defines as housing being a space where people have the ability to resume their normal daily responsibilities, whereas in shelter they cannot.

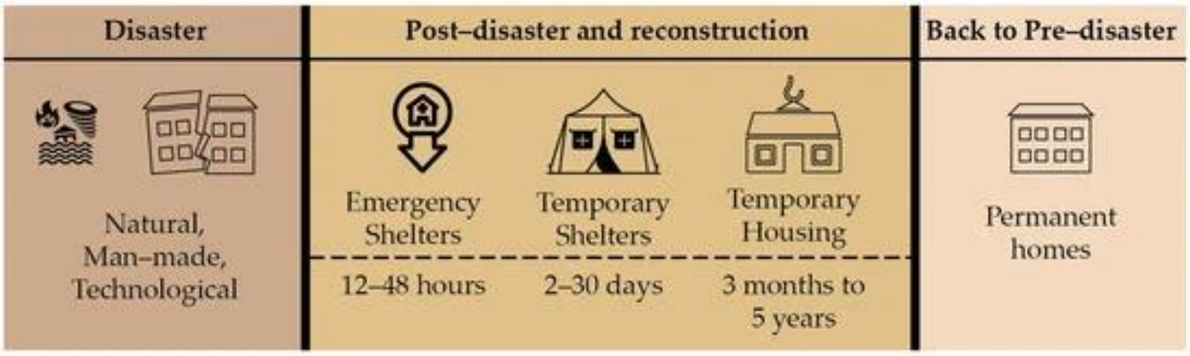


Figure 3: Different categories of shelter by Quarantelli
Source: Montalbano and Santi (2023)

Bakarat (2003) however takes the definitions for shelter and housing respectively as something temporary and permanent instead. Regardless of how long the shelter is in use for, even if this is longer than anticipated, shelter is simply a temporary space to live until a permanent solution is ready. Shelter thus also being a space where normal life can continue. Using an overarching definition for what Quarantelli would see as emergency, temporary shelter and temporary housing.

The IFRC and RCS (The International Federation of Red Cross and Red Crescent Societies) say that the decision on which terminology to use for a shelter should be instead based on a mix of contextual factors. Ranging from their expected permanence and the materials used in construction to the site location and the influence of local political conditions. Which is why they proposed five categories in their report “Post-Disaster Shelter: Ten designs” (2013) to differentiate between them; Emergency shelters, temporary shelters, transitional shelters, progressive shelters and core or one room shelters. Emergency shelters are used for the brief periods of time after the disaster to deliver lifesaving support and a safe space. Temporary shelters are the next step and defined as a rapid solution for a roof over people's heads. Prioritizing speed and keeping costs as low as possible, with a limited lifespan. Transitional too are meant to be rapidly available, however, keeping in mind that they should be able to be upgraded over time, reused in the construction of their new home or relocated from a temporary to a permanent location. They are expected to grow with the displaced along their recovery process, creating a more durable solution. Progressive shelters are designed to be upgraded to a more permanent solution, adding future transformation and altercation possibilities into the design. Core and one room shelters are designed to become permanent solutions, or part of. Often consisting of one or two rooms with standards close to permanent housing standards and facilities.

In the transitional shelter guidelines of the IOM (International Organization for Migration; 2012), they instead take transitional shelter as an approach to recovery where the shelter might start out as an emergency solution but over time grows with the displaced until it becomes part of the permanent solution as seen in the figure below (Figure 4)

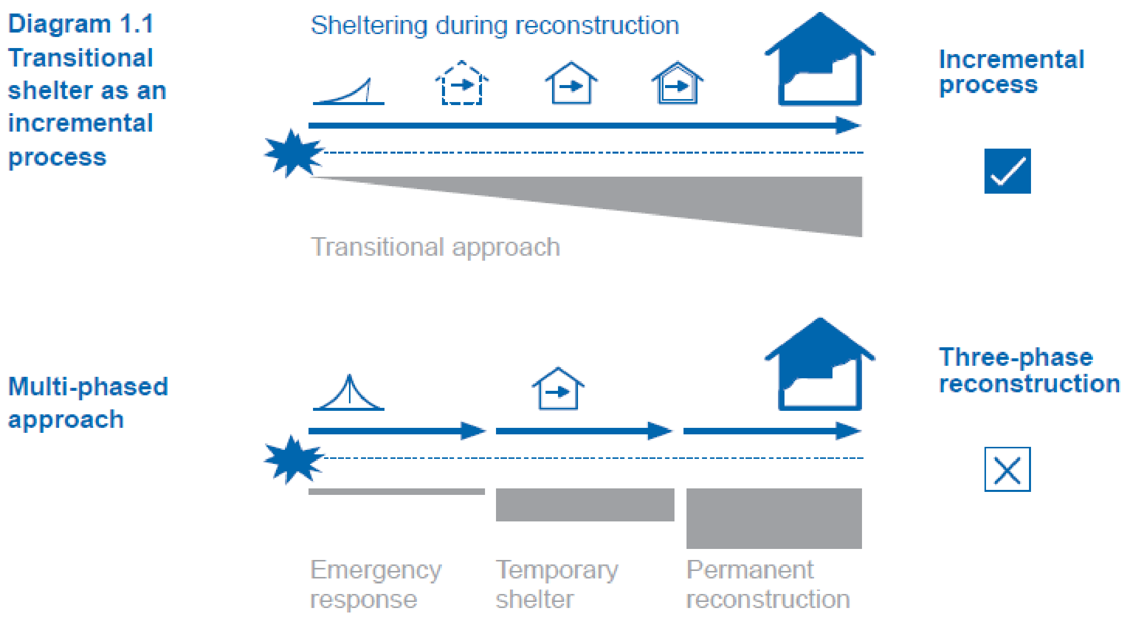


Figure 4 Transitional shelter according to the IOM
Source: IOM (2012)

Alshawawreh et al. (2020) however argues while transitional shelter should be seen as an incremental process that offers temporary housing to families in need, it is meant to provide an interim solution, not a step directly tied to permanent structures. Defining transitional shelter as something to be upgraded, reused, relocated, resold, and recycled. Which is why they use the term one-room or core shelter as something not necessarily part of the permanent solution but rather as a shelter consisting of just one room which could fall under any of the terms from emergency shelter to temporary housing.

Albadra et al. (2018) in their paper noted this irregularity in terms as well, however found commonality among them stating that: “Although the terminology used is inconsistent in the literature, it is clear that humanitarian responses are divided into ‘emergency’, ‘temporary’ and ‘permanent’, and the length of each stage and its corresponding shelter types will vary in different situations.” (p.4). Quarantelli (1995) too stated that the provision of shelter cannot be viewed as a uniform process and thus the categories he defines shelter with should merely serve as tools for understanding the complexities of disaster recovery, rather than exact reflections of reality. The IFRC and RCS as well, are aware that the categories they sufficed do tend to overlap as seen in the figure below (Figure 5) or that depending on the context like local regulations and laws, the same shelter can in one situation be seen as an emergency but in others as temporary shelter or even transitional shelter. An example they name is a timber frame covered in tarpaulin which they say could thus be seen as: emergency, temporary, transitional or even progressive shelter depending on where and when it is deployed.

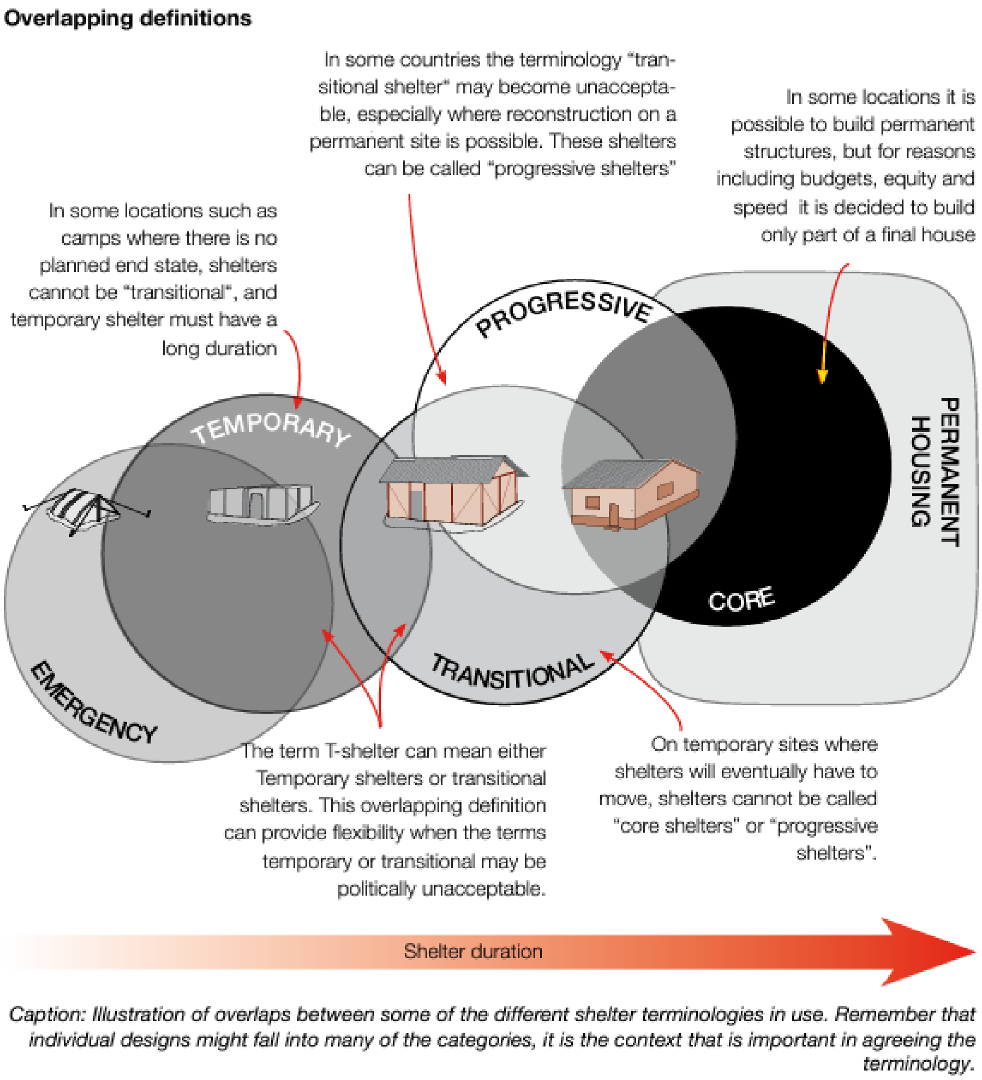


Figure 5: Overlap of definitions in disaster shelter
Source: IFRC and RCS (2013)

Additionally, something meant or designed to one way could turn into or be used as something entirely else.

An example of this came to light following the 2010 earthquake in Haiti, where many displaced people were forced to resettle in a series of temporary camps in the outskirts of Port-au-Prince. The most extensive of these, at first called Canaan, was supposed to function as a temporary camp. However, without government intervention or formal planning, residents of Canaan started building more permanent homes, opened businesses, and developed community infrastructure-including schools and roads. In the process, what was to become an emergency shelter site was gradually transformed into a settlement of more than 200,000 people (World Bank, 2016; Thomson, 2015).

“Anything that was built as a T- shelter (temporary shelter) became a P- shelter (permanent shelter)” - Marc Lee Steed (photographer born and raised in Haiti; Thomson, 2015)

So, while keeping in mind that some shelter can fit into multiple categories, transition into one another or be part of the final solution for the sake of clarity a set of three terms will be adopted in this thesis: emergency shelter, temporary shelter and permanent housing. Using the term shelter as an umbrella term for everything not to be considered part of permanent housing. Emergency shelter is defined as shelter provided in the first few hours or days. Temporary shelter to temporarily house people in need until a permanent solution is found. Both types can range from anything, from the provision of tents, shelter kits, and shelter elsewhere in either larger public buildings or with other residents. The difference being the time they are used for. Temporary shelter also includes prefabricated structures and temporary structures. The focus of this thesis is on Temporary shelter. To create a bridge between emergency shelter and permanent housing, a shelter that will help the people through the various stages of the disaster aftermath until a permanent solution is ready.

1.3 Challenges in shelter design

So, what is it that makes a shelter design 'proper' and where do most issues arise when it's not?

Sphere (2018) states in their handbook that adequate shelter is "more than four walls and a roof" (p.244). That for shelter to be properly designed, it should at least take the following into account: Affordability, habitability, cultural acceptance, functionality and accessibility. Emphasizing that for a shelter to meet all requirements, it must ensure physical security, privacy, protection from weather, adequate lighting, proper ventilation, heating, and overall comfort of the user.

To the IFRC and RCS (2013), a shelter should balance factors such as safety, lifespan, size, comfort, privacy, costs, timeliness, number to be built, material availability, maintenance, equity with the host population, cultural appropriateness and construction skills.

In the Transitional shelter guidelines of the International Organization for Migration (IOM, 2012) they name 5 similar points to take into consideration while designing including:

- Designing with the community: Creating options together with the community so it fits with their customs and traditions, family composition, and what materials they know best to work with. Making it accessible to anyone.
- Minimizing risk: The shelter should address vulnerabilities, ensure safety in areas prone to natural disasters such as floods, earthquakes, or high winds.
- Climate: The design should fit the local climate, considering factors like ventilation, insulation, and protection from extreme weather.
- Building materials: The use of locally available materials is encouraged for ease of maintenance, cost-effectiveness, and to promote local economies. Emphasis on sustainability, constructed from materials that can be recycled, reused, or upgraded.
- Construction: Fundamental construction techniques, focusing on durability, structural integrity, and ease of assembly by communities.

The UN refugee agency name in their handbook (UNHCR, 2015) that the key points to take into consideration are that shelter responses must consider the broader settlement context, offering diverse options that evolve from emergencies to durable solutions. Design should prioritize safety, cultural appropriateness, environmental impact, and cost, while involving displaced people and host communities early on to ensure their needs are met. Close coordination with protection staff is essential to mitigate risks like tenure, insecurity and exploitation.

Karimi et al. (2023) analyzed 16 similar sources as to the ones named above here, discussing what they see as key factors to take into consideration while designing for shelter. Demonstrating the complex nature and multidisciplinary nature of shelter design. As they created a list of 35 key design features with 145 sub-features, they thought to be incremental for the design of shelter. Categorized into 5 different dimensions, social-cultural, environmental, physical-technical, economical and organizational as seen here below (Figure 6).

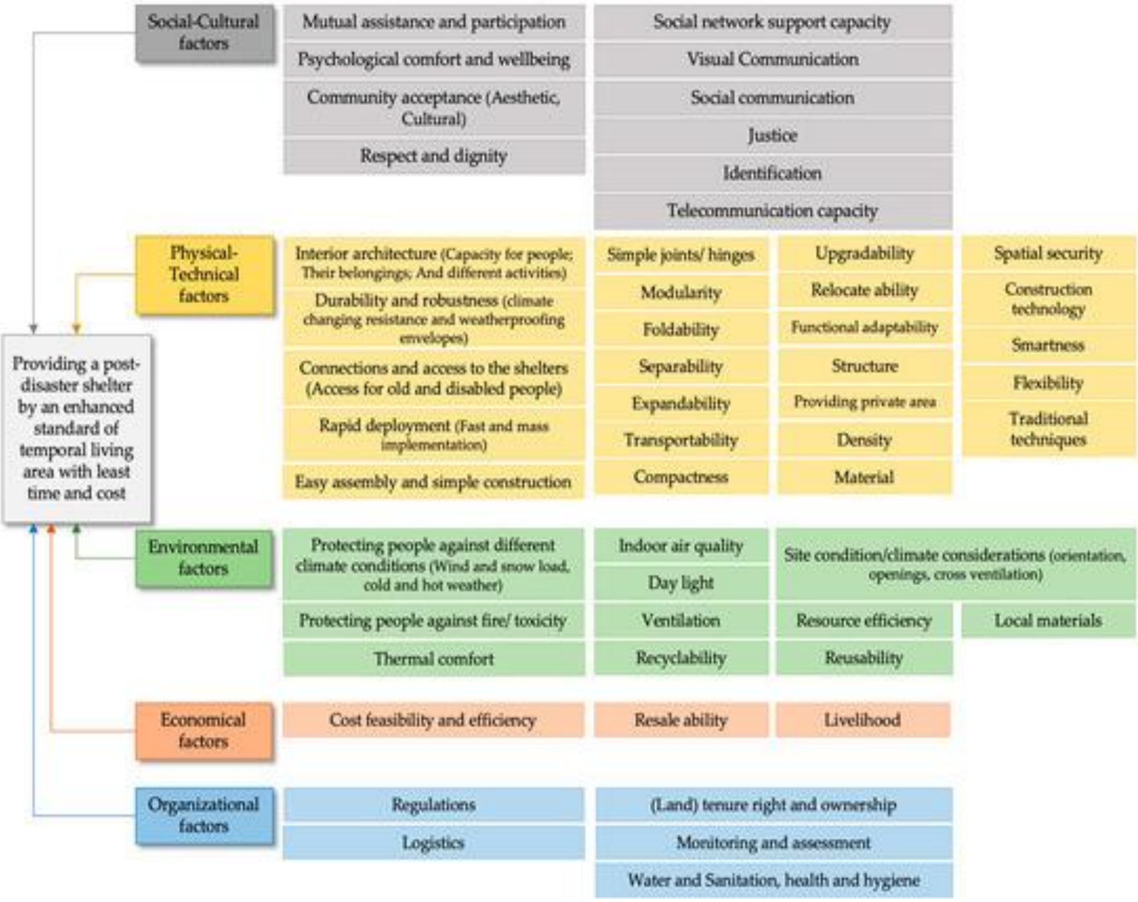


Figure 6 Key factors of shelter design
Source: Karimi et al. (2023)

While organizations tasked with shelter provision, such as the UNHCR, IFRC and RCS and their local operational partners, strive to meet all requirements within these different dimensions as quick and affordable as possible they are often confronted with limitations in time and resources. Many times, this leads to a predominant focus on transportability, costs and speed over habitability, leaving social, cultural, and environmental needs unmet (Albadra et al., 2018; Alshawawreh et al., 2020; Bakarat, 2003; Ghomi et al., 2021; Kim et al., 2021; Montalbano & Santi, 2023). Not only negatively affecting the quality, sustainability and suitability of shelter but also affecting the will to recover and individuals' physical and emotional states. Keeping people from being able to recover and delaying the process towards a permanent home (Alshawawreh et al., 2020; Bakarat, 2003; Kim et al., 2021).

"A sense of safety, community and social cohesion are essential to begin the process of recovery." (Sphere, 2018, p.240)

So, what are the common bottlenecks that come up during the process of design and utilization of the current shelter designs?

Numerous challenges arise while designing shelter for displaced communities spanning over various dimensions and sometimes bleeding over in each other. Things such as social-cultural inadequacies, environmental and economic issues, lack of long-term viability and poor indoor environments all are bottlenecks that hinder the effectiveness and sustainability of shelter solutions.

1.3.1 Social-cultural inadequacy

Lack of area

A recurring issue in shelter design is the inadequacy of the provided living area, particularly in larger households. The Sphere handbook (2018) is known to many humanitarian organizations as the minimal standard for shelter design. They recommend a minimum area of 3.5 in warmer climates or 4.5 square meters per person in colder climates where people tend to be more inside. However Alshawawreh et al. (2020), among others, argue that these numbers are not based on anything scientific and in reality, do not always seem to meet the needs of the displaced. This was seen in the Zaatari camp 32.29° N, 36.33° E a large refugee camp in Jordan, Mafraq near the Syria border. A survey was done among 75 families, and only 8% indicated to have used their shelter as provided by the UNHCR and NRC and at least 70% built extensions to their shelter to meet their needs. Even though these shelters met Sphere's regulations of a minimal of 3.5 square meters per person (Albadra et al., 2018).

Similarly Cerrahoğlu and Maden (2022) made an analysis of 18 current shelter designs and found that most were designed to only accommodate up to four or five people. Even though the average household size in some countries lie above that number (PEW, 2019). Take for example Guatemala which has an average household size of 6.1, for the people there this would mean that either most households would have to be split up or endure overcrowded and cramped living spaces.

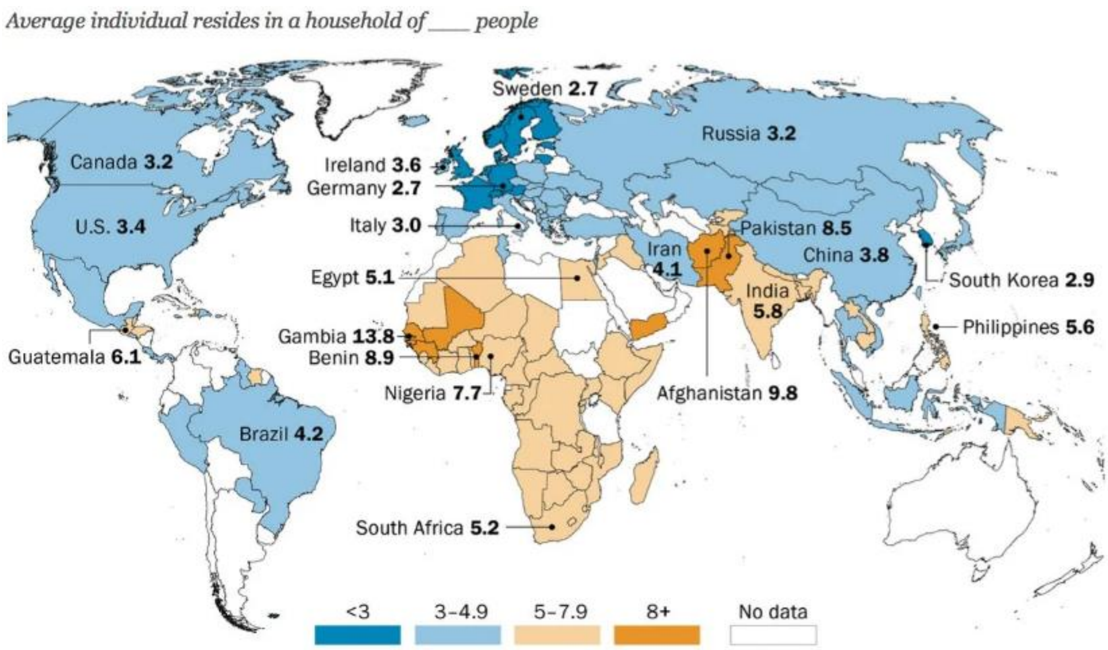


Figure 7: Household size per country
Source: PEW (2019)

Privacy and functional space

In addition to insufficient area, the lack of privacy and functional spaces remains a critical concern.

Humanitarian organizations like the UNHCR, the Sphere Association, IFRC and RCS all emphasize the importance of privacy in shelter design. A shelter should provide emotional security, comfort, and protection, allowing families to maintain their dignity and traditional practices. The UNHCR (2015) emphasizes the importance of separate or designated areas for cooking, sleeping, and hygiene purposes, especially in colder climates where people would stay indoors for longer periods of time. Living spaces should accommodate daily activities such as eating, dressing, storing belongings, and protecting assets, with internal subdivisions designed to respect cultural norms and privacy requirements. They also add that while collective shelter is an option, individual family shelters provide greater privacy, psychological comfort, and emotional safety. Similarly, the Sphere Association (2018) calls for particularly in contexts where gender segregation and cultural customs require internal divisions, to at least incorporate things such as screens or partitions to divide the area.

Despite these well set regulations privacy as well as the segregation of functions remains a significant concern. Albadra et al. (2018) noted in her survey of the Zaatari camp that while 62% of respondents expressed satisfaction with the safety and security of their shelters, only 32% were satisfied with the privacy provided. Additionally Cerrahoğlu and Maden (2022) and Alshawawreh et al. (2020) both noted in their analysis that very few shelter included places like private kitchens or bathrooms. Alshawawreh et al. (2020) noted that only 17% of existing shelter designs included private toilets, and kitchens were only found in 8% of the cases. Also adding the fact that in more rural areas livestock is often forgotten to be incorporated into the design. They also note that in 58% of the cases they analyzed a one-room shelter approach was still chosen. A shelter that only consists of one space where all daily activities occur in a single undivided area. On top of often having a too small area these designs fail to meet the needs of privacy as it is inadequate especially in contexts where gender segregation is culturally important.

1.3.2 Environmental and economic sustainability

Transportation, local and global materials and costs

A major challenge in shelter provision is transport. After disaster places can be hard to reach due to damage to the infrastructure, remote locations or conflict affected regions (Johnson (Johnson, 2007). An example is the aftermath of the Tsunami and earthquake in Indonesia Aceh from 2004. For the first few weeks, instead of international help, their own government had to handle shelter provision due to logistical challenges and limited access because of damage to the infrastructure and travel restrictions resulting from the ongoing conflict there. This case also highlighted a different problem that often occurs, which is scarcity of materials. The project started out building shelters based on local designs with brick and concrete foundations and timber frames, corrugated iron roofs and timber panels. However, they had to redesign their shelters to reinforced concrete framed structures with brick walls and a wood framed roof about ten months into the project (Ashmore et al., 2008).

Additionally material scarcity doesn't only just influence the provision or design of shelter it can also cause problems for the local economy as well as the environment. Alshawawreh et al. (2020) warns that, even though local resources are often preferred due to their familiarity, ease of repairs and low transport costs in some cases, this can have a counterproductive effect on the local economy by depleting too much of the local resources. When the demand for a certain material suddenly increases drastically this can raise their prices significantly. The local community then won't be able to afford to pay for the materials that are often also needed for the reconstruction of the permanent homes, delaying the recovery process even more. Or then when natural resources are depleted so much it starts to influence the local environment. An example being the Kenya-Dadaab project of 2009. There they provided mud shelters but could help a limited number of people as mud and water were scarce. On top of that, the unplanned excavation of mud nearby created during the following rain season a cesspool for mosquito breeding grounds (UN-Habitat, 2010).

However, when shelter design fully consists of 'global' materials, ones that aren't locally available, and need to be imported or shipped over long distances, it can really drive up the price of the shelters as well. Or as in the case of Aceh it would be impossible to provide all materials, or they would be very delayed. Which is another point to take into consideration. In disaster situations the budget is often limited so the higher the cost of the shelter, the less people will be able to receive the much needed help they deserve.

Ghomi et al. (2021) notes that, especially in transitional shelters, these costs can rise quite steeply. Saying that some options would even cost the same as a permanent house or even three times as much. Alshawawreh et al. (2020) and the IFRC and RCS (2013) made a similar discovery. And found that due to transport issues or ongoing conflicts or delays but also just material costs some shelters turn out way more expensive than the people can afford. Which is why the IFRC and RCS (2013) indicate that the when deciding on costs per shelter to compare the cost with disposable income in the affected area to make sure it is affordable.

Carbon intensive materials and recyclability

Environmentally Alshawawreh et al. (2020) name that many shelters often rely on the use of carbon intensive materials such as plastic, steel, nylon, aluminum and concrete. While they are often chosen for durability, availability, and ease of deployment, they have a significant environmental impact due to their high embodied energy, the energy consumed during their production, transportation, and disposal.

The reliance on these materials also poses a challenge when talking about recycling and disposal. Once a shelter reaches the end of their lifespan, these materials often end up in landfills as they are difficult and expensive to recycle. Montalbano and Santi (2023) confirm this as they note that most shelter is not designed with recycling, recovery or reuse of the materials in mind leading to significant amounts of waste at the end of their use in disaster-stricken areas. While these materials may reduce initial construction costs, their long-term environmental impact and high carbon footprint are significant drawbacks.

Poor indoor environment

Aldabra, Coley & Hart (2018) mention in their research they found that often the thermal comfort and climate adequacy in shelter design is ineffective which can lead to increased morbidity and mortality. Saying that in their survey only 15 of the last 60 publications of emergency and temporary shelter (from 1980 to 2018) considered thermal performance. Even though the indoor climate is a large part of the comfort people experience while making use of the shelter.

1.3.3 Lack of long-term viability

Albadra et al. (2018) name that the process for people to return to their homes or create a new permanent solution for themselves to live in can take years to decades to be resolved.

Alshawawreh et al. (2020) too mentions that it usually takes two to fifteen years depending on the situation to resolve land rights alone affecting the reconstruction time of the damaged homes. The lifespan of a post-disaster shelter varies depending on its design, materials used, and the conditions it is exposed to. While some shelters may initially be intended for short-term use, in many cases, due to various circumstances delaying the process of providing people with proper shelter, they thus end up serving as long-term homes for displaced individuals.

Which Cerrahoğlu and Maden (2022) noted they are often not designed for. Since most of the projects they analyzed types and found that most shelter designs they analyzed did not meet spatial or technical requirements for long-term use.

An example where this caused problems was discussed in the research of Kim et al. (2021) where in 2017 an earthquake had struck Pohang in South Korea leaving 1300 people to be sheltered 'temporarily' in a nearby gymnasium. Due to the frequent aftershocks, instead of a few days or weeks people were stuck there for over two years, suffering from extreme heat in summer and cold in winter, lack of privacy, noise pollution as well as small living spaces causing physical as well as psychological problems among the community.

1.3.4 Standardization

Montalbano and Santi (2023) note that in shelter design there are two main approaches: top-down and bottom-up. The top-down approach is defined by a centralized decision-making prosses where the affected community is not or barely involved in the recovery process and external stakeholders (humanitarian organizations or the government for example) make the key decisions. Focusing their energy on rapid deployment and standard solutions to address immediate needs. Whereas bottom-up does include local stakeholders and displaced communities in the planning and construction process, ensuring that the solutions align with their cultural, social, and environmental contexts.

Top-down strategies commonly rely on closed prefabrication systems manufactured elsewhere and a 'one-size-fits all' approach where there is assumed that a single design can be applied to various disaster situations.

Even though, the UNHCR (2015) stresses that the design of a shelter cannot be looked at in isolation. That for every response one must consider the context and there should always be a variety of shelter options available. Sphere (2018) too emphasizes considering the specific needs, preferences, and behaviors of different groups based on age, gender, and disabilities and that every household and community will require different support.

“No single design is suitable for all responses.” (IFRC & RCS, 2013, p. 13)

These 'standardized' shelter designs often fail to accommodate the community's needs. They do not incorporate local architectural styles, cultural practices, and community structures, undermining the local resilience and adaptability of the community. Which with the lack of consideration for local building traditions and community involvement can lead to alienation and disengagement (Alshawawreh et al., 2020; Karaoğlan & Alaçam, 2019; Montalbano & Santi, 2023)).

Still, these types of shelter are often chosen for their quick deployment, ease of production in bulk and ease of construction. Alshawawreh et al. (2020) too noted in his study that most novel designs they analyzed still went for a so-called 'one-size-fits-all' or global approach. Even though most of the existing projects are often designed for a specific case and might at first have been relocated, due to changes often eventually end up as a more fixed solution. Which would suggest that something that 'fits all' or focuses on transport does not work in practice.

Additionally, Montalbano & Santi (2023) mention that many of these shelters are constructed using high-carbon materials like steel, plastics and concrete. Materials that are very energy intensive to produce and difficult to recycle. On top of that they are often manufactured elsewhere, which raises their transportation and logistical costs are well as increasing their carbon footprint even more.

Take the RHU (the refugee housing unit) for example, developed by Better Shelter, Sweden, UNHCR and the IKEA foundation. The shelter consists of a lightweight steel frame with roof and wall panels that can be built within 5 to 6 hours by four trained people and costs around 1150 dollars without transportation costs.

Figure 8 The RHU Unit
Source: (UNHCR, 2016)

The unit is produced and shipped from Gdansk in Polen, only has one size of 17,5 square meters for a family of 4, is made with high carbon materials, does not include a bathroom, kitchen or any division, though the opportunity is given to divide the space with sheets. The shelter is listed to last only 3 years with maintenance by the UNHCR and 1.5 without (UNHCR, 2016).

1.4 Technological participatory solutions

So, what can we do to improve the conditions of the people living in shelters? How can we improve upon the designs that are already there?

1.4.1 User participation.

The UNRDO (1982) already concluded very early on that the success of a shelter design is mainly measured by the local community's participation and found that early user involvement in the project would support the resilience and sustainability of the outcome.

Montalbano & Santi (2023) too concluded that a 'bottom-up' approach, which involves local communities and stakeholders, offers flexibility, cultural sensitivity, and sustainability by utilizing open prefabrication systems and allowing for self-construction, though slow, result in more sustainable solutions by incorporating local knowledge.

The Global Shelter Cluster (2022) to in their report Pathways home they also highlight that a people led approach to shelter design can be very beneficial, by empowering people trough co-creation, building self-reliance among the community and overall achieving better fitting solutions that address the unique needs of those affected.

It provides solutions that are sensitive to the local community's cultural and practical needs, increasing their acceptance while retaining community identity. It also strengthens social cohesion by empowering relations and ensuring that marginalized groups are included. The use of indigenous materials, labor, and expertise not only saves costs but also lowers the environmental impacts, hence making the designs more sustainable and viable.

Community engagement increases capacity and resilience, equipping people with the skills needed to help them recover as well as prepare for future disasters. In addition, participatory approaches foster a sense of ownership, which increases acceptability and proper use of shelters, while at the same time promoting psychosocial recovery through restoration of purpose and control during the recovery process.

In their analysis of case studies of humanitarian shelter responses in 2021 to 2022 (IOM, 2023) it also came forth that community engagement was seen as a strength. Though they did realize that a weakness of an approach involving the community is difficult to organize especially in cases where a lot of marginalized groups are involved or there are negative relations between some parts of the community.

1.4.2 Wood based materials

As an alternative to high carbon materials researchers and practitioners are increasingly advocating for the use of sustainable alternatives, such as wood-based materials and composites derived from natural fibers. These materials not only have a lower carbon footprint but are also biodegradable or easier to recycle, making them more aligned with circular economic principles. Dodoo et al. (2014) point out that timber structures, for instance, store carbon throughout their lifecycle, making them a more environmentally friendly option compared to steel or concrete. In addition to their ecological advantages, wood-based materials are widely available in many regions, which reduces the need for long-distance transportation and the associated carbon emissions. Local availability of materials also enables faster shelter construction and allows communities to use accustomed resources for maintenance and repair, enhancing the practicality and accessibility of designs using wood-based components.

1.4.3 Computational tools and digital fabrication

As mentioned before, shelter design is a complex process that integrates multiple disciplines and dimensions such as social cultural adequacy, environmental contexts, and availability of materials. As well as the organization of marginalized groups or dealing with negative relations between some parts of the community balancing these diverse needs and expectations which can be difficult.

However, the use of computational tools and digital fabrication can offer a helpful incitive to smoothen these complexities and enable effective user participation.

Digital tools such as CAD (computer aided design) systems can allow users to visualize and interact with a design in a virtual space from anywhere around the world. Making it easier to communicate ideas and preferences without requiring specialized knowledge as an environment can be set up that ensures users stay within boundaries. With these tools the user is able to adjust, explore alternatives and see the impact of their choices within a safe environment. This participatory design process fosters inclusivity and ensures that shelters meet the unique needs of their future occupants.

Digital fabrication in their turn can then bridge the gap between these models and physical reality, providing a means to produce complex and customizable designs at scale. Using technologies such as CNC milling, 3D printing, and robotic assembly, digital fabrication can achieve high levels of precision and repeatability (Cutieru, 2020). As Stoutjesdijk (2012) emphasizes in his project to create a fully CNC-routed shelter solution that these tools are central to the transformation of design and manufacturing, making high-end techniques accessible to everyone and bridging the gap between digital and physical worlds.

Once example where the combination of computational tools and digital fabrication has helped simplifying an otherwise complex design assignment is the project of Tsugite of the University of Tokyo (Larsson et al., 2020). They created an interactive system to design and fabricate complex wood on wood joints. These types of joins are often used in traditional architecture and furniture manufacturing and are valued for their visual appeal, durability and easy of assembly. There are quite a few different types including dovetails, cross lap and tongue and groove joints just to name a couple.

Figure 9: Different types of wood-on-wood joints Source: Kumar (2024)

Analyzing such joints can be quite a challenge due to the intricate geometries and complexity of the requirements that must be addressed in the design. As well as the fact that using traditional hand tools to craft these can be quite a time consuming and labor-intensive process. Which is precisely why they used the help of computational tools, to create a tool to let anyone digitally design the joints as well as produce the necessary files to be able to CNC-mill the pieces yourself.

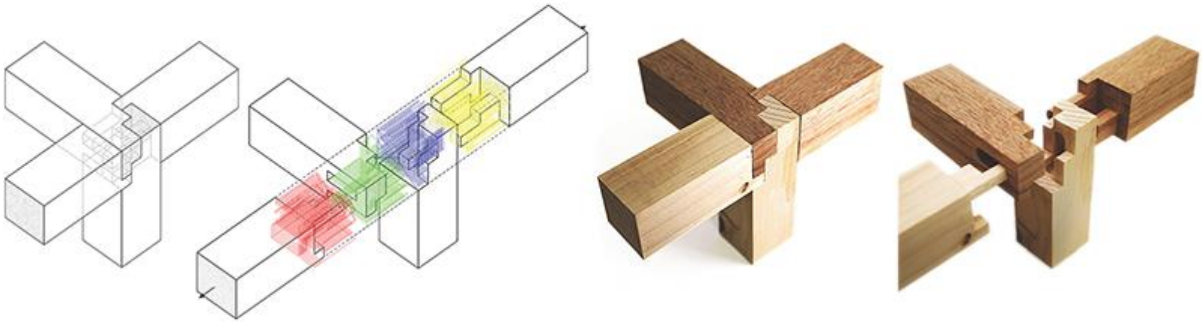


Figure 11: Tsugite from interface to reality
Source: (Larsson et al., 2020)

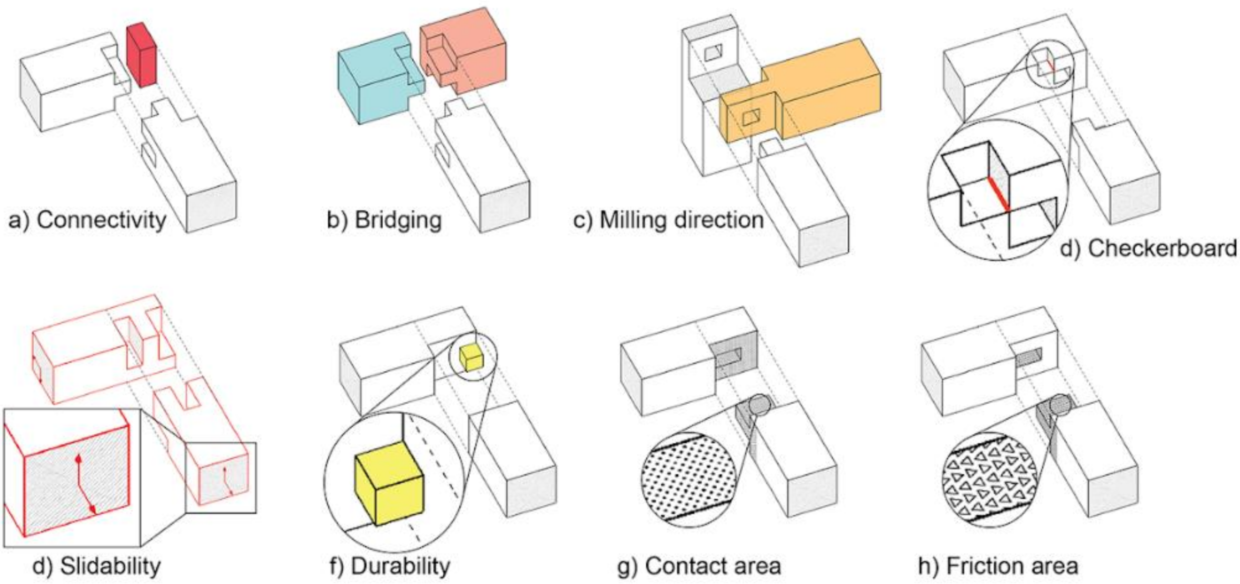


Figure 10: Viability checks on the joints
Source: (Larsson et al., 2020)

A perfect example of how a combination of computational means and digital fabrication like these can help create intricate custom pieces for each situation without the user needing the skill to create it. Meaning users are be made able to participate in an otherwise too complex design and fabrication process. In the context of shelter design this could provide the opportunity for the user customize their shelter to their needs and preferences, democratizing design while still being able to verify things such as structural stability without the need of expert involvement. Lowering the bar for people themselves to create their own design within the constraints the tools provide. Such an approach facilitates the creation of adaptable, culturally and climatically appropriate shelters that prioritize the well-being of occupants.

1.4.4 The role of Makerspaces

One of the barriers to more widespread use of digital fabrication is simply that most people do not have access to these advanced tools, especially in remote locations or disaster-stricken areas. However, as highlighted in the thesis of Stoutjesdijk (2012), Makerspaces can provide the critical solution in this case. Makerspaces are a global network of local fabrication labs that provide individuals with access to an array of tools including the more specialized ones such as CNC machinery, laser cutters and 3D printers regardless of their technical background. They are open to anyone and offer the opportunity for people to realize their low tech as well as high tech projects (Makerspaces, 2022).

In his thesis Stoutjesdijk (2012) highlights how these spaces can democratize production and enable communities to become self-sufficient by providing access to digital fabrication tools. They reduce dependency on distant supply chains and, hence, overall production costs by encouraging local manufacturing. Especially in post-disaster scenarios when traditional infrastructure can be broken or inaccessible, makerspaces, by setting up temporary or permanent workshops in the affected areas, allowed communities to fabricate shelter components locally, tailor-made to specific needs and resources available.

Makerspaces encourage community interaction, skills development, and long-term resilience: they empower individuals to repair, upgrade, and maintain their shelters; this promotes self-sufficiency and reduces dependency on external aid. Moreover, the collaborative environment of a makerspace allows for sharing knowledge and innovation, therefore allowing communities to come up with solutions that are both practical and appropriate for the context.

Additionally, helping people build their own shelters gives them a lot of purpose and control at a time when, in the aftermath of a disaster, feelings of helplessness and alienation are most prevalent. Involvement in the recovery process strengthens not only their perceived value in society but also hope, dignity, and a sense of accomplishment. Allowing them to be the creators, not just recipients of aid, enables individuals to rebuild not only physical structures but also their confidence and resilience Cluster (2022).

2. Research Framework

2.1 Research goals

The main objective of this thesis was to see if with the help of computational design and digital fabrication it is possible to let individuals with limited expertise in architecture, engineering, and design, to design and actualize personalized shelter solutions within their own community using the resources that are locally available without the need for expert involvement.

The proposal is to do this through the design of an application where such individuals will be able to design their own custom shelter through a parametric design. Incorporating the user in the process, steering them in the right direction and secure the structural integrity and resilience of the shelter by computational means. Also giving them the tools to then produce each custom element using digital fabrication to make them able to create each custom piece themselves locally. Promoting a sense of ownership and self-resilience.

The results consist of the general shelter design and its digital parametric model, the design of the application and scripts necessary to get all results, a structural analysis and a physical scale model.

2.2 Research setup

Main question:

How can CNC-routing and computational tools facilitate the design and local production of customizable wood-based shelters by non-experts in post-disaster contexts?

Sub-questions:

- Temporary shelter design:
    - What are the regulations and guidelines for designing shelter?
    - How can these be incorporated into the computational models?
    - What are the main types of post-disaster shelters, and how do they differ in terms of usability, adaptability, and sustainability?
- Structural design in wood and CNC-machinery:
    - What are the key principles of structural design in wood, particularly with plywood and other wooden plate materials?
    - How can computational tools ensure structural stability and optimization of wood-based shelters?
    - How does CNC-routing influence the structural integrity of the wooden components in shelter design?
    - Are there currently any (shelter) designs using CNC-milling and what are the benefits and bottlenecks?
    - What are the properties of different wooden plate materials, and which are most suitable for structural CNC-routing shelter components?
    - What are the capabilities and limitations of CNC machinery in producing shelter components?
    - How can CNC-routing balance material efficiency, precision, and durability in wooden shelter designs?

- Web application and CAD integration:
    - How can a web application be designed to make sure non-experts are able to interact with CAD models effectively?
    - What are the technical requirements for integrating computational design tools (e.g., Grasshopper, Rhino) with a web application?
    - How can the application guide users to design structurally sound and culturally appropriate shelters within regulatory constraints?
- User experience and Accessibility:
    - In what way can we involve the user in the design as well as the fabrication phase?
    - What are the constraints to guide the user in the right direction when designing, what can, and can't the user customize?
    - How do we make the design user friendly?
    - How do we ensure the costs are as low as possible and structural integrity is guaranteed without the help of experts?
    - How can the design process be simplified for non-experts using computational tools and web applications?
    - How can the web application empower users to design and produce their shelters locally while promoting creativity and ownership?
- Local production:
    - How can the use of CNC-routed wood-based shelters contribute to local resource utilization and reduce dependency on external supply chains?
    - What strategies can ensure that the shelters are sustainable, reusable, and culturally appropriate?

2.2 Scope and focus

In this Thesis the focus lays on investigating a method to enable non experts to locally design customizable wood-based shelters using computational tools and digital fabrication technologies, specifically focusing on 3-axis CNC milling as this is the most common version of CNC machines that are available in makerspaces. The design is limited to single- or two-story temporary shelters in post disaster scenarios and that will be built and produced on site. The assumption is thus that an environment similar to a Makerspace is also temporarily or permanently available nearby or on site with the necessary tools.

Furthermore, the structural analysis is conducted adhering to the Eurocode 5 regulations to make sure it follows the European safety standards as well as local or national context which is documented in the national annexes (Area specific regulations in Eurocode). For this reason, two geological areas are chosen to study:

- The Netherlands, Delft and surroundings
- Türkiye, Istanbul and surroundings

Next to that, in the analysis of the structural design the structure is considered rigid even though this might not be the case in reality.

This thesis also does not address the logistical challenges of setting up of makerspaces or sourcing materials in post disaster environments. Focusing on the design and fabrication process within the given context instead.

2.3 Methodology

The methodology this research follows adopts a typical cyclical design methodology including problem definition, research, defining constraints, implementation, evaluation and refinement. Ensuring an outcome that is based on well-informed decisions and through an iterative process will continue to improve.

The first phase after the problem has been identified (see introduction), a comprehensive study of literature is done to establish a theoretical framework for the design. Which involves studying temporary shelter typologies and regulations, structural design principles of wooden plate materials in the context of 3 axis CNC-routing. As well as research into both contexts The Netherlands and Türkiye to get a better understanding of specific contextual requirements for the shelter. Considering subjects such as site conditions, local materials, cultural preferences and climatic challenges.

With this information a set of objectives, constraints and requirements were made for the design of a temporary shelter, and a concept was set up with in mind that the design would have to be modeled digitally as a parametric object.

The digital parametric model was then created using Rhino Grasshopper and Python. The model allows for customization of structural elements, materials, and layouts while adhering to Eurocode 5 for structural safety. The optimization focusses on minimizing the weight and size of structural members to ensure efficient material usage, ease of transport, and assembly. From this model the outputs are then generated to facilitate the fabrication of the members using 3-axis CNC-routing.

Parallel to this a local application was designed to handle the user interaction and create a connection with the parametric model where the user did not have to understand the inner workings of the model in grasshopper. This was done with a combination of Python and Viktor, a worker that connects UI (user-interface) with a range of other programs or databases. In this case it was to set up a link between grasshopper and the interface without the user having to install grasshopper to be able to make use of its inner workings.

To test the feasibility of everything, a scale model is made of the shelter, and the parametric model ran through an FEM (finite element model) program to ensure validity. Then an evaluation is done to see the results and find where possible problems occur.

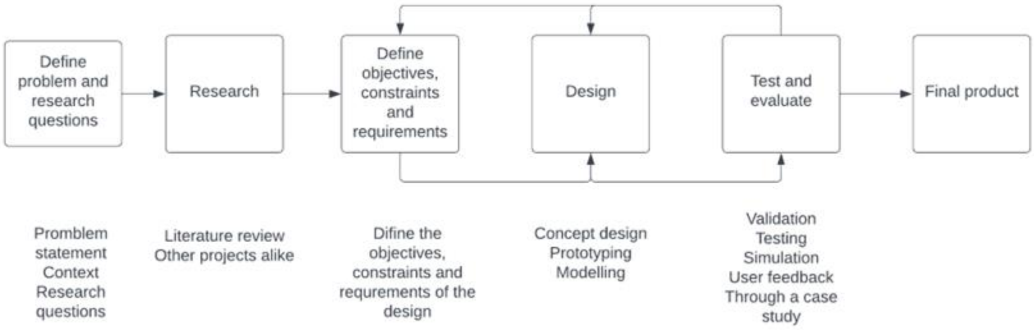


Figure 12: Overview of methodology
Source: Own diagram

3. Literature research

The following chapter delves deeper into the subjects named in the introduction including research into shelter- topology, regulations and design, structural design in wood, digital manufacturing like CNC-routing. Also looking at already existing projects using digitally manufactured wooden structural elements. To create a basis for the concept design of the shelter.

3.1 Temporary shelter design

3.1.1 Temporary shelter typology

Temporary shelters are typically designed to address the needs of the disaster-stricken population and provide the necessary steps from emergency relief to a permanent solution. Offering better durability and functionality than emergency shelter. They can be broadly categorized based on their construction method, materiality and deployment.

Albadra et al. (2018) name that shelter typology can be diverted into two categories based on their manufacturing and transport approach: Transportable shelter and build-on site shelter. Transportable shelters are manufactured elsewhere and shipped to site. Such as the container homes deployed during the aftermath of the earthquake in Türkiye in 2023. They are units that are prefabricated elsewhere and sent to site as flat packets to site and basically unfolded there (Shelter Sector Türkiye, 2023).

Figure 14: Flat packed containers
Source: Elitist Steel (2024)

Figure 13: Fully erected container unit
Source: Elitist Steel (2024)

Build-on-site shelters are, like the name suggests, built locally by the community themselves with the available materials there under the supervision of humanitarian organizations. Here tool kits and training are provided to guide the people in building their own shelter with any locally available materials and often traditional construction methods. Materials such as timber, mud, bamboo, thatch, and correlated iron sheets are common within these types of shelter. Though if concrete or brickwork are more common in the area or there is a lack of resources this is often chosen. It really depends on the context here what type of shelter should be chosen. What materials are available, what are traditional construction methods and how will this be realized?

Taking Aceh again as an example Traditional Achinese shelter uses local timber and thatched roofs and are on stilts to keep them off the ground or more recent ones use a concrete plinth or low brick walls with a timber structure. At first shelter was provided based on local design but due to shortages in resources they switched to reinforce concrete frames, brick walls and wood constructed roofs (Ashmore et al., 2008).

Figure 15: A later design of a shelter in Aceh
Source: Ashmore et al. (2008)

Another example of a build-on-site shelter are the ones in the Philippines after the typhoon in December 2011. Where the frame was made from a coconut wooden frame, plywood flows amaken walls and a corrugated iron roof, raised 750mm above the ground so potential water from floods doesn't immediately flow into the shelter and a high open roof so the warm air can easily escape (IFRC & RCS, 2013).

Figure 16: Build-on-site shelter
Source: IFRC and RCS (2013)

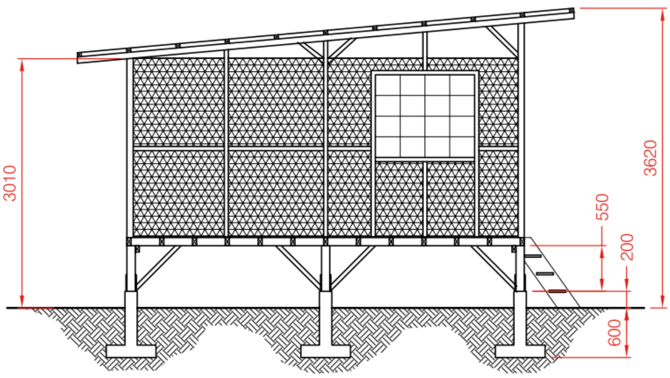


Figure 19: Section of the shelter showing the construction
Source: IFRC and RCS (2013)

Félix et al. (2013) differentiate shelters into two categories where 'ready-made' would fall under transportable shelter and 'shelter kits' that are more a combination of the two mentioned before. Where ready-made shelters are fully constructed units in a factory setting and transported as one item, like the container shelters. Where shelter kits are more like the RHU unit of the UNHCR (2016) where all the shelter parts are delivered in a supply kit and locally built on site.

The UNHCR (2016) themselves catalog their shelter types by permanence as well as the materiality. They segregate between global, emergency, transitional and durable shelters. Under global shelter they consider shelter with a standardized design and materials that are not locally sourced but from elsewhere. Mostly consisting of prefabricated units or kits. The examples they name: the UNHCR family, framed and self-standing family tents and their refugee housing unit. Under emergency shelters (not to confuse with emergency shelter as mentioned in the introduction) they name structures that are mostly quickly made from local materials (often wood thatch and or mud). Transitional shelters are then the more permanent form of the emergency shelter though often also made from the same type of local materials. Durable referring to structures, built in brick or concrete and more 'durable' as the transitional ones.

Figure 20: Four types of shelter - Right top: RHU unit global shelter, Left top: Tuareg tent in Sahrawi (emergency shelter), Right bottom: Compact bamboo shelter Ethiopia (Transitional shelter) and Left bottom: Shelter in Iraq (durable shelter)
Source: UNHCR (2016)

3.1.2 Standards and regulations

The Sphere handbook is recognized among multiple humanitarian organizations such as the Red Cross and UNHCR (The UN Refugee Agency) as the quantifiable minimum for humanitarian response. They set up several regulations and standards including shelter and settlements (Sphere, 2018).

The UNHCR has listed what they believe to be the key points of the document for any type of shelter (UNHCR, 2015).

- Ensure minimum standards of covered living space per person are respected
- Shelter solutions should be adapted to the geographical context, climate, cultural practice and habits, and local availability of skills and accessibility to adequate construction materials in any given context
- Consider the lifespan of shelter materials as they deteriorate with time. Further to the initial distribution, installation or construction, replacement, reinforcement or maintenance may be required
- Individual family shelter should always be preferred over communal accommodation as it provides the necessary privacy, psychological comfort, and emotional safety. Whenever possible, displaced people should be empowered to choose where to live, and to build their own shelters, promoting a sense of ownership and self-reliance

As for the minimum standard of shelter units, they are stated as follows:

- Warm climate:
    - Minimum 3.5 square meters of covered living space per person (excluding cooking facilities or kitchen)
    - Minimum height of 2m at the lowest point (greater height being preferable to aid air circulation and ventilation, sphere suggests at least 2.6 meters at highest point)
- Cold climate:
    - Minimum 4.5 to 5.5 square meters of covered living space per person (excluding cooking facilities or kitchen)
    - Maximum height of 2m (to reduce heated space)
    - Structural stability (Resist snow weight and wind forces)
    - Consider Insulation, and provision of heating (indoor temperature of 15 to 19 degree celsius at least)
- Both:
    - Providing the opportunity to modify the shelter (add partitioning, future expansion etc.)
    - More space should be added if bathing and toilets are included (check WASH) in the individual shelters or if in a more developed context the displaced have more belongings.

3.1.3 Prior research

In preliminary research together with Amir Ghadiri in response to the two devastating earthquakes in southern Türkiye and northern Syria in February 2023 which displaced millions (CDP, 2024), we researched and designed customizable timber shelter construction using digital tools and digital fabrication based on Japanese wood joinery inspired by the project with the similar name of Tsugite mentioned in the introduction.

The focus was on creating shelters that are quick to assemble, customizable, and efficiently transportable as well as able to handle the aftershocks in the area after the earthquake as these can persist for months after the initial quake. To achieve this, we developed a user-centered interface using computational tools like Python, Rhino and Grasshopper, allowing for the rapid customization and production of CNC-routed timber structures. The goal: to go from a simple drawing to a digital model to reality.

Method

The first phase involved a literature review of existing shelter solutions, vernacular architecture, and traditional wood joinery techniques like Tsugite, Hımış, and Dougong. These were studied alongside computational design approaches for disaster management to conceptualize a modular design that aligns with the research objectives: easy assembly, disassembly, transportation, and customization.

A digital platform using Python and the Tkinter library was then developed to allow users to sketch floorplans and customize their shelters. The user inputs were processed into digital models via Grasshopper, Rhino, and CSV files. Structural evaluations were conducted using the Karamba3D plugin in Grasshopper to ensure stability and optimize the designs.

Finally, the design was tested by creating a scale model based on digital outputs, assessing construction ease and joint performance to identify and address any overlooked details.

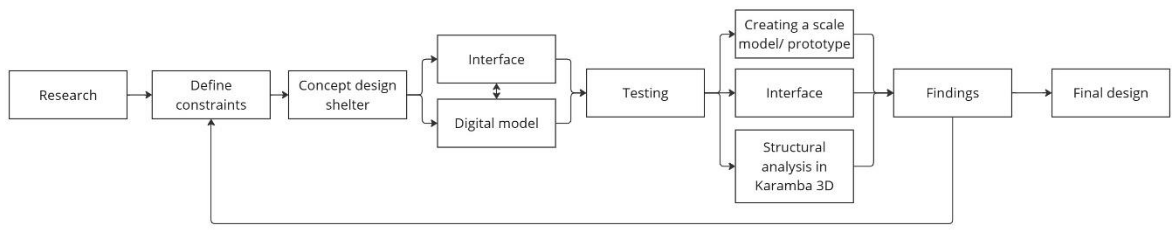


Figure 21: Flowchart of the process
Source: own diagram

Research results
To create a shelter that is easy to assemble and resilient to aftershocks, we focused on traditional wood joinery techniques relying solely on friction for structural integrity. These methods, requiring no specialized tools or large machinery, have proven durable, with numerous timber structures using such techniques, surviving for centuries in seismic regions. Key inspirations included:

- Tsugite (Japanese wood joinery): Tsugite, a Japanese wood joinery method, involves intricate puzzle-like connections. Despite their precision and durability, the complexity of these joints makes mass production challenging. Inspired by a tool developed at the University of Tokyo (Larsson et al., 2020) that simplified Tsugite joinery by utilizing CNC-milling and computational tools, the project adopted similar methods to create customizable, user-friendly joints for emergency shelters (see introduction).

- WAAS (Wooden Adaptive Architecture System): The WAAS project by Potvin et al. (2013) demonstrated modular adaptability with Dougong (Chinese wood on wood joints) and Chidori joints (Japanese wood on wood joints). Its grid-based system influenced the shelter's modular design, enabling flexible, user-defined layouts.

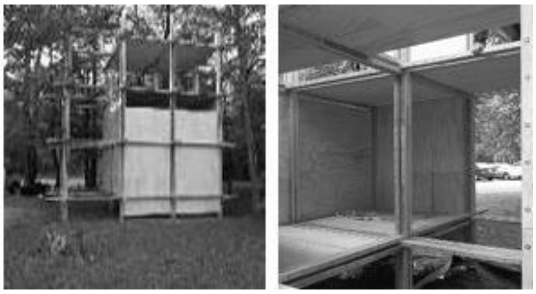


Figure 22: WAAS System
Source: (Potvin et al., 2013)

- Hımış: Traditional Hımış techniques, used in Türkiye and other regions across the globe, involve timber frames subdivided into smaller sections often filled with either bricks, stone or adobe. Known for their seismic performance, these structures inspired our grid system, emphasizing bracing and smaller subdivisions for stability under seismic loads (Gülkan, 2021; Usta & Bozdağ, 2022).

Figure 23: Left: an example of a Hımış building suffering only plaster cracks after the 1999 earthquake, Top right: View of Hımış house next to a RC building after the 1999 Düzce earthquake. Bottom right: View in Adapazari with Hımış house on left beside several blocks of pancake collapsed RC buildings
Source: Gülkan (2021)

Resulting Modular Design

The final modular design incorporated seven joint types, eight beams, one column type, and two bracing elements. Joints were based on Chidori, bracing and frames on Hımış, and a 1-meter grid size was selected for scalability and simplicity in construction. And all members are able to be fabricated with CNC based fabrication techniques.

Figure 25: Tsugite shelter design of a 3 by 3 unit
Source: own screenshot

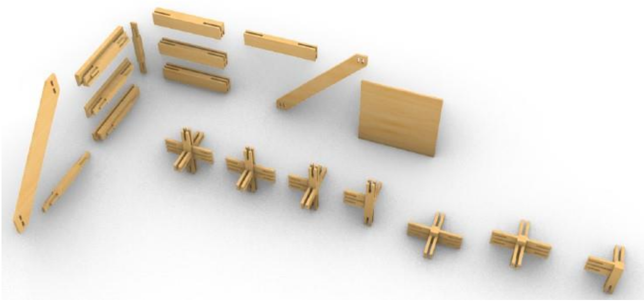


Figure 24: A joints and members of the shelter
Source: own screenshot

Developing the digital model

The modular design was brought to life through a parametric digital model, allowing users to adapt to the layout however they wanted. The process began with a Python-Tkinter interface where users sketched their layouts. These inputs were translated to a grid and exported as points to a CSV file where they were stored. They would then be processed in Grasshopper and Rhino to generate the 3D structure of the model. Structural components like beams, columns, and joints were automatically created using Python scripting and parametric tools.

However, the process was not without its challenges:

- Drawing-to-grid conversion: Early freehand drawings caused inaccuracies, such as overlapping or misaligned points. Snap-to-grid functionality was introduced to enhance precision, though it reduced flexibility.
- Data transfer issues: Initial attempts to use the HOPS plugin for data transfer led to errors. Switching to CSV-based point storage improved reliability but required manual updates in Grasshopper.
- Boundary challenges: Open spaces in layouts were sometimes misinterpreted, leading to unintentional filling. Script refinements were addressed but did not fully eliminate this issue.

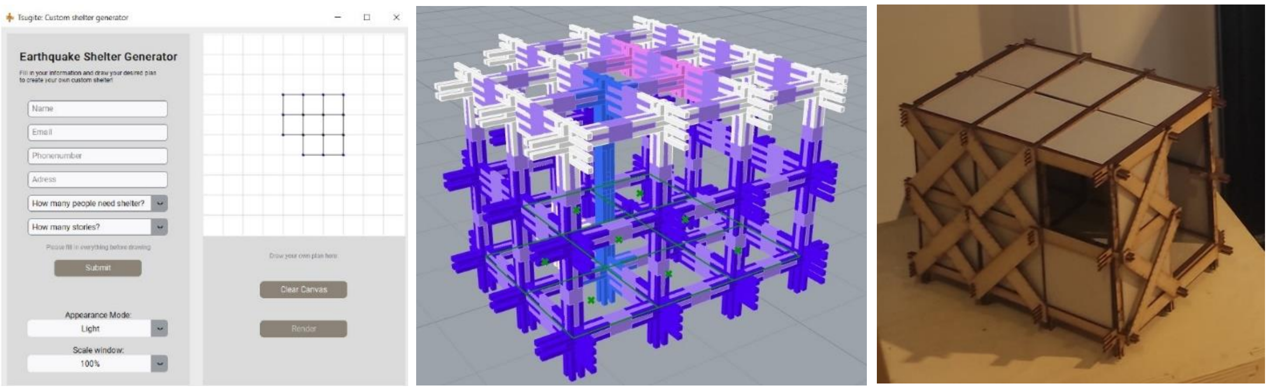


Figure 26: From interface to scale model
Source: Own picture

Outcome

After iterative refinements, the workflow successfully translated the user's layout into a structurally sound digital model. A scale model validated the system's ease of assembly, confirming the feasibility of integrating traditional techniques with computational tools. The resulting shelter system is modular, adaptable, and resilient.

Conclusions

This study demonstrates how traditional construction methods, such as Japanese interlocking joinery and Hımış techniques, combined with modern computational tools, can create sustainable, adaptable, and resilient shelters. These designs minimize the need for specialized tools and materials, are easy to assemble and disassemble, and empower users to contribute through simple drawings. While the project shows promise, it remains in its early stages, with several areas for improvement. Future developments include:

- Automating processes further, creating an online platform to replace Grasshopper installations, and generating CNC milling files automatically instead of by hand.
- Integrating seismic force analysis, optimizing joint sizes, and reducing material redundancy in the digital model could enhance structural performance and sustainability.
- Exploring alternative materials than just timber (in this case the focus was on oak wooden elements).
- Moving beyond the 'square box', creating something freer from uniform 1x1 grid to incorporate varied geometries and architectural elements such as stairs and openings could enhance usability and livability.
- Changing the user interaction, right now the user has a lot of freedom in layout, and currently can still create layouts that are not viable (like making separate 1 by 1 squares instead of one large space). Contrastingly giving the user, the opportunity to have more freedom in things as choosing the materials.
- Adapting the tool to other contexts and seeing what that does for the design
- The durability of the joints themselves, we noticed during the process of putting the model together that when too much force was used the pieces would break.

However, Tsugite does set a first step to offer a healthy foundation for shelter design in combination with digital tools and fabrication.

3.2 Structural timber design

3.2.1 Introduction

Timber has throughout history been widely used for structural purposes due to its abundance, versatility and strength. It is a natural occurring cellular material, renewable, has a low embodied energy and a high strength to weight ratio (Overend, 2022; SwedishWood, 2022; USDA, 2021).

Types of wood:

Timber can be classified within two categories as they are either made from softwood or hardwood. Where softwoods are from trees that are coniferous, evergreen and cone bearing. They have a shorter growth period and are relatively cheap, however they have poorer durability than hardwood. Examples are cedar, fir, hemlock, pine, redwood and spruce. Hardwoods consist of deciduous trees with broad leaves, known for their durability and thus more often chosen in structural applications. However, it is more expensive and harder to work with. Examples are beech, oak, elm, ash, cherry, maple popular and birch (Overend, 2022).

Eurocode:

The European union (EU) developed a set of construction codes for construction to apply to throughout the EU and facilitate a basis for the design of structures. There are 10 main subjects as seen in the table below, which are also subdivided into multiple parts.

EN number	The structural Eurocodes
EN 1990	Eurocode: Basis of structural design
EN 1991	Eurocode 1: Actions on structures
EN 1992	Eurocode 2: Design of concrete structures
EN 1993	Eurocode 3: Design of steel structures
EN 1994	Eurocode 4: Design of composite steel and concrete structures
EN 1995	Eurocode 5: Design of timber structures
EN 1996	Eurocode 6: Design of masonry structures
EN 1997	Eurocode 7: Geotechnical design
EN 1998	Eurocode 8: Design of structures for earthquake resistance
EN 1999	Eurocode 9: Design of aluminium structures

Table 1: Main Eurocodes
Source: Larsen and Enjily (2009)

Of course, the most relevant here is EN 1995 or Eurocode 5 (EU5) for the design of timber structures. Of which two parts are most relevant: EN 1995-1-1 General common rules for buildings and EN 1995-1-2 general rules structural fire design.

And since some countries have different regulations and standards, there are also National Annexes with information applicable to their territory. In chapter 5 the Eurocode will be discussed in further detail.

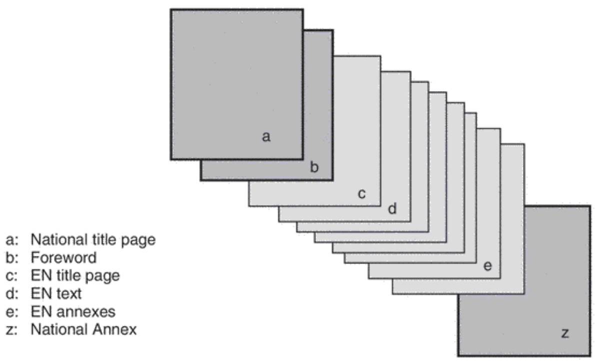


Figure 27: Structure of the Eurocode documents
Larsen and Enjily (2009)

Timber as anisotropic material:
Timber is a highly anisotropic material. Meaning the physical and mechanical properties of the material varies depending on the direction of which it is measured. It arises from the way the internal structure of wood is created particularly in the alignment of the fibers. For example, timber is significantly stronger and stiffer along the grain (longitudinal or parallel) than across it (radial or perpendicular) and weakest in the tangential direction. It also affects how the material acts under different loads. In terms of tension it behaves as a brittle material, meaning it does not deform much before it fails and will break on its weakest link. For example, a place where a small defect like a knot is situated. In compression the failure is more ductile (Overend, 2022). This also means the material is orthotropic, a particular subclass of anisotropic materials where a material has three mutually perpendicular axes of material symmetry each with its own distinct properties (EngineeringSoftware, 2021).

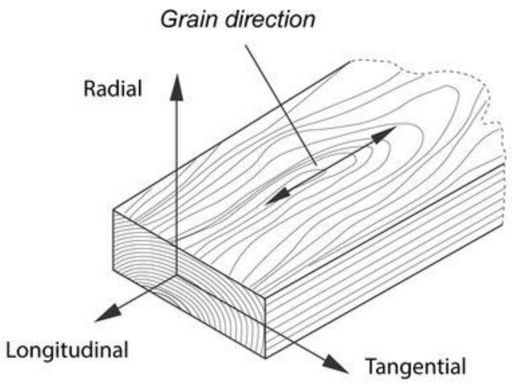


Figure 28: Planes of timber according to the grain direction
Source: Fragkia and Foged (2020)

Additionally, its anisotropic nature in terms of moisture and temperature, which can cause timber to swell or shrink, causes the largest deformations in the tangential and radial direction and they will be a lot smaller in the longitudinal direction.

It is important to note as well that the mechanical and physical properties do not only vary from grain direction or load direction but too from species to species and even within species there are quite a lot of variations (Overend, 2022; SwedishWood, 2022; USDA, 2021).

Moisture
Timber is a hygroscopic material. Meaning that it attracts and holds water molecules by either absorption of adsorption from its surroundings. Therefore, it is necessary to dry timber before using it so that it has the same moisture content as the environment it will be used in. Though even then as the humidity in the environment changes it will also change the moisture content in the wood which can cause shrinkage and swelling and need to be accounted for when designing.

Hence why the EC 5 identifies 3 service classes based on the humidity of its environment that affects the strength of the timber (EN 1995-1-1:2004):

- Service class 1: Materials with a moisture content that matches a temperature of 20 degrees and a relative humidity exceeding 65% for a maximum of a few weeks.
- Service class 2: Materials with a moisture content that matches a temperature of 20 degrees and a relative humidity exceeding 85% for a maximum of a few weeks.
- Service class 3: Materials with a moisture content that matches a temperature of 20degrees where the humidity exceeds service class 2.

Creep
Timber will creep if it is subjected to loads to a certain amount of time and will decrease in strength over time. Thus, the EC 5 set up 5 load classes based on the duration of the load. From instantaneous to permanent (see EN 1995-1-1:2004 table 3.1)

Wood is a very variable material and depending on the circumstances as well as material properties it can act differently in each situation. Properties such as cracks, knots, fiber angles, grain deviation, ring width and moisture can all influence the material's strength. There are, however, ways to reduce the unpredictability of wooden materials by either grading them (visually, mechanically or proof grading) or by using so called Engineered timber. Which also gives you more options in sizes and shapes beyond what is possible with just sawn timber.

3.2.2 Engineered timber products

Engineered timber products are timber or wood products that are processed to improve for example size, certain properties or lower the variability of the material. Conventionally they are made primary from wood products as timber, veneers, stands, particles or fibers with only a few percent of resin or other additives (USDA, 2021).

To name a few examples:

- Glulam (glue laminated timber)
- CLT (cross laminated timber)
- LVL (laminated veneer lumber)
- Plywood
- OSB (oriented strand board)
- Particle and fiber boards

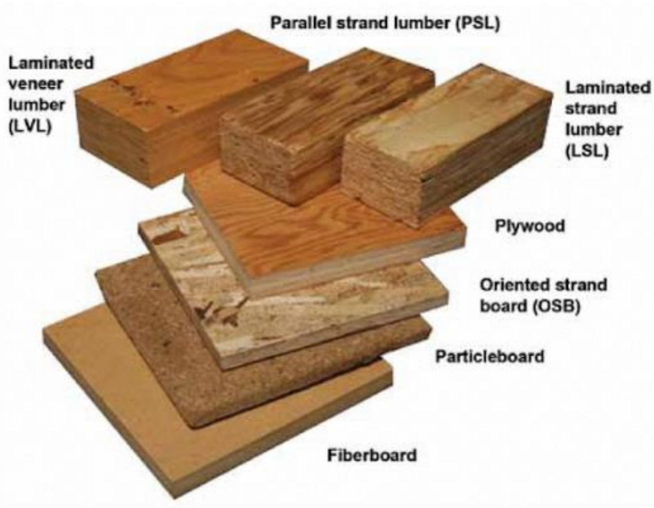


Figure 29: A few examples of engineered wood
Source: USDA (2021)

They can be categorized accordingly based on what timber product is used to create them (either boards, thin veneers or particles) and the orientation of the fibers as seen in the table below (Overend, 2022):

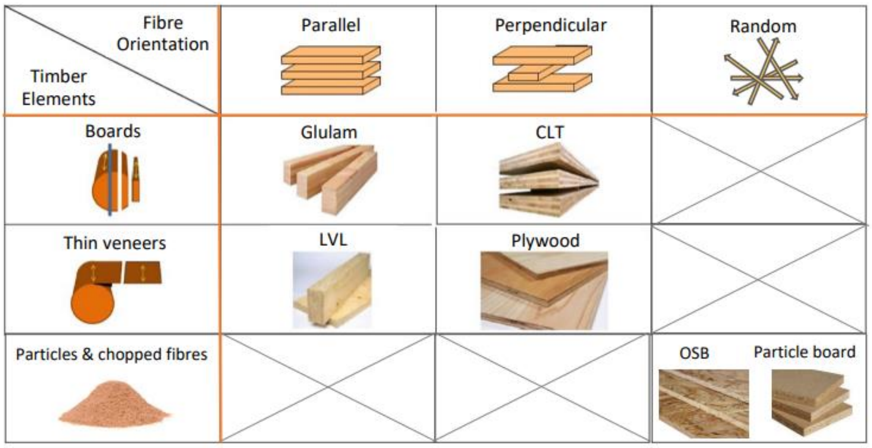


Figure 31: Categorization of engineered wood products
Source: Overend (2022)

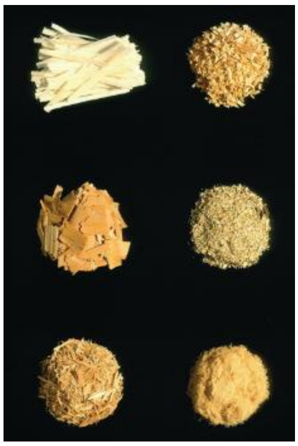


Figure 30: Common wood particles and fibers (Clockwise: shavings, sawdust, fiber, large particles, wafers and strands)
Source: USDA (2021)

Adhesives:

Most engineered woods make use of bonding by thermosetting (heat curing) adhesive resins. The more common adhesives include phenol-formaldehyde (PF), urea-formaldehyde (UF), melamine-formaldehyde (MF) or isocyanate (MDI) (USDA, 2021).

Additionally, Eurocode in EN 314-2 has set up bonding classes based on the performance of the glue in either dry or wet conditions as these can differ per type of adhesive. Class 1 being for dry conditions, class 2 for humid conditions and class 3 for exterior use. PF for example is highly waterproof, but UF deteriorates quickly when exposed to water (Kitronik, 2015).

Commonly there is also a different categorization, called Type A, B, C and D bonds. Though these basically refer to the type of adhesive used. Type A being the strongest bond and waterproof, and consisting of PF. B being less durable, is still waterproof but deteriorates over some time consisting of MF. And C and D both for UF generally only for inside uses (Veneer, 2016).

Phenol formaldehyde or phenolic resins are commonly found in construction applications, especially in exterior conditions as this type of adhesive is waterproof and does not deteriorate in wet conditions. They are slower curing and need higher temperatures to cure than the other options, though they are very durable (USDA, 2021). They are also often mentioned as WPB bonds, ‘weather and boil proof’ as one of the common tests that is done to verify the bond is a boil test (CEP, 2009). They are commonly used with Plywood and OSB.

Uera-formaldehyde are mostly for interior purposes only and used in different types of particleboards and medium density fiberboard (MDF). They are cured at lower temperatures and are prone to degradation from moisture and heat, so they are far less durable. One of the main concerns with this type of adhesive is the emission of the formaldehyde (USDA, 2021).

Which is why in the Eurocode (EN 13986, EN636, EN 717-1 and EN 717-2) there are regulations about the emission of the Formaldehyde the material must oblige to. Classes E1 and E2 where E1 refers to 0.1 ppm (low emission) and E2 between 0.1 and 0.3 ppm (Kitronik, 2015).

Melamine formaldehydes are somewhat more durable than UF’s, however they are still often used for interior use just in places with higher moisture contents as it has a greater higher resistance.

Isocyanates or diphenylmethane di-isocyanate (MDI) are commonly used as a replacement for PF. It is generally used in engineered or composite wood materials made from strands. This resin, when cured, has no known health concerns though for the production extra precautionary protective measures need to be taken to keep people from being exposed to the material while it cures. It has a higher water resistance than PF though is also often more expensive (USDA, 2021).

Glulam (glue laminated timber):
Glulam consists of several (at least 4) laminations of timber boards bonded together with adhesives. With all the boards their grain oriented in the same direction (towards the axial direction of the beam). It can be made up of homogeneous layers and use the same strength grade of timber each time or add higher grade timber to increase performance as stress concentrations at the ends are higher (see Figure 33). This way the imperfections of the timber are distributed throughout and lessens the variation in strength. It also gives the opportunity to create curved members as well as larger sized members (SwedishWood, 2022). As commonly timber has maximum dimensions of 75mm by 225mm by 5 meters, Glulam beams can go all the way up to 290mm by 2050mm by 31 meters (Overend, 2022).

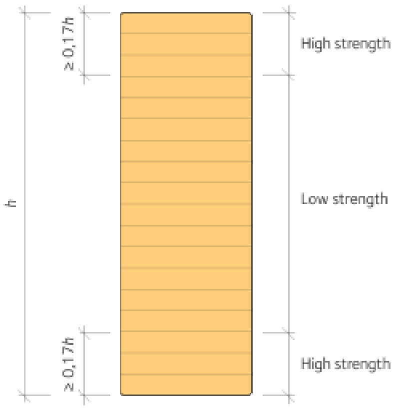


Figure 33: A non-homogeneous lay up of Glulam
Source: SwedishWood (2022)

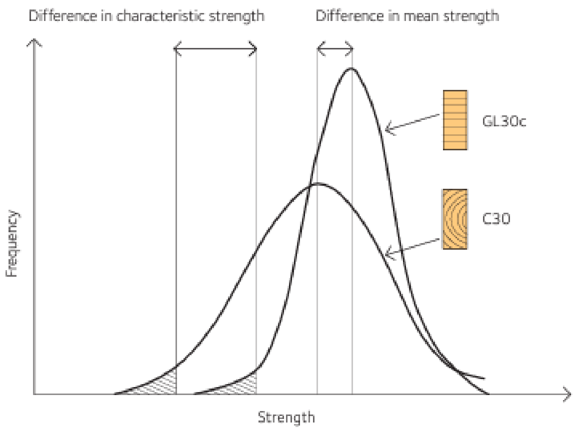


Figure 33: Difference in strength variation between Glulam and timber
Source: SwedishWood (2022)

CLT (cross laminated timber):
CLT is also made by glueing layers of sawn timber but instead orienting each layer perpendicular (see Figure *34*). Using an uneven number of layers to always keep the outer two layers in the same direction improving strength. Usually this means that 3, 5 or 7 layers are used to create members of at least 60 mm thick and boards up to 24 meters long and 3 meters wide. They can be even larger however this will be harder to transport. They are often used as wall or floor panels and once on site have already been foreseen of holes for doors and windows or notches for things such as electrical fittings. These are cut using specialized CNC-machines in the factory to create them (Overend, 2022; SwedishWood, 2022; USDA, 2021).

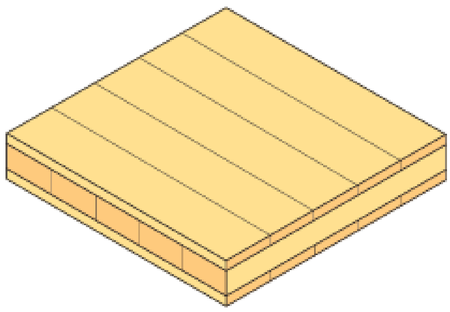


Figure 34: CLT
Source: SwedishWood (2022)

LVL (laminated veneer lumber):

LVL (or as it is often called Kerto) is made by bonding several layers of thin 3mm thick veneer sheets made from softwoods with adhesives, similar to glulam. All with their fibers in the same direction (Kerto S) or 20% laid crossways (Kerto Q). Kerto S LVL is generally used for beams while Kerto Q are used as panels for more compressive strength or dimensional stability (Metsä, 2024). The standard panels can be up to 2.5 meters wide and 12m long though there are ones up to 25 meters long (Overend, 2022).

Figure 35: Example of LVL
Source: (Metsä, 2024)

Plywood:

Plywood is made in the same manner as LVL. However here the veneers are laid perpendicular from each other on each layer. Again, the number of layers here is always odd so that the outer ones have the same grain orientation mostly in the direction of the longer side of the sheets. Regular sizes of the panels are either 1200 by 2400mm or 1220 by 2440mm and depending on the number of layers and thickness of the veneer 12 to 24mm (Overend, 2022).

The structural performance of plywood is dependent om the type, number and thickness of the veneers as well as the load direction. Keeping in mind the bending perpendicular to the plane and the in-plane bending. The layers with the grain direction in the same direction as the load do the most for the stiffness of the material, the other layers their stresses are so small they can often be disregarded (SwedishWood, 2022).

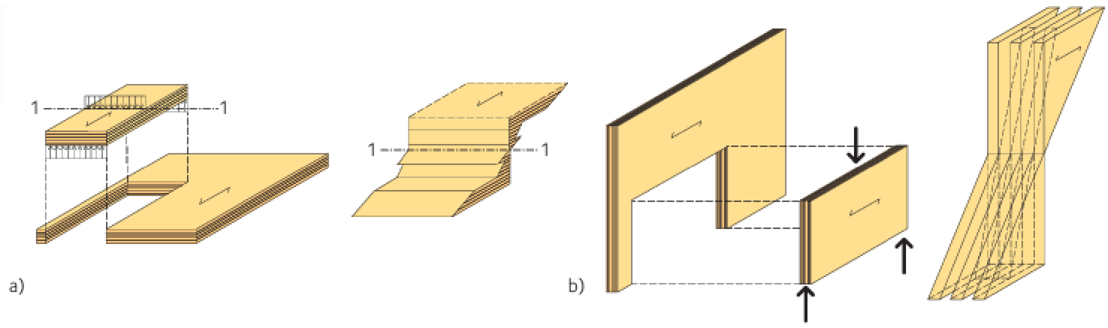


Figure 36: a) out of plane bending b) in plane bending
Source: SwedishWood (2022)

OSB (oriented strand board):

Oriented strand board is a type of engineered wood made from thin wood strands. These strands are compressed into layers and set in specific orientations in the outer layer for strength. It is mainly used as floor, wall and roof sheeting as they are very well in handling bending stresses (SwedishWood, 2022; USDA, 2021).

As for the mechanical properties in EN 300 of the Eurocode there are 4 sets of grades, all with their own requirements for the strength of the material.

- OSB/1: Non load bearing boards, general purpose boards and boards for interior fitments for use in dry conditions.
- OSB/2: Load-bearing boards for use in dry conditions
- OSB/3: Load-bearing boards for use in humid conditions.
- OSB/4: Heavy-duty load-bearing boards for use in humid conditions

Particle board and Fiberboard:
Fiberboard is a type of engineered wood product that is made from wood fibers. Types of fiberboards (in order of increasing density) include particle board or low-density fiberboard (LDF), medium-density fiberboard (MDF), and hardboard or high-density fiberboard (HDF). Mixing in adhesives and under heat and pressure forming it into a board.

Figure 37: Fiber board
Source: MUMU-Design (2023)

Particle boards are much like fiberboards, however they use larger wood elements like sawdust, planer shavings and other mill residues or other homogeneous waste materials by wood industries. It usually consists of 3 layers, where the core is made from particles and the outside is made of a coarser material so that it creates a smoother surface. It is widely used for furniture or as underlayment, flooring systems, or insulating panels. There are, just like fiber board, low, medium and high-density variations of the material.

Figure 38: Particle board
Source: A4 (n.v.t.)

Though where fiber board differs from particle board is that fiber boards next to the fact fiberboards are made from a different source of wood (wood fibers) instead is that they are generally stronger because of the fibrous nature of lignocelluloses (biomasses rich in cellulose) (USDA, 2021).

What fits best where?
From the above types of wood, for the structure, if thinking about CNC milling most of the parts for the shelter a few options already fall off as they are quite hard to work with, such as Glulam or CLT. Also, because those are often the pricier option. LVL, plywood, OSB, particle and fiber boards are better suited though for structural purposes for plywood it would need WBP adhesives, same for OSB and the others. OSB would at least need to be type 3. Things like Particle and Fiber boards are often made using UF however and mostly just fit for inside purposes and not really made for load bearing purposes but could be used decorative. In terms of price, between them are fiber and particle boards, the cheapest, as well as OBS. Plywood is in a higher price range though all are in the lower end spectrum as in everything in grey are different regular sawn timber products which seem to be more expensive.

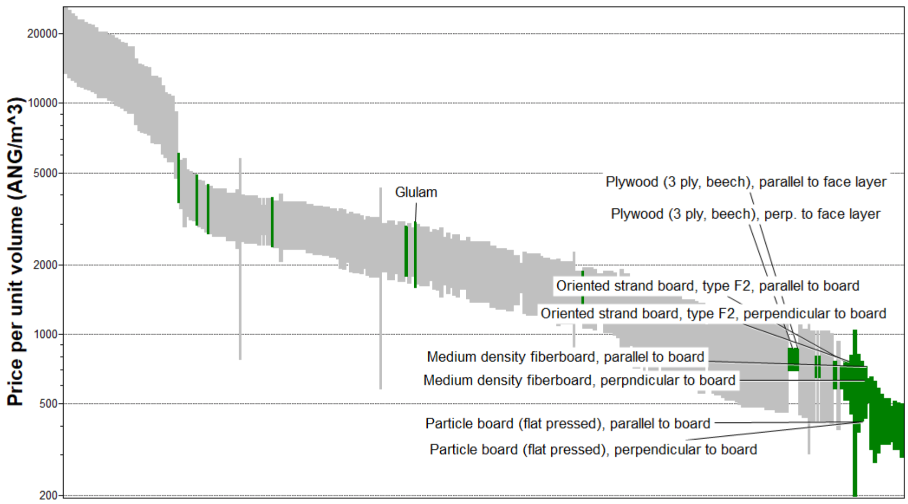


Figure 39: Price of composite wood materials
Source: Granta Edupack ANSYS own diagram

As for strength in comparison to the price value again it is seen that most composites are on the lower end of the price range yet plywood for example, performs high overall in terms of strength and stiffness in comparison to even most natural materials. Hence this is why for the structure plywood will be used but for other sheeting materials things like OSB or other materials with lower costs can be used instead.

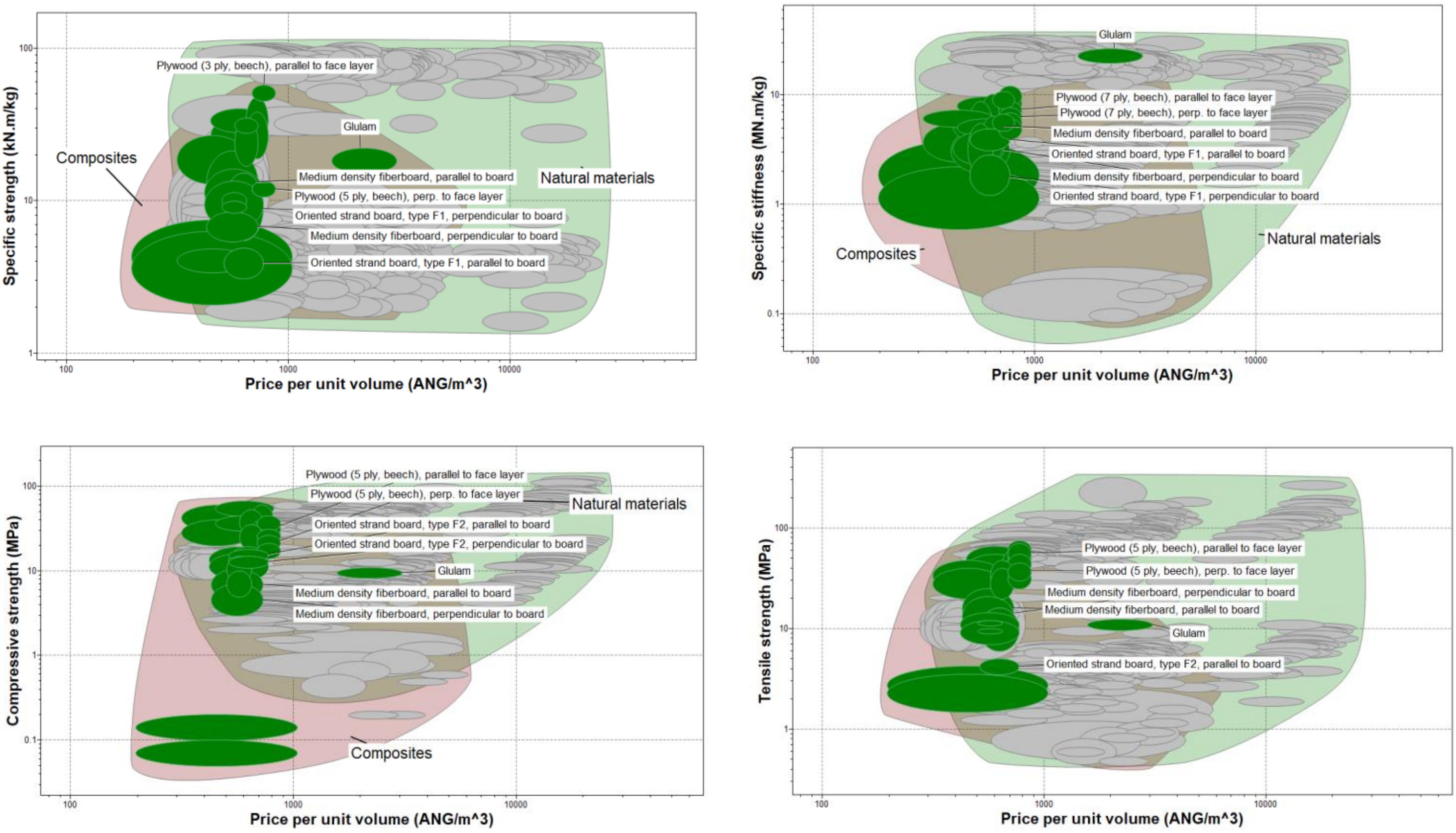


Figure 40: Strength and stiffness comparison with price
Source: Granta Edupack ANSYS – Own diagram

3.2.3 Interlocking timber joinery

To complete a structural system, you need joints to connect every member together. In timber structures there are 3 categories of joints: carpentry, glued and joints that include metal fasteners. In carpentry the forces of the structure are transmitted through only the contact between the members by creating enough internal compression and shear forces (Blaß & Sandhaas, 2017). Interlocking joints are a variant of these that do not need any additional fasteners like nails screws or other adhesives to create a strong bond and solely rely on the friction between the members. They have been used widely in the past before steel and other fasters were even a thing though over the years multiple variants and new designs for traditional solutions have popped up.

Traditional joinery:

Some of the more well-known joinery that have been traditionally used are joints like mortise and tenon, scarf, and dovetail joints. Both mortise and scarf joint are often used to connect beams or columns while dovetail or box joints are more often used to join surfaces together (Keller, 2024; Noll, 2002).

Figure 43: Mortise and tenon joint
Source: WOOD (2021)

Figure 43: Scarf joint
Source: Keller (2024)

Figure 43: Dovetail joint
Source: Keller (2024)

A few ways to join these traditional joints without the need for things like screws, nails or glue are among others with wedges or keys. With wedges a piece of wood is hammered into the joint to tighten it which increases their strength and reliability. It can also be used to improve a weakness in any type of joint. Keys or inlays are separate pieces from the two elements you want to join that basically lock them together. Keys can have various shapes like the butterfly joint seen in Figure 45.

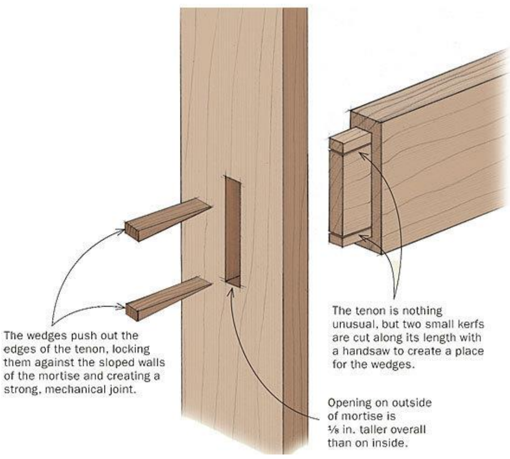


Figure 44: Mortise and tenon joint with wedges
Source: Becksvoort (2012)

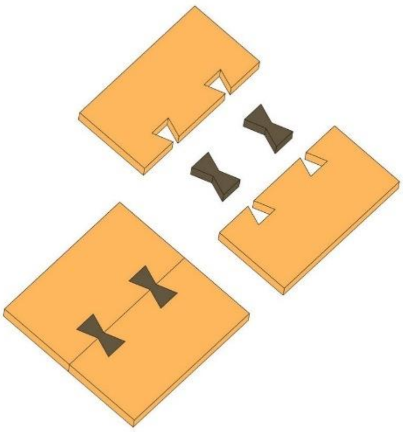


Figure 45: Traditional joint using keys (in this case butterfly keys)
Source: Craftmanspace (2024)

In the traditional Japanese carpentry, they are known for their intricate and high craftmanship in these types of joinery. Once such example is Tsugite which refers to a type of splicing joint for joining two wood pieces to make up for the lack of available materials and Shiguchi a technique to connect materials at an angle and are often used together, both having several variations based on the type and position of the wood (Kanasaki & Tanaka, 2013; Larsson et al., 2020).

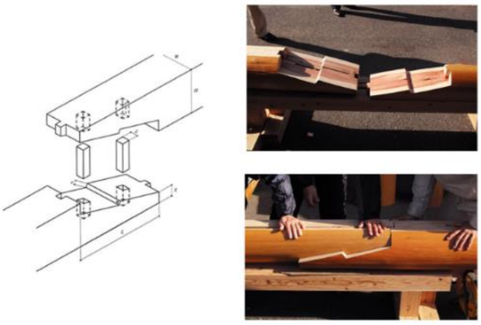


Figure 48: Daimochi Tsugite
(Shear resisting joint)
Source: Teuffel (2020)

Figure 47: Nuki - joint
(crosspiece joint)
Source: Teuffel (2020)

Figure 46: GC Prostho
Museum Research Center
Source: Kuma (2012)

Or Cidori which is a form of Shiguchi based on an old wooden game with a similar name that joins 3 members almost invisible by interlocking them like a sort of 3D puzzle. The last piece being rotated in and locking the three together. This can be quite hard to apply in buildings however as they need a certain order to build them in and rotating members in can be hard when members get large enough. Though in smaller sizes this is quite possible as seen in the project of Kengo Kuma & Associates who designed the GC Prostho Museum Research Center using these types of joints (see previous page Figure 46).

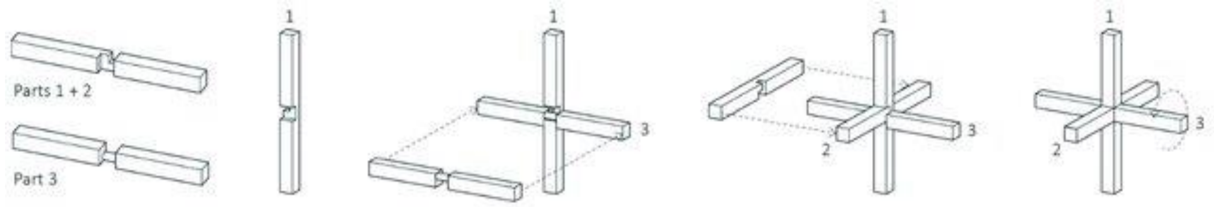


Figure 49: Cidori joint built up
Source: Petrović and Ilic (2021)

Another example of a very intricate though very effective joint can be seen in Chinese architecture where the so called dougong joint is often used in temples to support the roofs. The technique is seen as early as 500 B.C. When interlocked they still however have enough tolerance so that all the elements the joint consists of do not crack. They are even known to be resistant to the forces of an earthquake as many traditional buildings and temples even in seismic active areas have been there for decades without sustaining much damage.

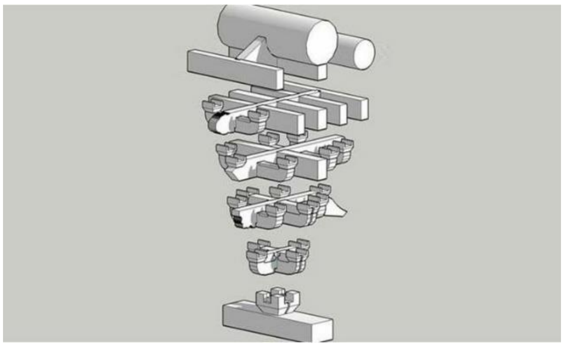


Figure 50: Dougong joint layup
Source: Noe (2017)

Figure 51: Dougong joint in a temple
Source: Noe (2017)

These intricate traditional methods of joinery rely on precisely cut, puzzle-like joints, allowing wood to be seamlessly connected. Which is exactly the problem. Due to their complexity, it is hard to produce them, and are often hand-made, the skills handed over decades and passed on through generations and not easily replicable (Kanasaki & Tanaka, 2013). So, in more modern joinery people have tried to find easier ways to either replicate them using CNC or simplify the joints to fit or try to mass produce this intricate joinery.

For example, a more recent development using the benefits of CNC are Snap-fit joints. They are joints that rely on the elastic character of wood to be able to ‘snap’ the connection in place. The consist of a male and female part where on the male part the cantilever hook temporary bends to go through the opening of the female part. Then snaps back in place once through and can be disassembles quite easily again by pushing the two ends on the male part back together again. This is now still used for constructions indoors or to quickly set up a temporary structure for events though in the study of Robeller et al. (2014) he studied the possibility for using the joint in a structural applications as well.

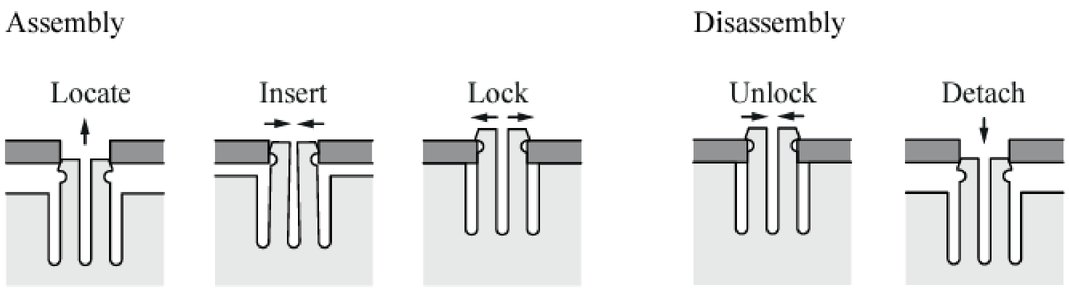


Figure 52: Snap fit joints, lock and unlocking them
Source: Robeller et al. (2014)

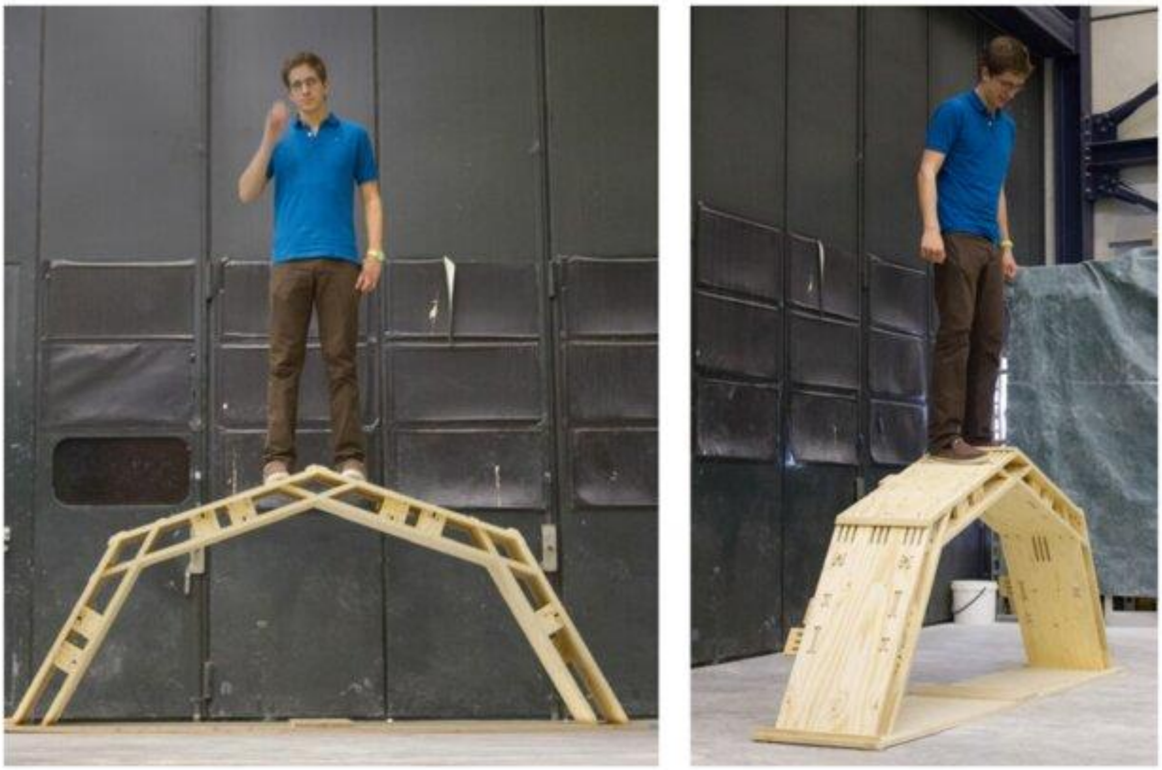


Figure 53: Snap-fit joined arch from Kerto-Q 21 mm panels over a 2.5-meter span
Source: (Robeller et al., 2014)

3.2.4 CNC-routing timber elements

CNC machining is a very accurate subtractive manufacturing method that has been widely used in timber component fabrication, though it is also used for materials like foam, stone, acrylic, PVC, glass and even metals. It employs a rotating cutting tool that removes material along a path predetermined by a computer design to create complex and precise components from various materials, including wood.

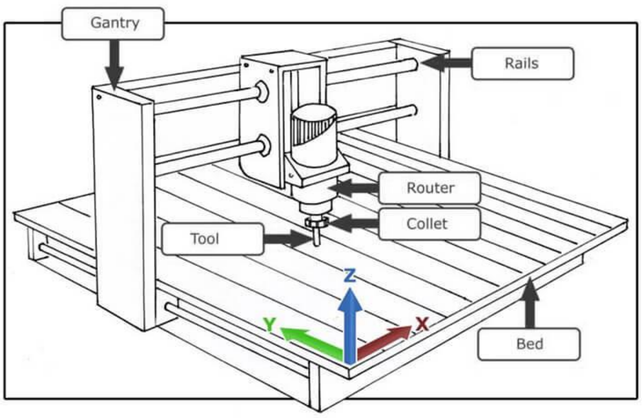


Figure 54: CNC machine set up
Source: Claire (2024)

Within CNC (computer numeric control) machining there are two common types of manufacturing: CNC milling and CNC routing. Both work in almost the same way, capable of precise automated machining however the difference between the two is mainly in application, work bed size, freedom of movement, tolerance and cutting speed. Milling is usually used for more detailed, smaller and precise applications. They also have more options in freedom of movement as CNC-routing often only offers 3 axes of freedom while milling can go up to 5 or even higher. Though these are considered more specialized equipment and aren't always available.

CNC routing also often has a far larger working bed than a mill and can work faster though less precise. Also milling more used for harder materials like metals and plastics while a router is mostly used for softer materials like wood and composites (Claire, 2024; Kief et al., 2022). So, in this case the focus will be on CNC routing as this is a more standard approach for milling larger wooden or composite wood components and even though it might not be as precise, WikiHouseNL (2023) were for example able to keep a precision of 0.01 mm so this might not be too big of a problem.

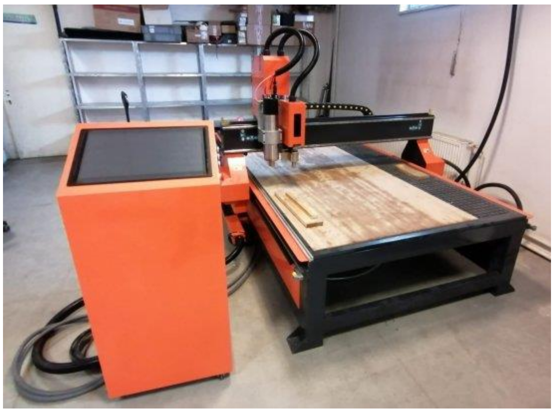


Figure 57: CNC-routing machine
Source: RaptorTechnologies (2021)

Figure 57: CNC-milling machine
Source: Pedregosa (2022)

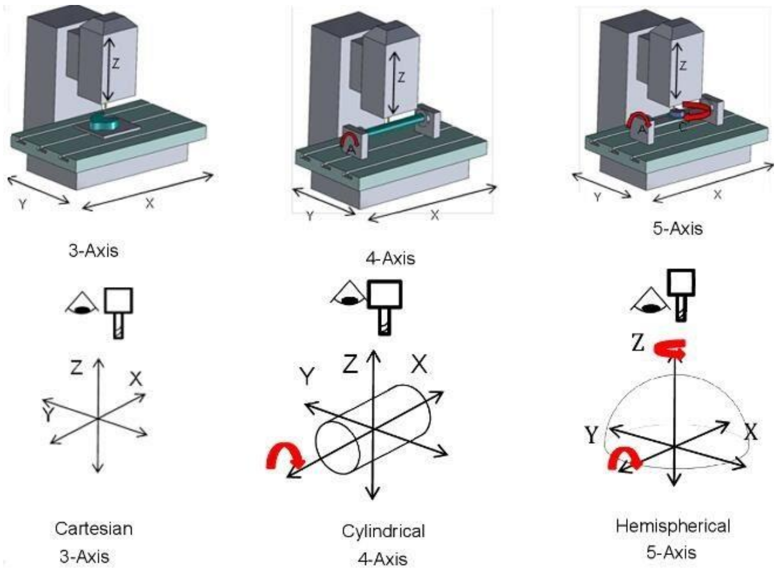


Figure 57: Possible axis of freedom
Source: Stevens (2024)

The entire process from digital model to product can be summarized as the design phase, post-processing and a manufacturing phase. The design phase consists of creating the 3D model in CAD (computer aided design) software like for example Rhino. This model is then saved to standard CAD format files like: .stl, .iges or .step. In post processing the files are then translated to something the CNC machine can read: G-code. This code basically consists of all the instructions for the machine on how and where to cut the material. Things like toolpath, drilling speed depth etc. The manufacturing phase is where the actual cutting happens guided by the G-code and the machine will mill each piece from the chosen material.

There are a few things, however, to consider when designing CNC-routed elements and joinery. Things such as machine type and its limitations, the toolpath, accuracy, and the materials behavior.

Machinery

In the case of the CNC router one of the limitations is that the machine can't fully remake 3D joinery as the 3 axes of freedom does give it 3 options to move but it is limited to only move from top to bottom while drilling which is why it is also often referred to as 2.5D milling instead.

Additionally, there are numerous different drill bits all for different purposes as well as results so choosing one that fits with the material is strong enough to go through the material and the type of edge or finish you want.

Toolpath

Another point to watch out for is the movement of the drill, the toolpath. CNC machinery uses drill bits which are circular and have a radius. So, it will be unable to make straight edges or sharp corners like a traditional joint. Hence why some of these traditional joineries have been adapted to fit with a CNC toolpath with the more rounded edges or notches where the tool will fit. For example, in the figure below where multiple adaptations are made to a traditional joint to be able to be CNC machined.

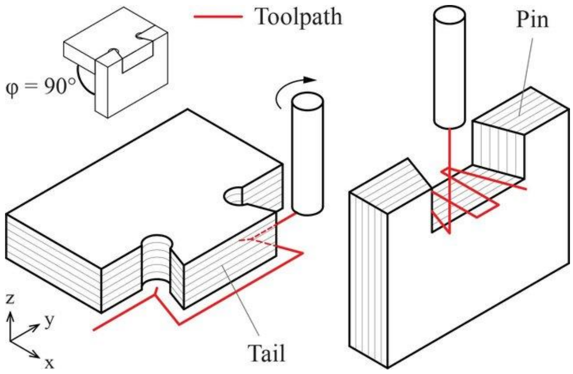
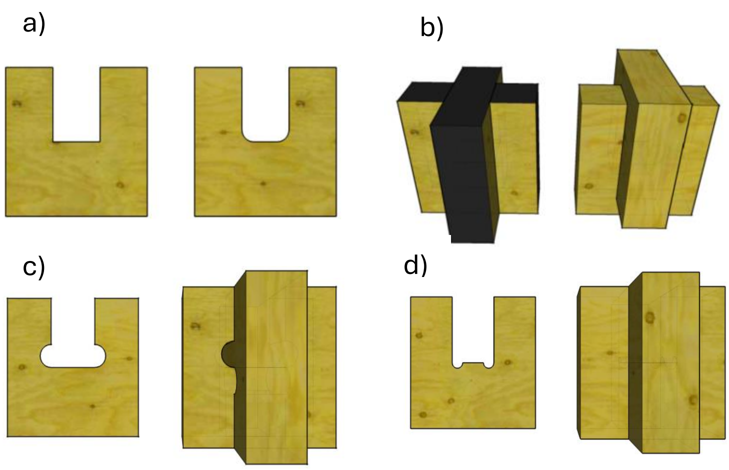


Figure 58: CNC toolpath
Source: Robeller and Weinand (2016)



a) Traditional joint (left) vs CNC machined joint (right) with rounded edges due to tool bit.
b) Normal joint versus joint as seen in a. Due to the rounded edges, it sits higher and does not properly fit all the way down anymore.
c) CNC milled joint with large openings fully fitting
d) CNC milled joint with smaller openings fully fitting

Figure 59: Implications of CNC machining traditional joinery
Source: Ragan (2014)

Nesting

As CNC is a subtractive process there is a lot of waste produced so it is vital to try and keep it to a minimum, by for example trying to keep the tool path as short as possible and nesting the different elements so that the least amount of waste is produced.

Material behavior

Another point to take into consideration is the material behavior. Wood does have the tendency to swell or shrink due to changes in moisture or temperature which can make the joints suddenly not fit anymore. So, it is vital to keep the materials in a controlled environment before manufacturing or designing for these differences.

3.2.5 Example projects using CNC milling and structural composite wood materials

To get a good idea of what is possible and what does and does not work with structural plywood and digital fabrication I also investigated a set of different designs using these principles to get an idea of what to look out for when designing.

Haiti shelter by Pieter Stoutjesdijk (Stoutjesdijk, 2012)

In response to the earthquake in Haiti of 2012 the now Dutch architect Pieter Stoutjesdijk designed an emergency architectural shelter for his master thesis in 2013. The shelter is entirely produced using CNC-routing machines allowing for the precise production of each part from its digital blueprints. Each part can be constructed without using screws or nails by interlocking wood on wood joints and put together in just under 5 hours using basic tools.

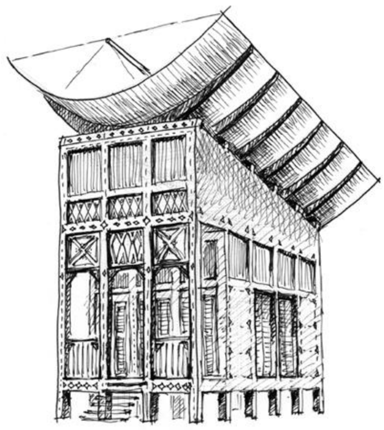


Figure 60: Concept sketch
Source: Stoutjesdijk (2012)

Figure 61: Model of the shelter
Source: Stoutjesdijk (2012)

The plan of the one shown above is 18 square meters and made for a family of 3 or 4 though the design is modular and upgradable if needed. There are two elevated levels where people can sleep separately from the rest of the space.

In terms of materiality, he decided to go for a wood composite material created out of local agricultural residues and made waterproof with nano coating. Next to that he also takes the local context into consideration. Basing the design on vernacular architecture in the area and applying that so the design fits with its context.

Structurally the shelter is composed of columns and rigid walls with a set of different joints each with their own strengths. Mainly using key joints or types of finger and snap fit joints to bring the entire structure together creating an earthquake and storm-resistant shelter.

Figure 62: Types of joints
Source: Stoutjesdijk (2012)

Another large focus in this project, next to the use of combining digital tools and CNC machining, was energy generation and its climate responsive design. For shelter it's important that the indoor environment is comfortable and doesn't overheat or get too cold. As well as the fact that if there is damage to the infrastructure or electrical network incorporating passive climate systems and on-site energy generation becomes highly beneficial. Which is why the roof here is quite high and open at the top to the warm air can rise and escape from the top creating a passive ventilation system. Another detail of the roof is the obvious curvature which was very deliberately done as it mimics a system called CSP (concentrated solar power).

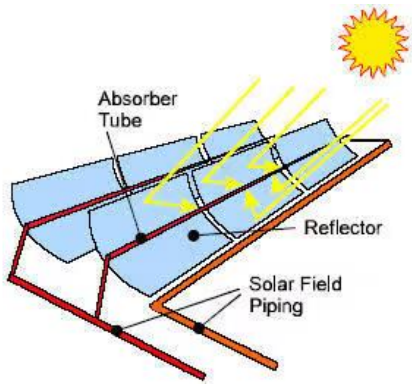


Figure 63: CSP system
Source: SolarPACES (2024)

The type of CSP he incorporated uses a curved mirrored surface to focus sunlight on a pipe that runs through the middle and absorbs the heat, which is then used to generate electricity through a steam generator. The mirrors are mounted on a single axis tracking system that can follow the sun's movements throughout the day, catching as much sunlight as possible (SolarPACES, 2024).

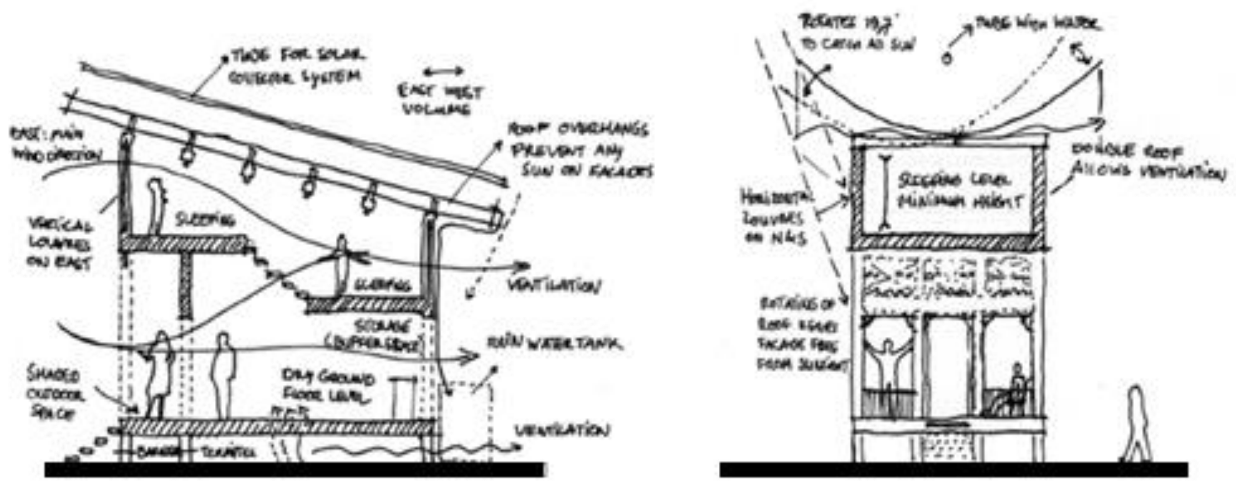


Figure 64: Climate concept
Source: Stoutjesdijk (2012)

Though here, instead of the roof, the concentrator (the rod in the middle) would move so the roof could be fixed to the rest of the structure. Additionally with this system he was able to create not only the opportunity to naturally produce electricity but a water supply as well.

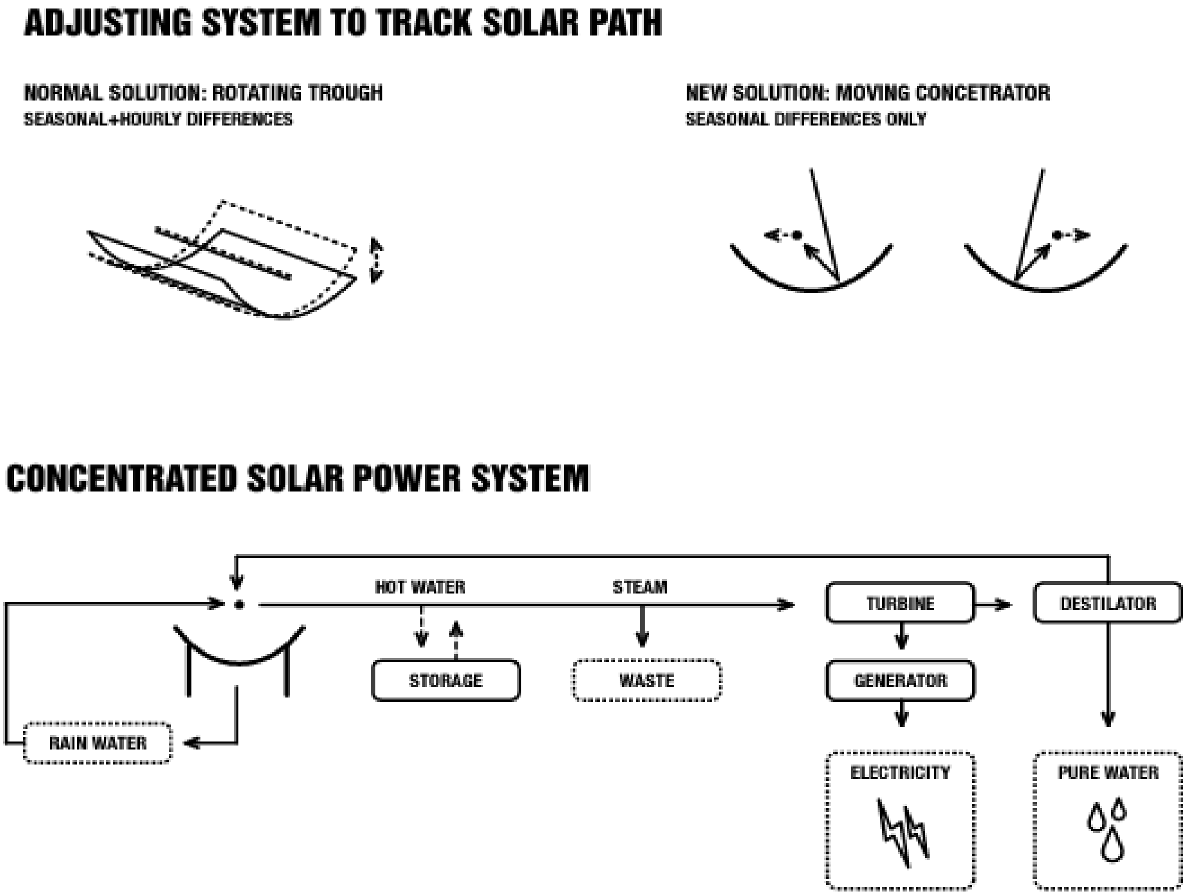


Figure 65: Roof system
Source: Stoutjesdijk (2012)

However, one thing that he himself also names is that the manufacturing costs still need improvement. Stoutjesdijk estimates that it would cost around 10.000 dollars in developing countries and even twice as much for developed countries like the US to manufacture the shelter.

IMBY Building Kit by Adriano Pupilli (Pupilli, 2023):
'IMBY' stands for In My Back Yard as well as for the modular building system Adriano Pupilli designed. It focusses on a simple and flexible construction that can be erected by anyone 'in their own back yard'. It uses CNC to produce precise cut parts using adapted versions of the traditional wedged mortise and tenon joints.

Figure 67: IMBY located in Manyana on the NSW South Coast
Source: Pupilli (2023)

Figure 66: A wedged mortise and tenon joint
Source: Pupilli (2023)

They use standard plywood sheets to create all their elements and then flatpack them in a kit to be shipped off to site. Users on their webpage can customize various elements such as widow types, insulation, façade materials and the length of the structure. And since all joints are friction fit the structure is easily erected as well as dismantled.

Structurally the building is made up of a set of portal frames. This allows people to easily upgrade and expand the structure simply by adding a few frames. However, the portal itself is not delivered in a larger variant so it can only be elongated.

Figure 69: Construction of the IMBY kit by 2 people
Source: (Pupilli, 2023)

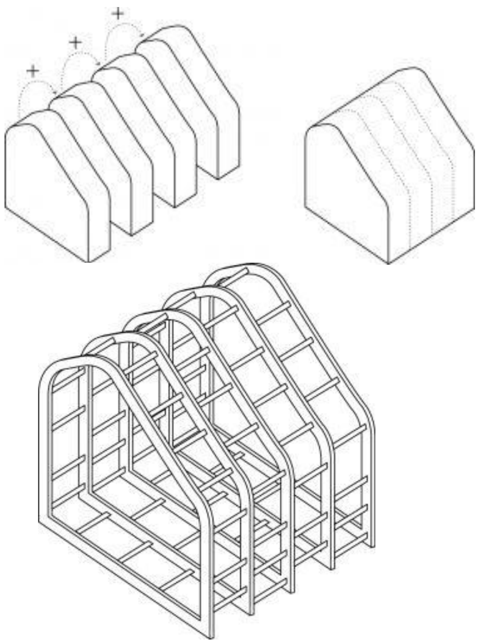


Figure 68: Construction principal
Source: Pupilli (2023)

WikiHouse by Alastair Parvin (WikiHouse, 2024; WikiHouseNL, 2023):
WikiHouse makes use of an open-source concept. They created an online platform where people can with their library of building blocks design their own house within different 3D modeling software like Sketchup, Rhino, AutoCAD, Blender or IFC. It enables communities themselves to design, customize and construct their own homes by using CNC-fabricated components. Their goal to create 'architecture for people by people'. The platform not only provides the people with designing their homes digitally but also connects all people involved in the process of building a house. They offer services such as reaching out to architects, project planners, digital fabrication factories and even building crews. Making sure the house will adhere to the national regulations and is structurally sound and approachable for anyone.

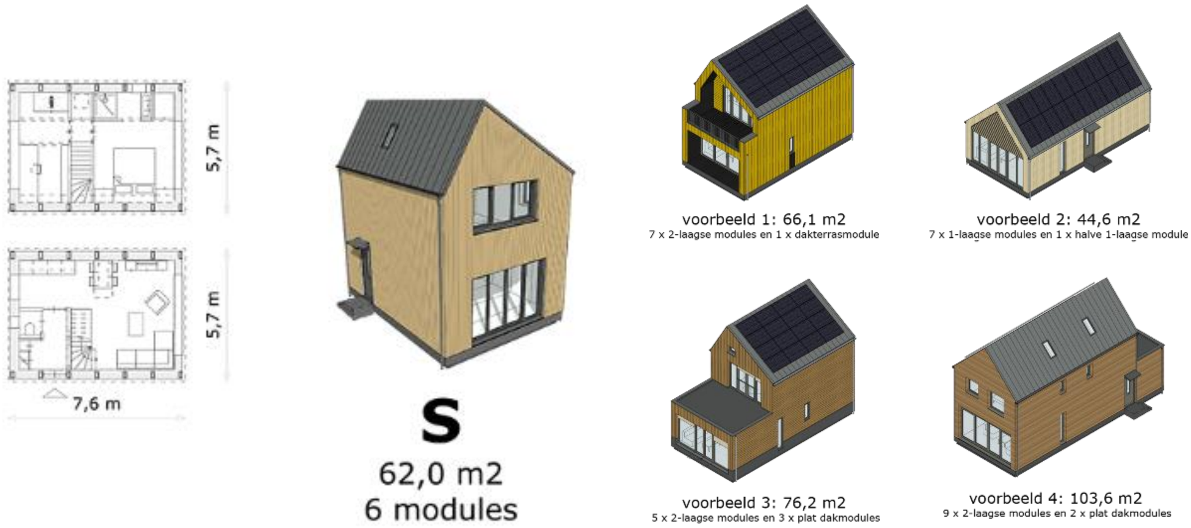


Figure 70: Standard units from the Dutch database
Source: WikiHouseNL (2023)

The process starts with people designing their home with the block or the Dutch branch even provides a way for users to share their designs and take that as a start as well as giving the user the option to choose a standard design. They are then translated into the necessary files for production and flat packed and shipped to site, though they are working on giving people the opportunity to also fabricate the elements on site.

The structure relies on mostly friction-fit interlocking peg in slot joints and tries to stay away from fasteners as much as possible. They use either plywood or OSB, whatever is locally available or cheapest. Here the structure is based on a double layered frame/portal system.

One of the things that I found nice to take away from the design and everything I read about the system of WikiHouse is that they designed it in such a way that they make sure joints never fit 'wrong'. To either make them only fit in one way or it doesn't matter if it is backwards or not.

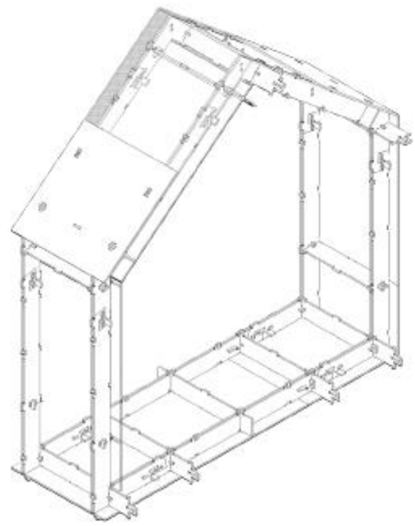


Figure 71: Structural principal of Wikihouse
Source: WikiHouse (2024)

One of the things that, however, still would need some improvement here is the nesting of the elements. Below is shown one of the documents needed for the CNC fabrication and as can be seen there is quite a lot of space between members and a lot of space on the sheet that is not used for anything and thus seen as waste.

Another thing though is in terms of the building itself as the concept is more guided towards permanent solutions. However, the use of an open library where everyone can contribute their ideas to being able to improve upon the design is a good concept to democratize it.

For an overview of all the designs and their pros and cons see the Appendix 1.1

4. Concept design of a temporary shelter

4.1 Context

As already mentioned before, context is an important subject to consider ensuring that the structure meets the needs of its users, but also to adhere to local regulations and consider factors like geography, climate, social and cultural factors regulations, available resources and the specific circumstances of a disaster or situation for when shelter is needed. Each can create different outcomes for similar problems. So, to be able to meet the need of any disaster situation we first need to look at the context and what has influence on the design. The application eventually should be universally applicable but for the sake of time for this thesis, I have chosen to look at 2 locations: Delft in the Netherlands and Istanbul in Türkiye.

4.1.1 Netherlands

Geography

The Netherlands is a small country located in northwestern Europe, bordered by Germany to the east, Belgium to the south, and the North Sea to the northwest. The terrain is defined by its geography as a river delta shaped by the Rhine, Meuse, and Scheldt rivers and predominantly flat. The highest point reaching just 322.5 meters above sea level. In fact, 26% of the land lies below sea level and much of it has been reclaimed from wetlands and shallow seas by an extensive polder system. This centuries-long reclamation effort has allowed for agricultural and urban development but also underscores the country’s vulnerability to water-related challenges.

As flooding remains a significant concern, particularly during heavy rainfall, when rivers overflow and inundate low-lying areas. The Netherlands has implemented advanced water management systems, including dikes, programs such as "Room for the River," which creates natural floodplains and adjusts dike placements to manage river overflows, canals, and the world-renowned Delta Works, to protect against storm surges and rising waters. However, localized flooding still occurs, highlighting the need for elevated building designs and robust flood barriers.

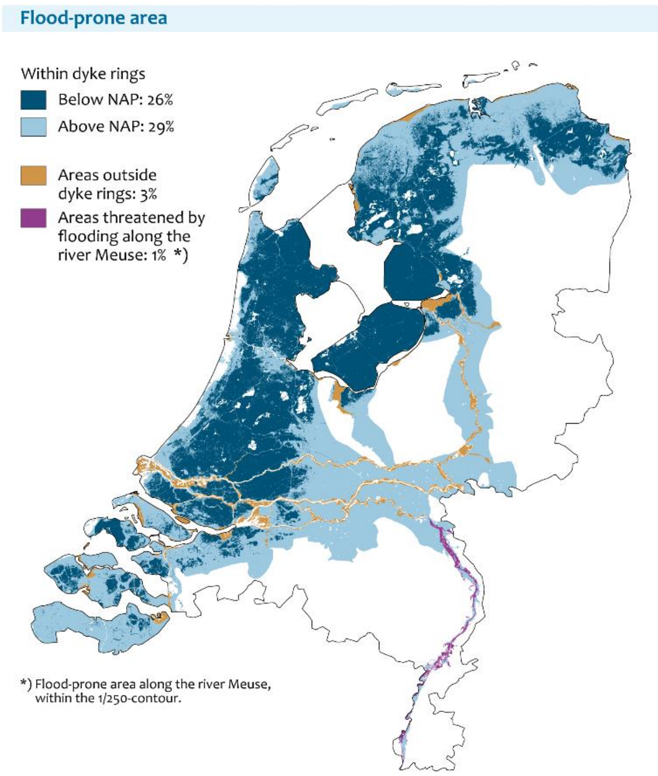


Figure 72: Flood prone areas in the Netherlands
Source: PBL (2007)

Additionally, the country’s deltaic environment means much of the soil consists of clay and peat, which is prone to subsidence, a slow sinking of the ground. To counter this, foundations are typically anchored deep into firmer sandy layers, though inadequate construction can lead to structural issues. This is most evident in cities like Amsterdam but affects areas throughout the Netherlands.

Climate

The Netherlands in terms of climate can be categorized as a temperate maritime climate, influenced primarily by its proximity to the North Sea. This climatic zone brings moderate temperatures, consistent rainfall throughout the year, and relatively high humidity levels.

This includes mild to cool winters and warm summers, with average temperatures ranging from 6°C in winter to around 22°C in summer. Winters are typically moderate compared to other northern European countries, though occasional cold snaps can occur due to easterly winds bringing continental air from Central Europe. Summers are generally mild with few extreme heat events, although occasional heatwaves have become more frequent in recent years due to climate change.

Rainfall in the Netherlands is relatively evenly distributed throughout the year, with no distinct dry or wet season. As we take a look at Delft for example, year-round an average of around 600 mm of precipitation falls each month. Rain often falls as light, steady drizzle rather than heavy downpours, though occasional storms can occur. Snowfall is rare and typically light due to the maritime influence, with occasional brief periods of frost in winter (Klimaatinfo, 2025).

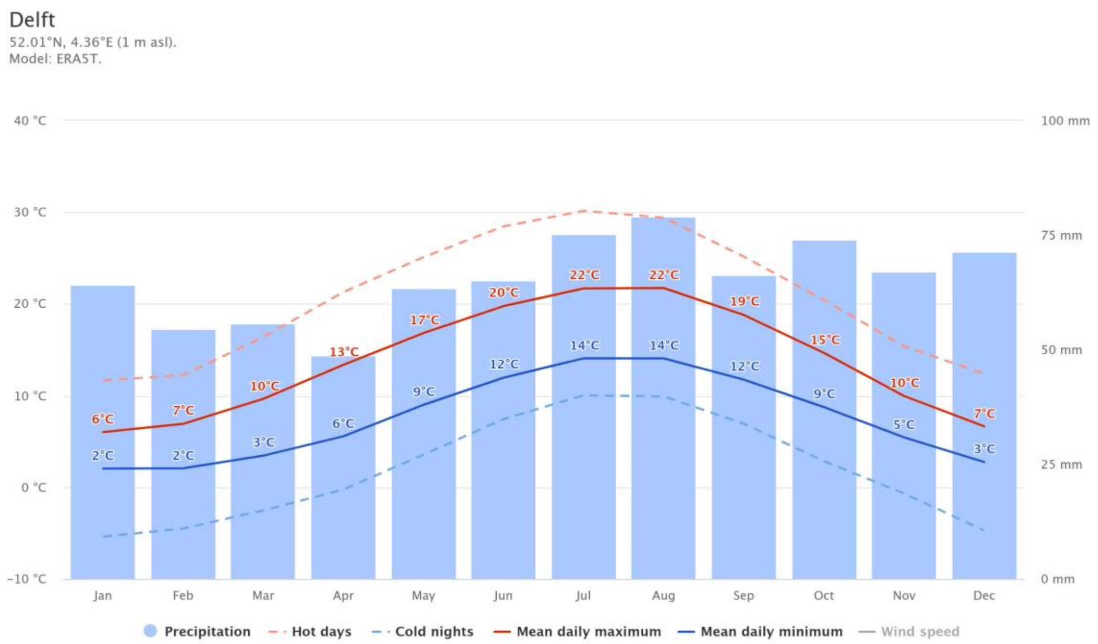


Figure 73: Average temperatures and precipitation Delft
Source: MeteoBlue (2024a)

The Netherlands is also known for its windy conditions, especially during autumn and winter. Wind speeds often range between 10-50 km/h, with stronger gusts during seasonal storms. The flat landscape and lack of natural barriers contribute to the wind's strength, making wind-resistant architectural design essential features in urban planning. This is much the same as we look closely at Delft where on average the wind sits around the 20km/h mark mainly from the southwest (Klimaatinfo, 2025; MeteoBlue, 2024a).

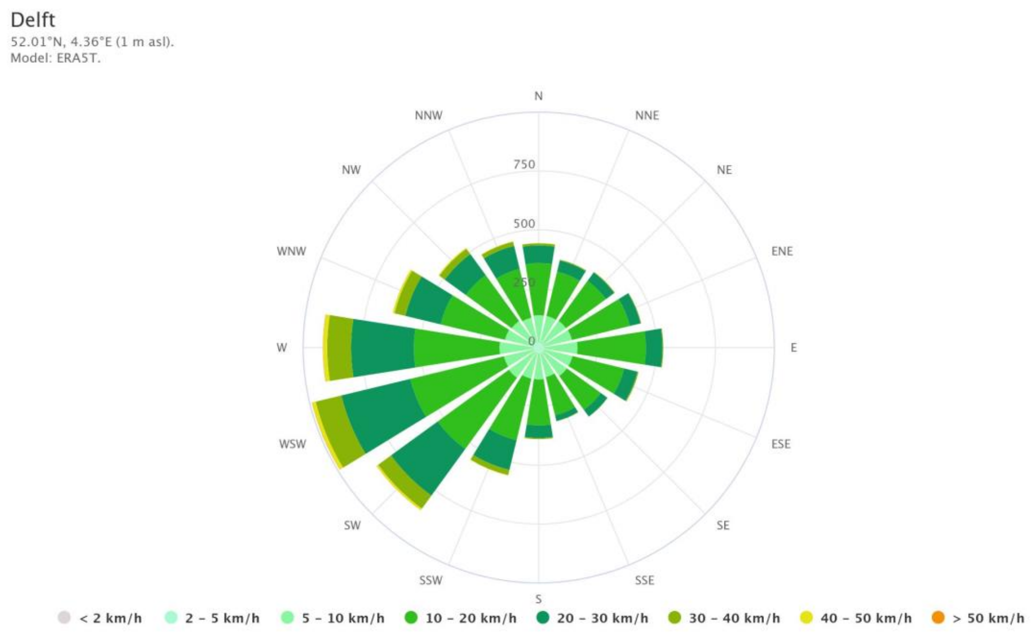


Figure 74: Windspeeds and direction in Delft
Source: MeteoBlue (2024a)

Roof design is crucial for managing wind forces, as the pitch and shape significantly affect how wind interacts with a building. A low roof pitch can create negative pressure (underpressure) on the windward side, potentially lifting the roof structure due to suction forces. Conversely, a high roof pitch can result in overpressure, where wind pushes against the roof surface with increased force, making it more susceptible to damage during high wind events.

For optimal wind stability, a roof pitch of around 30 degrees is generally recommended. This angle offers a balance, reducing both underpressure and overpressure by allowing wind to flow more smoothly over the structure while still shedding wind effectively (Allstate, 2024).

Figure 75: Optimal roof pitch
Source: mypdh (2024)

Among common roof types used here in the Netherlands, the hip roof is often considered the most wind-resistant due to its sloped surfaces on all sides, which help deflect wind and reduce pressure buildup. Gable roofs, while common, can be less wind resistant as their vertical end walls (gable ends) create flat surfaces that can catch wind more easily. However, orienting the sloped sides of a gable roof toward the prevailing wind direction helps mitigate this effect by directing airflow more smoothly over the structure and minimizing wind pressure on the gable ends.

Additionally due to its proximity to the North Sea, the Netherlands experiences consistently high humidity levels, often ranging between 75% and 85%. This elevated humidity can contribute to damp conditions and poses challenges for both building maintenance and personal comfort. Proper ventilation and moisture control are key considerations in Dutch architecture to prevent mold growth and structural damage especially when designing in wood as mentioned before from the literature study (WeatherAndClimate, 2020).

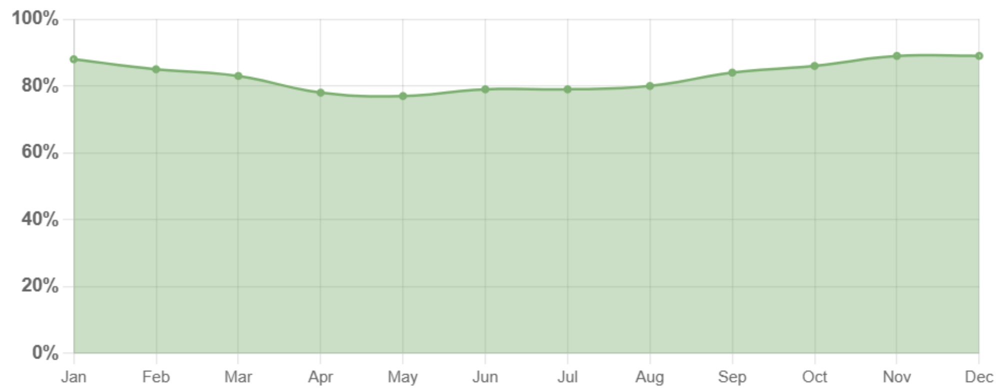


Figure 76: Relative humidity in Delft
Source: WeatherAndClimate (2020)

With cold winters, mild summers, limited sunlight, strong winds, and high humidity, building design in the Netherlands should prioritize strategies for heat retention, wind resilience, and effective ventilation to maintain a comfortable indoor climate. In disaster shelter design, these challenges become even more complex, as damage to infrastructure often leaves shelters off-grid with no access to conventional heating or cooling systems. This situation makes it essential to rely on passive design strategies that can regulate indoor comfort using natural methods, such as strategic insulation, wind protection, and natural airflow management.

One effective passive design strategy commonly used in the Netherlands is the incorporation of overhangs, which help regulate solar gain throughout the year. During summer, when the sun's angle is higher, overhangs block excessive direct sunlight, preventing overheating inside the shelter. In contrast, during winter, when the sun sits lower in the sky, the overhangs allow sunlight to penetrate deeper into the living space, providing natural warmth and reducing the need for additional heating.

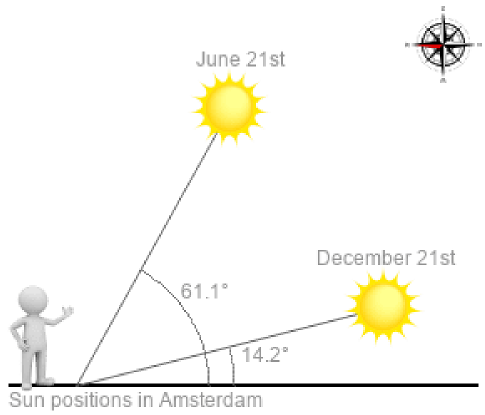


Figure 77: The sun's angle difference June vs December
Source: (Worlddata, 2025)

To maximize the effectiveness of this strategy, building orientation plays a crucial role. The most optimal approach is to orient the façade with the largest window area and greatest potential for heat gain toward the south. This allows the structure to capture the limited sunlight available during the winter months while minimizing heat loss on the cooler, shaded northern side. This strategic positioning works most effectively when paired with thermal mass materials, such as concrete or brick, which absorb heat during the day and release it gradually as temperatures drop at night, further enhancing indoor comfort without reliance on mechanical systems.

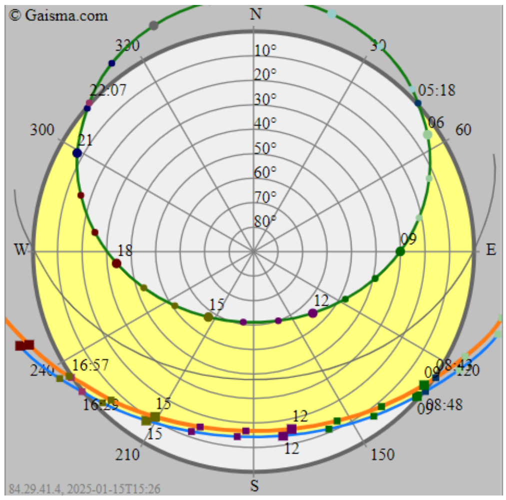


Figure 78: Sun path in the Netherlands Amsterdam
Source: Gaisma (2005a)

Ventilation is equally critical in maintaining indoor air quality and temperature balance. Cross-ventilation, achieved by positioning operable windows on opposite sides of the shelter, encourages natural airflow, helping to cool the space during the summer and reduce humidity levels, which can be high in maritime climates like the Netherlands (Clarke, 2020).

To sum it up, a few passive strategies to consider while for climate design in the Netherlands are:

- Adding overhang, to keep the sun out during the summer and let it in during the winter.
- Outlets for warm air in the roof for the warmer summers.
- Building orientation, so that most is made from the warmth of the sun while not overheating, in this case facing south.
- Cross ventilation

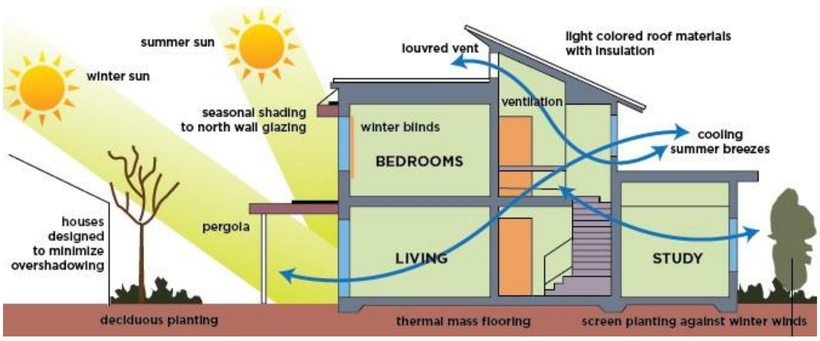


Figure 80: Passive climate strategy
Source: Trium (2023)

Social cultural factors
The average household size in the Netherlands has been steadily decreasing, with the figure dropping from 2.23 in 2009 to 2.11 in 2024 (CBS, 2024; Statista, 2024b)

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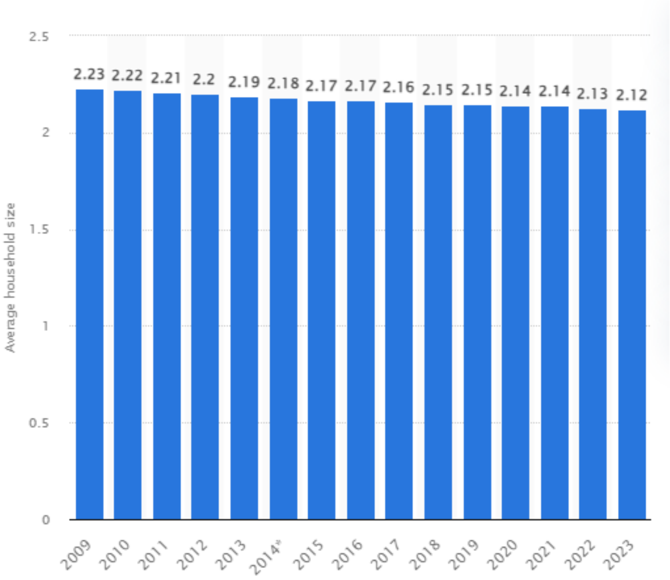

Figure 81: Average household size Netherlands
Source: (Statista, 2024b)

This trend reflects an aging population, an increase in single-person households, and changing family dynamics (Capital, 2024; CBS, 2024). As a result, building designs often prioritize flexible smaller living spaces such as studio apartments and compact homes. Take, for example, the student housing scattered across Delft: small, one-room apartments often paired with shared spaces like living areas, kitchens, and bathrooms. These setups are tailored to the dynamic nature of student life, where new residents arrive each academic year and move on once they complete their studies.

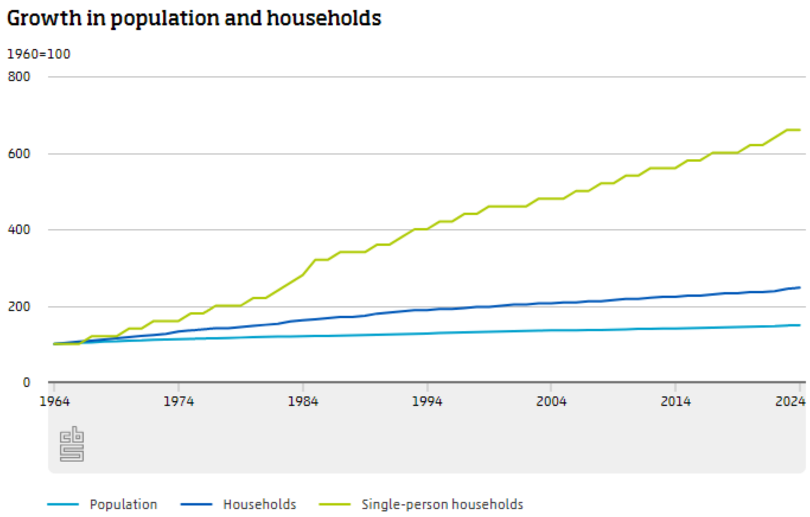

Figure 82: Increase in single person households
Source:(CBS, 2024)

The emphasis on compact living aligns with the Netherlands' spatial constraints. As a small country with limited available land and high population density, efficient land use is a necessity. As per square kilometer there are 436 people living in that area, listed 33rd in the world's ranking Hence why land use is also quite strictly planned (Wikipedia, 2023). Modern architectural designs further emphasize simplicity and functionality of its architecture, consistent with the cultural value of "doe maar normal je bent al gek genoeg" (just act normal, you're crazy enough yourself), which encourages modesty and pragmatism.

Socially the Netherlands is renowned for its multicultural society, with a significant portion of the population having a migration background. This cultural diversity profoundly influences building design, fostering the creation of inclusive spaces that accommodate various cultural practices and preferences for communal living.

Resources

In terms of building materials, the Netherlands has traditionally relied heavily on bricks. This preference is deeply rooted in the country's geography, as abundant clay deposits from nearby rivers and waterways have historically provided a readily available resource for brick production. Though currently concrete is the largest competitor on the field is concrete of which 13.000 kton of material is used in construction (EIB & Metabolic, 2020).

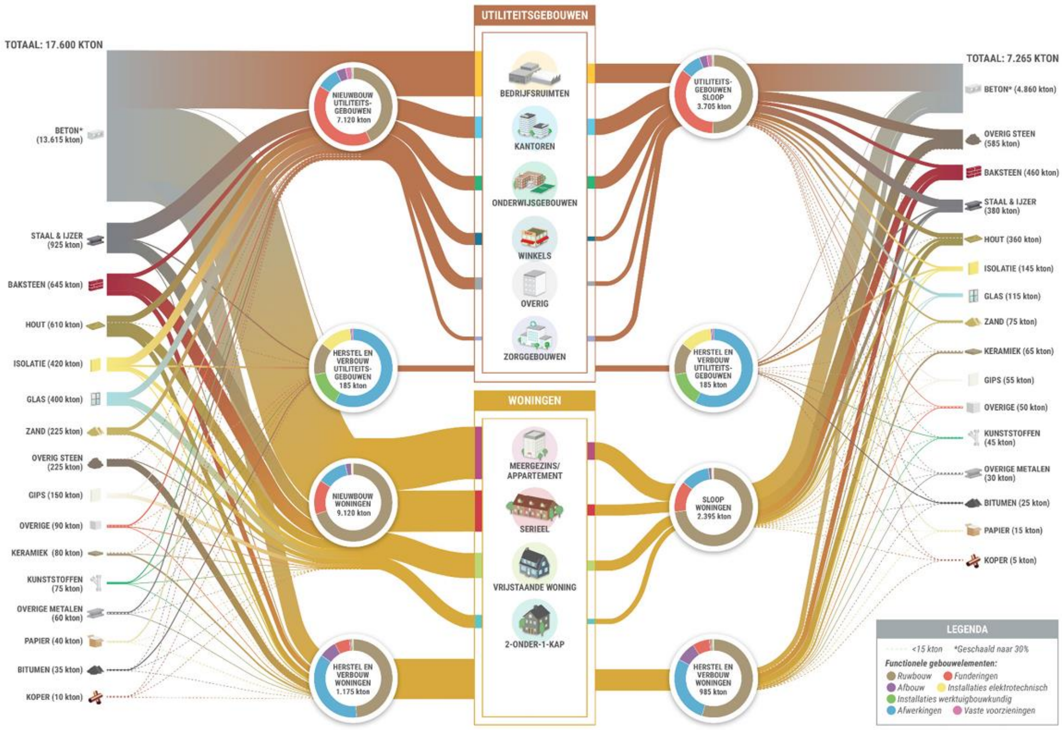

Figure 83: Material streams in the building environment
Source: (EIB & Metabolic, 2020)

Wood, on the other hand, is less commonly used as a primary construction material for homes in the Netherlands. This is partly due to the availability of other materials and a long-standing tradition of masonry construction as well as the limited supply. However, in recent years, wood has seen a resurgence in interest, particularly in sustainable and modular building designs, as it is a renewable resource with a lower carbon footprint compared to concrete and brick (Fraantje, 2023).

The Netherlands produces approximately 1.3 million m^3 of workwood annually, with 918,000 m^3 sourced from domestic forests, of which 90% is industrial roundwood. Dutch forests, covering 365,500 hectares, contribute mainly coniferous species like Douglas fir, larch, and Scots pine, which make up 73% of the production. However, the country heavily relies on imports, bringing in 7.3 million m^3 of roundwood, sawn timber, and panel materials in 2018, with 89% coming from European sources such as Germany (24%), Belgium (16%), and Sweden (14%). Additional imports of tropical hardwoods and panel materials come from Southeast Asia (3.6%) and South America (3.1%), including radiata pine from Chile and plantation wood from Asia. This also means that with a limited domestic supply most plate materials like plywood and OSB are imported and rely on the international market (Oldenburger et al., 2020).

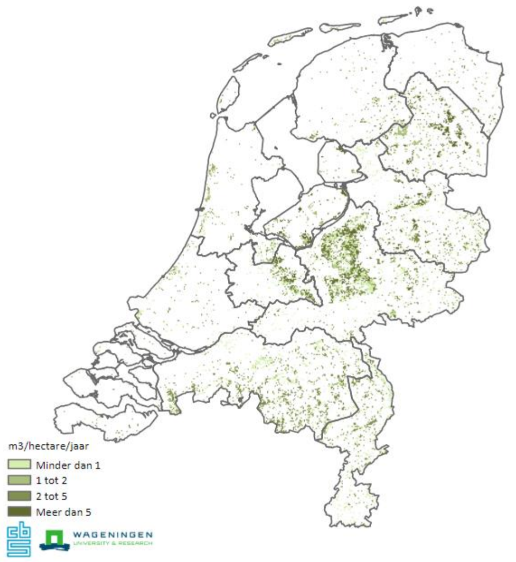

Figure 84: Wood production for industrial use
Source: Wageningen Universiteit (2018)

In terms of sustainability of these materials, the Netherlands emphasizes certified sustainable wood sourcing, particularly from tropical regions, reflecting a commitment to ethical and ecological practices. One of these certifications being FSC (Foresty stewardship council) who oversees the production, distribution and use of wood materials in the EU and make sure everything is handled properly with sustainability and circularity in mind (FSC, 2024).

Larger distributors like Pont Meyer and Shiho are key suppliers of FSC-certified plywood and other building materials across the Netherlands. Well-known hardware stores such as Hornbach, Praxis, and Gamma also offer certified plywood options, although their stock is more suited for individual projects, personal construction, repairs, or additions, rather than the large quantities required for constructing a large quantity of shelters after disaster.

As for the necessary space and machinery for the production of the components needed for this concept there are quite a few Makerspaces and or similar environments where guided DIY incorporating CNC machining is available (see Figure 85). In Delft I found two, Makerspace Delft and the Makerzone at the campus.

However, what I did realize was, was that many of these makerspaces are equipped or set up for quick prototyping and smaller more detailed projects work rather than large-scale construction projects. A review of the FabLabs network reveals that only a handful of these spaces around the world house machines meet the scale and specifications required.

Figure 85: Fablabs in the Netherlands
Source: Fablab (2024)

Figure 86: Larger CNC machine and available locations
Source: Fablab (2024)

However, a solution would be to instead use the services of private companies and specialized organizations in the Netherlands do offer large-scale CNC routing services and could provide essential support during disaster scenarios. These companies, often having their own stock of supplies and network of suppliers, can bridge the gap by delivering both the tools and the materials needed to fabricate building components, even in challenging circumstances.

Then you would not have to look far as in the surrounding areas of Delft like Rotterdam and The Hague there were plenty of options.

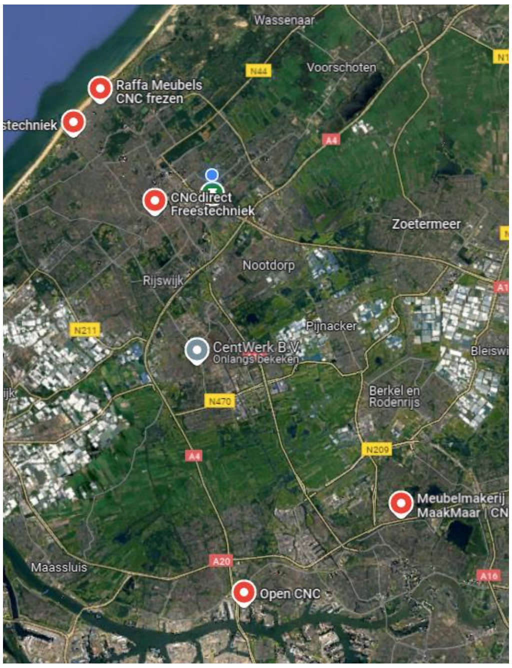

Figure 87: Locations of companies providing large scale CNC routing services
Source: Google Maps (2024)

For this project though, I went out from the specifications of the 3-axis CNC router available here at the University in the CAMlab. Mainly to use for the 1:1 models of the of the CNC routed connections as well as having a general idea of what parameters to take into consideration when designing the application. In this case they have ISEL Flatcom milling machine with 3-axis and a maximum working area of 3200mm x 1510mm with a 300mm working depth and drill bits with a diameter of 10mm (CAMlab, 2024).

In terms of what people generally could have available as budget to realize a project like this, the Netherlands benefits from a relatively high standard of living, with an average household of approximately 48,400 euro per year. Which would amount to about 4.000 euro a month (Statista, 2024a).

The forest wood and products organization estimated that for a simple 2 story detached house someone would need about 14.58 cubic meters of wood (FWPA, 2021). The price of plywood and OSB depends on the quality type or wood and market conditions. The average import price for Plywood in the Netherlands was 198.04 euro per cubic meter in 2023. Which would mean the material costs would be about 2892.68 euro for the wooden construction. For a cheaper option OSB can be used as this is at least half the price, (102.90 euro) which would amount to 1500.28 euro (IndexBox, 2023b). However, OSB does perform less well than plywood in terms of strength, moisture resistance, and long-term stability; plywood is lighter, easier to modify, has a smoother appearance, and is better suited for projects requiring durability, aesthetics, or performance in fluctuating climates. Though both options seem to be affordable for the Dutch in case of an emergency.

Regulations and Standards

Shelter design in the Netherlands must comply with Bouwbesluit (Building Decree), which governs safety, health, usability, energy efficiency, and environmental sustainability in all structures. This includes specific requirements for structural stability, fire safety, ventilation, and insulation, ensuring shelters are habitable and safe. Additionally, should also uphold to the Eurocode, which in case of the Netherlands are coded as NEN norms.

In terms of sustainability there are also stringent energy efficiency regulations, such as the current BENG (bijna energie neurtale gebouwen: almost energy neutral buildings) based on NTA 8800 that replaced the from Energy Performance Coefficient (EPC) from 2012 based on NEN7120 in 2021, ensure that homes are equipped with features like solar panels, green roofs, and high-performance insulation (Rijksoverheid, 2024)

Build environment and Urban context

Zooming in on the built environment of Delft, this section explores key aspects such as building typologies, architectural layouts, and material usage, providing insight into how these elements reflect the cultural, historical, and functional context of the area.

Figure 88: Map of Delft Netherlands
Source: Google Maps (2024)

Delft is a smaller city located in the Randstad region of western Netherlands, sits between major urban centers like Rotterdam and The Hague Because of the presence of the University, Delft is often referred to as a "student city" housing many of the attendees in the surrounding areas. Though it also has a rich historical background as a major hub for trade and industry. During the Dutch Golden Age, Delft flourished as a center for commerce, particularly known for its production of the world-famous Delftware ceramics, as well as its strategic location along trade routes connected to nearby cities like Rotterdam and The Hague. The city's canals, originally constructed for water management and defense, played a key role in facilitating the transport of goods, contributing to its prosperity. Though now they are mostly used for recreational purposes but the history of the place is still best reflected in the buildings in the city center.

The area can be divided into roughly 4 areas: the historic city center, residential areas, industry around the Schie and the campus of the University.

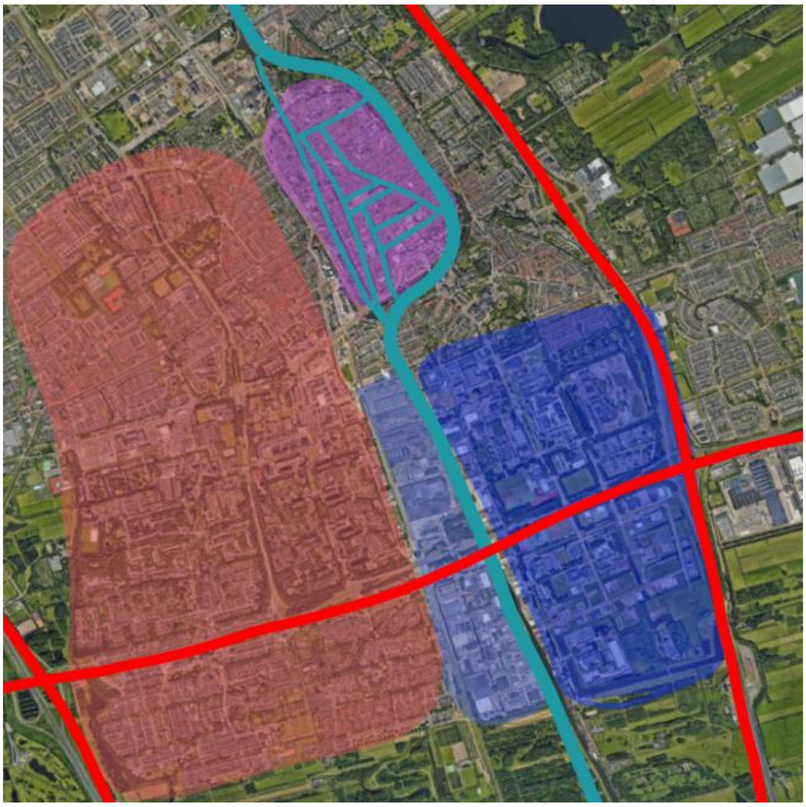

Figure 89: Zones in Delft
Source: Own drawing, satellite image from
Google Maps (2024)

Main waterways
Main roads
Residential area
Schieoevers (industrial are)
TU delft
Old city center

The center primarily consists of traditional Dutch "herenhuizen" or porch houses, which are narrow, deep, and often three to four stories high. These homes are characterized by stepped gable facades and large windows, a style typical of the 17th and 18th centuries. Built in rows along the city's scenic canals and cobblestone streets.

Figure 90: Herenhuizen in Delft
Source: Digikhmer (2024)

In the areas surrounding Delft’s historic town center, a mix of midrise and low-rise residential buildings is present, including gallery flats with external access galleries and two to three-story family homes, often in terraced or semi-detached layouts.

Figure 91: Residential buildings and apartments in Delft
Source: Google Maps (2024)

The gallery flats or apartments/ studios for students are often set up in larger buildings with either a common outdoor area in a courtyard or large open space around the flats. Most family houses are terraced and have an open semiprivate front garden and a private back garden. The ones that are close together are the Herenhuizen who are smaller and tall with different heights layouts and a more organic setup following the water’s edges.

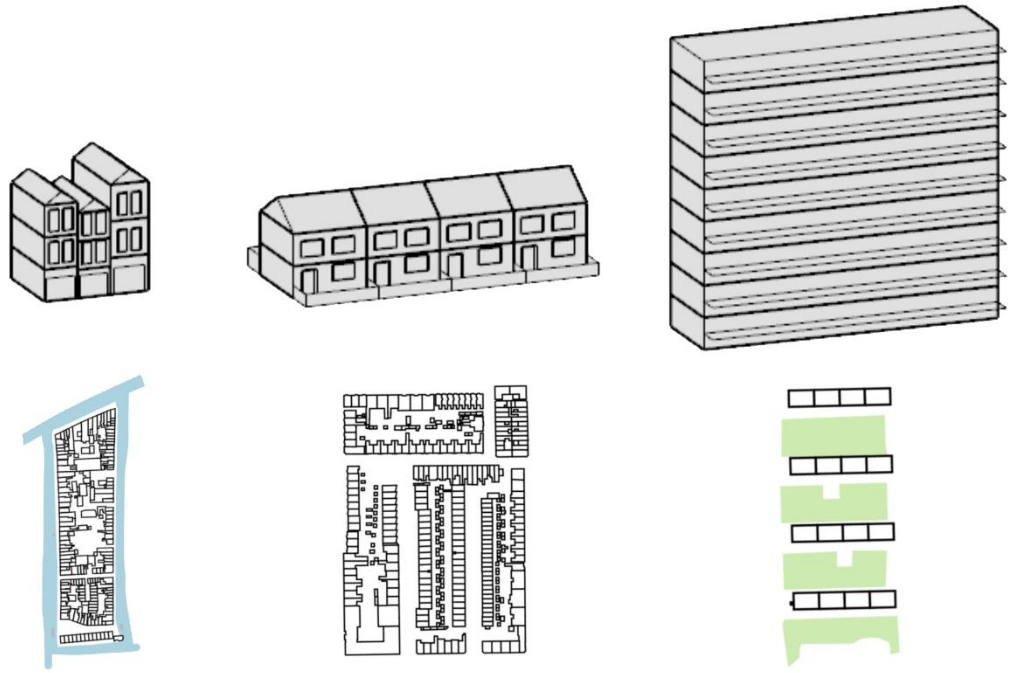

Figure 93: Overview of typologies and urban layouts
Source: Own drawings

In the southern part of Delft, on both sides of the Schie canal, lies a prominent industrial area that remains actively in use today. This zone is characterized by a concentration of warehouses, manufacturing plants, and other large industrial buildings, many of which are dedicated to logistics, production, and storage.

Figure 92: Delft Schie industrial area
Source: Google Maps (2024)

To the east of the industrial zone along the Schie lies the expansive campus of Delft University of Technology (TU Delft). Covering a significant area, the campus hosts a wide array of academic and research facilities, including modern faculty buildings, laboratories, and innovation hubs. The architecture varies from contemporary glass and steel structures to repurposed older buildings.

Figure 94: TU Delft campus
Source: Menacoo (2013)

Zooming in further, the specific location for the case study will be The Green Village in Delft, located at latitude 51.996384 and longitude 4.377818. This unique site, situated within the TU Delft campus, serves as a living laboratory where students, particularly from the Faculty of Architecture, can test and experiment with their design concepts on a full 1:1 scale. The area is surrounded by trees and greenery and accessible through a bridge from the main road.

Figure 95: Delft green village
Source: TUDelft (2024)

4.1.3 Türkiye

Geography

Türkiye is a vast and diverse country, spanning two continents and encompassing a wide range of geographical features, climates, and urban centers. While this diversity presents numerous areas of interest, the scale of the nation makes it challenging to address every aspect comprehensively. Therefore, the focus here will be on Istanbul, the country's largest and most populous city, as it serves as a microcosm of many of the challenges and opportunities faced by Türkiye as a whole.

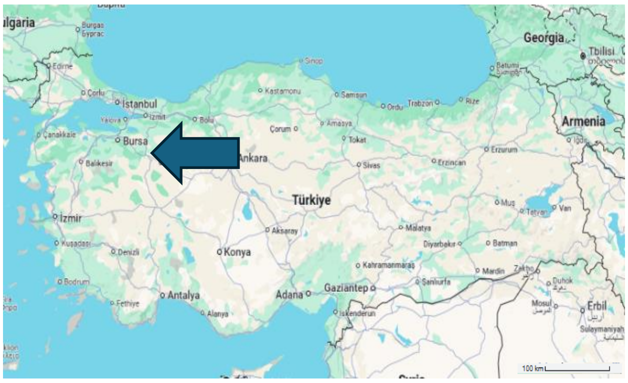

Figure 97: Map of Türkiye
Source: Google Maps (2024)

Figure 96: Map of Istanbul
Source: Google Maps (2024)

Istanbul, the biggest city of Türkiye, has a rich history that dates back all the way to 667 B.C. Its strategic location, nestled between the Black Sea and the Sea of Marmara, and divided by the Bosporus Strait into a European and Asian part, along with the Golden Horn estuary, has profoundly shaped the landscape and established it as a highly coveted area throughout history. Originally established as Byzantium under Greek influence, the city served as an important city-state. In 330 A.D., it became the capital of the Roman Empire under Emperor Constantine, who renamed it Constantinople. In 1453, it was conquered by the Ottomans and served as the heart of their empire for centuries. While officially renamed Istanbul in 1923 with the establishment of the Turkish Republic, the name had already been in common use for centuries, evolving from the Greek phrase "is tin poli" ("in the city") into its modern form (Wikipedia, 2024).

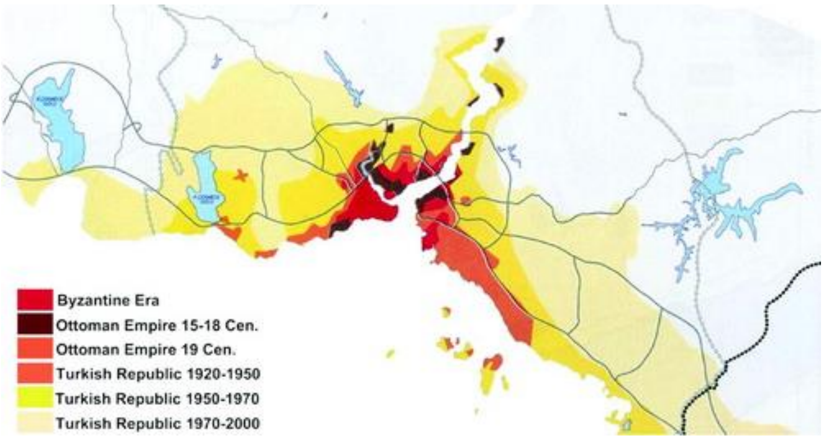

Figure 98: Growth of the city over the years
Source: Enlil (2011)

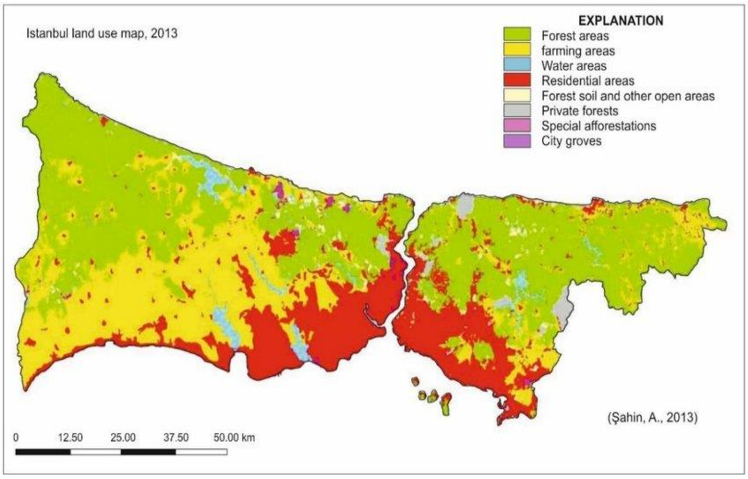

Figure 99: Land use
Source: Kam and Yümün (2021)

The city's topography is characterized by a series of hills and valleys, with elevations ranging from sea level along the coastlines to higher terrains inland. Despite the common reference to Istanbul's "seven hills," based on the hills that Constantinople was built on top of, the city encompasses more than 50 hills within its boundaries, with Aydos Hill being the tallest at 537 meters. Most of the city scape however lies along the Marmara Sea and the Bosporus straight grown from the oldest settlements and empires along these areas.

One of the primary hazards in the city are earthquakes, a risk that affects the entire country of Türkiye as it is one of the most seismically active regions in the world, owing to the tectonic activity caused by the northward movement of the Arabian and African plates against the relatively stationary Eurasian plate. This interaction has created a wedged continental crust encompassing much of the country. The majority of seismic activity occurs along two major fault systems: the North Anatolian Fault, which extends approximately 1,500 kilometers from west to east, and the East Anatolian Fault, spanning 550 kilometers in the eastern region (Gökkaya, 2016). The NOAA (national centers for environmental information) listed 63 significant earthquakes (a magnitude above 5.0 resulting in fatality) between 1950 and 2023. The latest being the 2023 earthquake in the south near Gaziantep, with a 7.8 on the scale of Richter with at least 30000 aftershocks in the months that followed.

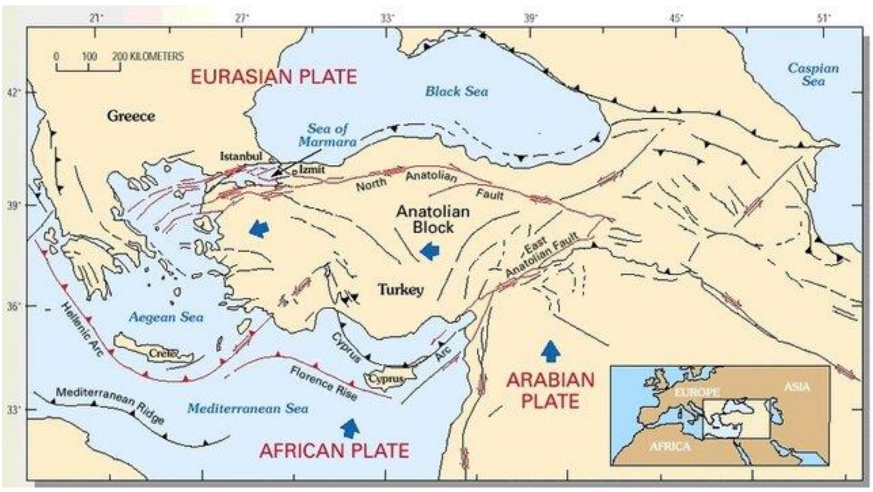

Figure 100: Tectonic map of Türkiye
Source: Gökkaya (2016)

Istanbul itself is mainly affected by this because of its proximity to the North Anatolian Fault Zone in the Marmara Sea. For example, one of the more significant quakes in the past was the one in Izmit (a neighboring city) in1999. The earthquake had a scale of richer of 7.6 and caused more than 70,000 houses to be destroyed or damaged and 17,000 people lost their lives. This was not only due to horizontal ground displacements but also due to slumping, landslides as well as the tsunami that formed in the Marmara Sea area (Karaman & Erden, 2014).

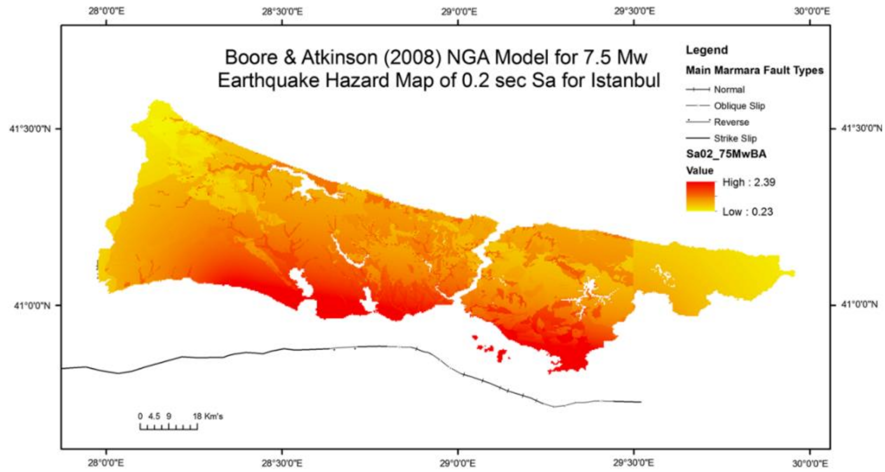

Figure 101: Risk factor map for earthquakes in Istanbul
Source: Karaman and Erden (2014)

However, in addition to earthquakes, landslides and floods in Istanbul are also driven by a combination of other natural as well as human factors. The city's hilly terrain and loose soils make it prone to landslides, which are often triggered by heavy rainfall, deforestation, and urban development destabilizing slopes. Floods are exacerbated by rapid urbanization, which replaces absorbent landscapes with impermeable surfaces, inadequate drainage systems.

Additionally, Istanbul's proximity to water bodies like the Black Sea, Sea of Marmara, and Bosporus also cause risks for flooding especially in case of rising water levels and storm surges. Though overflow from rivers or clogged canals could also lead to localized flooding. Climate change further intensifies heavy rainfall and storm surges, while deforestation reduces the land's capacity to absorb water, increasing surface runoff and flooding risks (Ekmekcioğlu et al., 2021)

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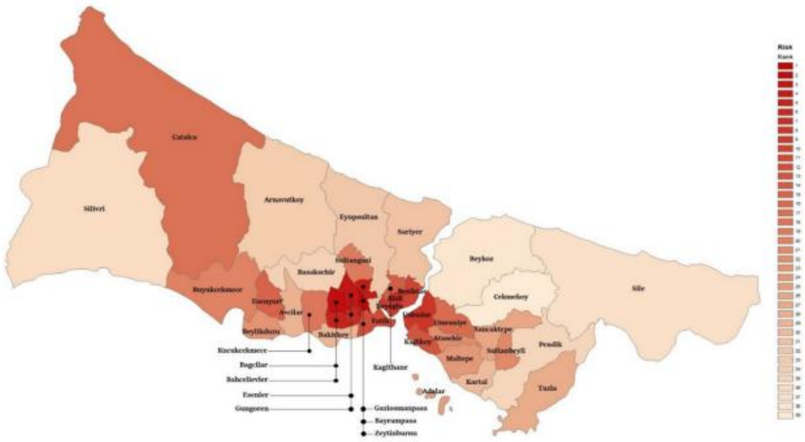


Figure 102: Flood risk map in Istanbul per district
Source: Ekmekcioğlu et al. (2021)

Climate

Istanbul experiences a temperate Mediterranean climate, classified as Csa under the Köppen climate classification system (Beck et al., 2018). However, the city's large geographic area results in diverse microclimates, blending Mediterranean and oceanic influences. Its climate is shaped significantly by its position between the Sea of Marmara to the south and the Black Sea to the north, creating consistent maritime conditions. For example, the Bosphorus Strait area exhibits a classic Mediterranean climate, while the northern regions, closer to the Black Sea, experience higher rainfall and cooler conditions, reflecting a subtler Black Sea influence. Western areas lean towards a Balkan climate, with colder winters and occasional snow.

Winters in Istanbul are cool, often rainy, and occasionally snowy, with average temperatures ranging from 5°C to 10°C. In contrast, summers are warm to hot, with temperatures frequently exceeding 30°C, intensified by high humidity. Precipitation is moderate, averaging 800–1000 mm annually, and is more pronounced in the south. Fog is common, and seasonal lag ensures relatively mild temperatures compared to more extreme climates.

While Istanbul generally lacks a pronounced dry season, rainfall is distributed between late autumn and winter, with summer remaining relatively dry. The coastal Black Sea regions are cooler due to their mountainous surroundings, while higher altitudes see occasional snowfall. Overall, the city enjoys warm, humid summers and mild, rainy winters, with limited extreme temperature fluctuations (MeteoBlue, 2024b; Weatherspark, 2024; Wikipedia, 2024).

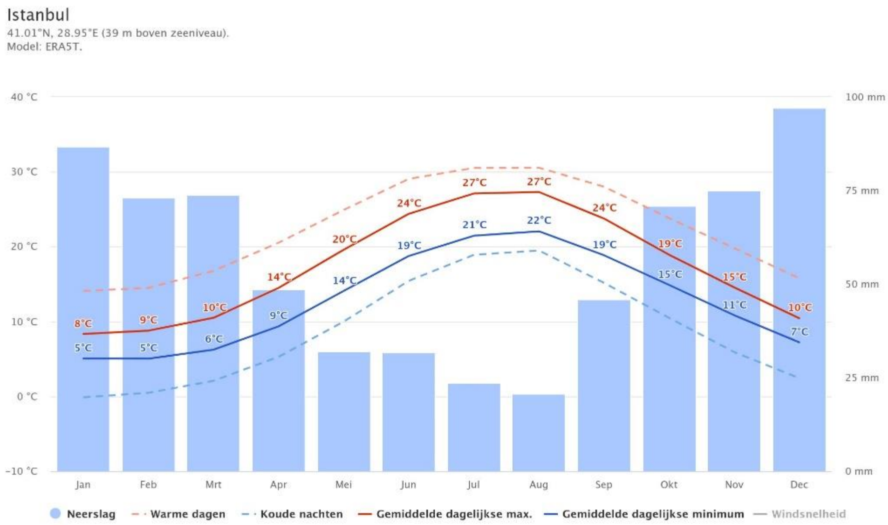


Figure 103: Climate diagram showing precipitation and temperature ranges
Source: MeteoBlue (2024b)

Looking at the wind in Istanbul there are a few predominant winds that bring different weather patterns with them to take into consideration.

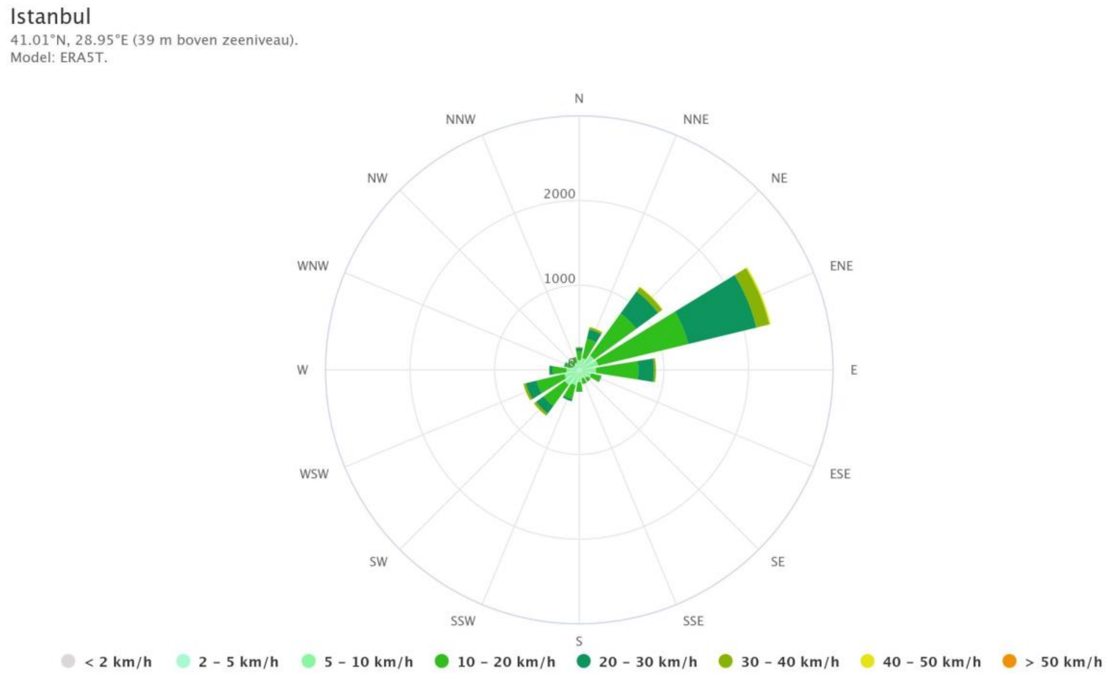


Figure 104: Wind diagram
Source: MeteoBlue (2024b)

The Poyraz (Northeasterly wind), is the most predominant one as can be seen in the figure below. It brings cooler air from the black sea in the summer moderating the heat, and in winter can intensify cold spells, occasionally bringing snow from the north.

The Lodos (Southwesterly wind), which a warm and humid wind blowing in from the Mediterranean via the Sea of Marmara. It often brings stormy weather and is associated with heavy rainfall and turbulent seas. During the winter, the Lodos can lead to sudden temperature increases, creating a temporary thaw. While it's a vital part of the city's maritime life, the Lodos is also notorious for disrupting ferry services due to rough seas.

The Karayel (Northwestern wind) is a cold and dry wind that blows from the northwest. It often accompanies cold fronts and can bring sharp drops in temperature. During winter, it may bring snow and icy conditions, particularly in higher-altitude areas of the city.

Kıble (Southernly wind) is a warm and humid wind that is less frequent but still notable. When it occurs, it often contributes to Istanbul's warm, sultry weather, particularly in late summer or early autumn.

The Yıldız, (Northern wind), brings cool and fresh air from the Black Sea. Similar to the Poyraz, it moderates summer heat but can also intensify winter cold. It is more consistent in the northern districts of Istanbul, closer to the Black Sea. Istanbul's winds are also influenced by its topography, particularly the Bosphorus Strait, which acts as a natural wind tunnel. This phenomenon intensifies winds in areas along the strait, impacting daily life (Weatherspark, 2024; Wikipedia, 2023).

Istanbul experiences moderate to high humidity throughout the year, influenced by its maritime location between the Black Sea and the Sea of Marmara. Humidity levels typically range from 60% to 80%, with variations depending on the season. Summers in Istanbul are particularly humid, with high humidity intensifying the sensation of heat, even when temperatures hover around 30°C. This is most noticeable during late July and August when warm winds from the Sea of Marmara contribute to sultry weather conditions.

In contrast, winter months also see elevated humidity levels, often exceeding 75%, as cold, damp air accompanies frequent rainfall. Fog is a common occurrence during the colder months, particularly in the early morning, adding to the moist atmosphere. The city's high humidity contributes to its characteristic damp winters, where even mild temperatures can feel colder due to the moist air.

Humidity in Istanbul is not evenly distributed across the city. Coastal areas, such as those along the Bosphorus and the Sea of Marmara, experience higher humidity levels compared to the inland regions. The Black Sea coast in the northern part of the city is also notably more humid due to the cooler and wetter climate influenced by the surrounding forests and mountainous terrain.

While the high humidity can pose challenges, particularly during the peak of summer, it also plays a role in moderating temperature extremes, making Istanbul's climate relatively mild compared to regions with drier conditions (WeatherAtlas, 2024; Wikipedia, 2024).

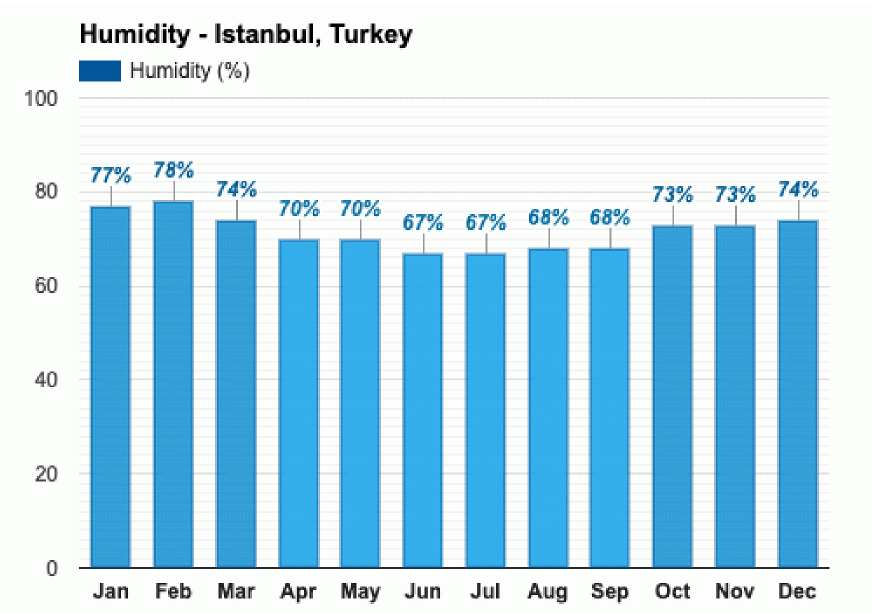


Figure 105: Relative humidity Istanbul
Source: WeatherAtlas (2024)

As for effective passive strategies in the area of Istanbul to keep the indoor climate comfortable without the necessity for electricity, a lot can be learned from traditional buildings, though the same factors as with the design in the Netherlands apply. Adding overhang, to keep the sun out during the summer and let it in during the winter, cross ventilation and building orientation.

As for building orientation, this is about the same as the Netherlands as well. You want your windows to the south, some to the east and west and keep the north façade as closed as possible.

Though here it is vital to keep the sun out in the summer even more so as in the Netherlands as temperatures do rise above 30 degrees quite often in the summer, though less so than in hot and drier climates because of the influence of the seas and the strait. Though it can still be useful to look at traditional architecture in hot and dry climates employ to keep cool in summer.

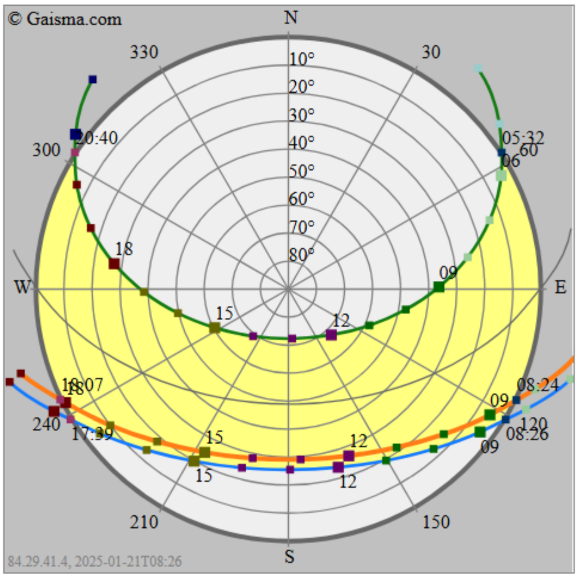


Figure 106: Solar path Türkiye
Source: Gaisma (2005b)

The urban landscape in hot and dry climates is often characterized by narrow, inward-facing streets and buildings, minimizing exposure to harsh solar radiation while maximizing mutual shading. Often oriented in a north-south direction. This layout ensured that the streets remained largely shaded throughout the day. Street junctions, exposed to greater solar radiation, contrasted with the cooler, shaded side streets, which had a higher shading ratio. The resulting temperature differences between these areas created pressure variations, facilitating natural ventilation and providing an effective cooling mechanism for the urban environment.

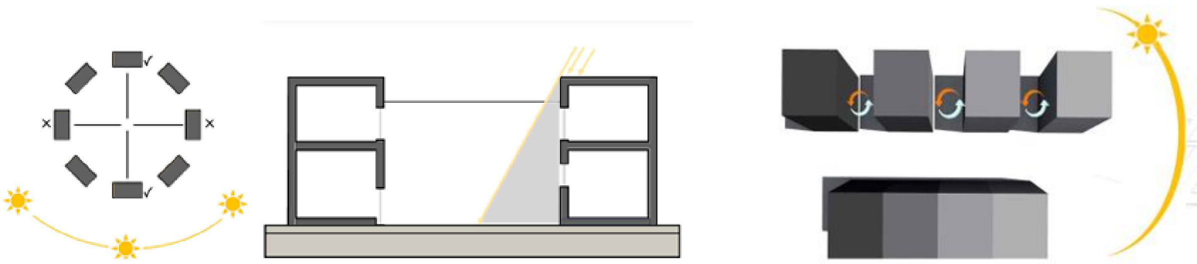


Figure 107: Building orientation and urban layout of hot dry climates
Source: Ergün and Bekleyen (2024)

Landscaping also plays a significant role, with deciduous trees and grapevines providing seasonal shading and cooling courtyards, while water features like fountains enhance evaporative cooling. Courtyards, central to these designs, serve as multifunctional spaces, offering shade, facilitating airflow, and cooling adjacent rooms through a cycle of rising warm air during the day and cooler air settling at night. Semi-open spaces such as iwans and takhtabushes act as transitional zones, buffering indoor spaces from outdoor heat and promoting natural ventilation.

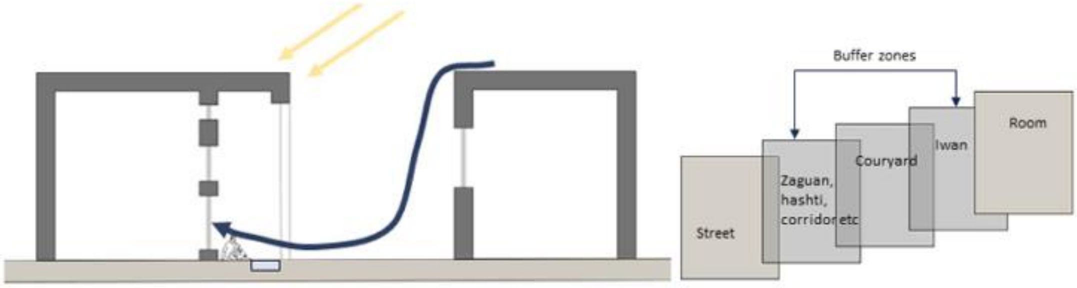


Figure 108: Example of transitional zones
Source: Ergün and Bekleyen (2024)

Building envelopes are designed to withstand intense heat, with thick walls and domed or vaulted roofs functioning as thermal masses that stabilize indoor temperatures. Small, strategically placed windows encourage cross-ventilation while minimizing heat entry. Shading devices such as overhangs, latticed screens, and shutters further protect interiors from solar radiation. Light-colored surfaces reflect heat, and wind catchers' channel cool air inside while expelling warm air, sometimes integrating with water or soil for enhanced cooling.

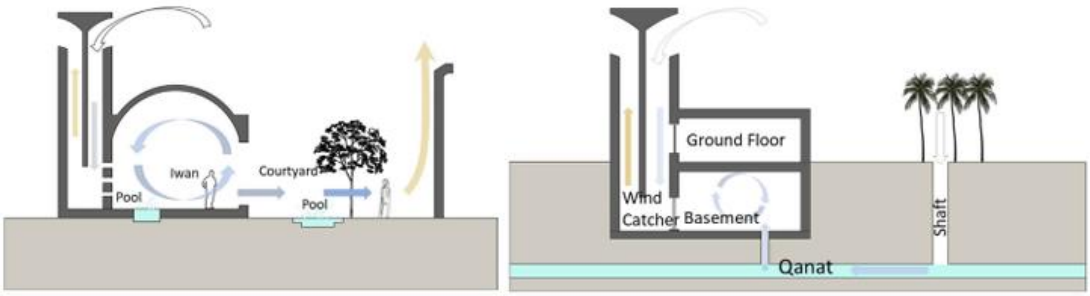


Figure 109: Examples of traditional wind catchers
Source: Ergün and Bekleyen (2024)

Social cultural

The average household size in Türkiye was approximately 3.17 in 2022, though significant variation exists between urban and rural areas. In Istanbul, household sizes range from 3.02 to 3.29. Most households comprise nuclear families, but it is not uncommon for extended family members, such as grandparents or unmarried siblings, to live together (TUIK, 2023). This diversity necessitates adaptable housing designs capable of accommodating multi-generational families or smaller units as needed. Modular and expandable living spaces are particularly important, allowing households to adjust their environments over time.

Gender segregation, rooted in cultural and religious traditions, is observed in some conservative communities in Istanbul, including among Turkish, Kurdish, and Arab populations. This segregation often applies to sleeping arrangements and social spaces within the home. Housing designs should incorporate internal partitions or separate living areas to provide privacy, particularly for women and children. Privacy is a broader cultural priority as well; homes are typically designed with closed facades toward the street, featuring more open spaces, such as courtyards, at the back.

Another thing clear in the layout of their homes is an emphasis on separation between private family areas and public spaces for receiving guests. Courtyards or shared open spaces are central to family life, acting as a hub for gatherings, meals, and children’s play. So-called sofas inside the house or in hot climates spaces like verandas or enclosed outside spaces are usually included as a type of living space or circulation space that separates the individual rooms.

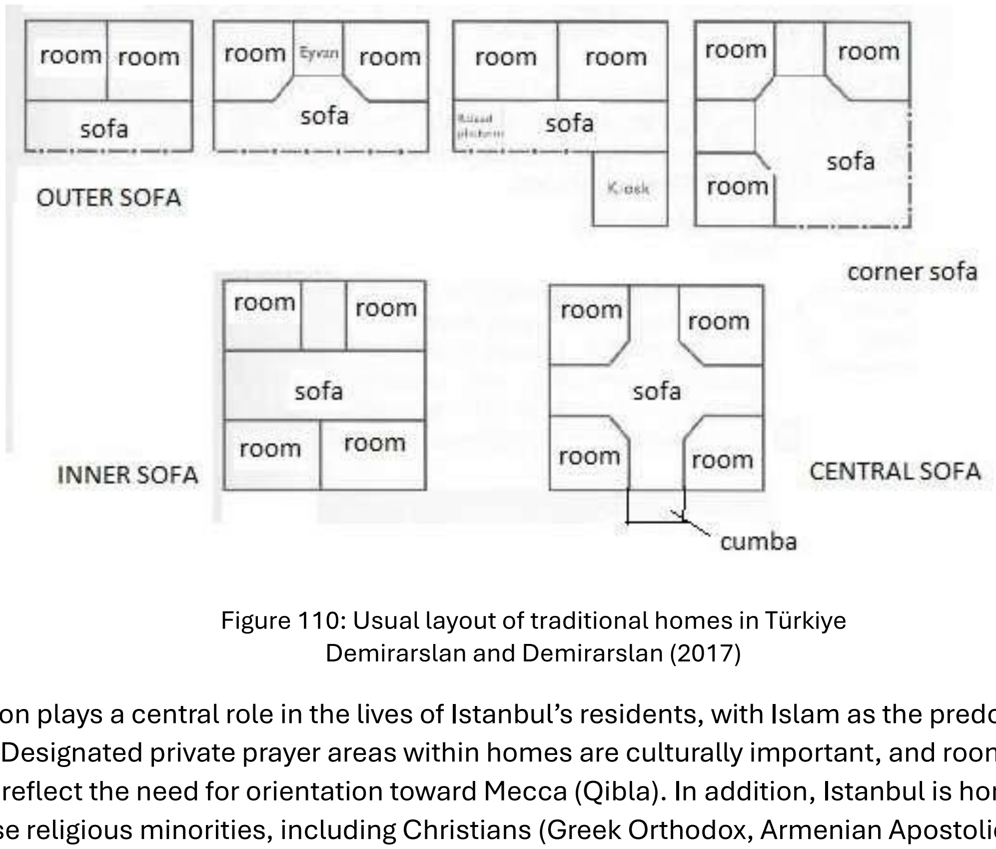


Figure 110: Usual layout of traditional homes in Türkiye
Demirarslan and Demirarslan (2017)

Religion plays a central role in the lives of Istanbul’s residents, with Islam as the predominant faith. Designated private prayer areas within homes are culturally important, and room layouts often reflect the need for orientation toward Mecca (Qibla). In addition, Istanbul is home to diverse religious minorities, including Christians (Greek Orthodox, Armenian Apostolic, and Roman Catholics), Jews, and Alevis. For Alevis, communal spaces for worship or gatherings may be essential. Housing designs should aim for inclusivity and adaptability to accommodate the diverse spiritual practices of these communities (Kaya, 2012).

Resources

Zooming out to Turkey, to look at the available resources the country provides, we see that traditionally building materials have been significantly influenced by regional availability and cultural practices. Historically, wood played a central role in construction, especially in areas abundant with forests. Traditional Turkish houses often featured timber-framed structures, with wood serving as the primary material for both structural elements and decorative details. This method was prevalent in regions like Anatolia and Thrace around the black sea and Marmara area, where timber was readily accessible.

Figure 111: Traditional wooden house
Source: TurkeyHomes (2018)

However, due to the risk of fire by using timber, the use of wood as a primary construction material for homes became restricted in certain areas after World War One. Regulations were introduced to reduce fire hazards, mandating the use of less combustible materials like concrete, brick, and stone for residential and commercial buildings.

This shift was further influenced by the country's urbanization efforts, which favored modern materials for high-density housing projects. Concrete and steel became dominant in construction, not only for their fire-resistant properties but also because they were perceived as symbols of progress and urban development.

While the restrictions were effective in mitigating fire risks in urban settings, they also led to a decline in the traditional craftsmanship associated with wooden architecture. Over time, however, advancements in fireproofing technology and growing interest in sustainable building practices have prompted a resurgence of wood use in certain contexts, such as modular and eco-friendly construction. Modern engineered wood products, including fire-retardant plywood and OSB, are now being utilized in compliance with updated safety regulations (TurkeyHomes, 2018).

In contrast, regions with limited timber resources, such as Şanlıurfa, utilized locally available materials like limestone. The distinctive beehive houses of Harran, for instance, were constructed using sun-dried bricks made from a mixture of mud and straw, reflecting adaptation to the local environment.

Forests in Turkey cover 23.2 million hectares, which accounts for approximately 29% of the country's total land area. These forests are predominantly state-owned (99%) and managed by the General Directorate of Forestry. The country has seen a steady increase in forested areas, growing by 3 million hectares since 1973.

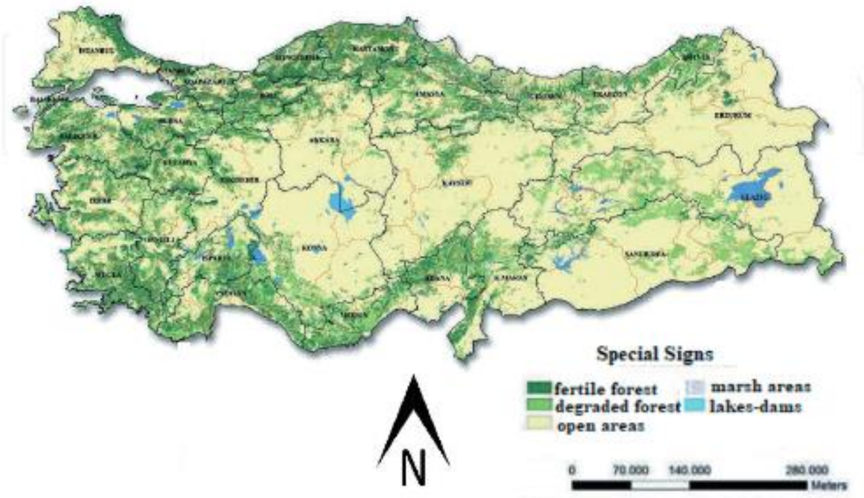


Figure 112: Forest areas in Türkiye
Source: Sarikoc (2020)

In terms of industrial use, Turkey produced 25.5 million cubic meters of industrial roundwood in 2022. This figure has grown significantly over the decades, reflecting increased demand and improved forest management practices. However, the domestic supply is sometimes insufficient to meet the growing demand. For example, in the wood-based panel sector, raw material shortages are a challenge despite rapid increases in production capacity. Turkey imports additional wood resources to fill this gap, sourcing approximately 138,000 cubic meters of roundwood.

The wood-based panel industry in Turkey includes the production of plywood, oriented strand board (OSB), particleboard, and medium-density fiberboard (MDF). These products are primarily used in construction, furniture manufacturing, and other industrial applications. Among these, plywood and OSB production are significant, though the country relies on imported materials to support this sector. In addition to particleboard and fiberboard, Turkey has expanded its capabilities to meet both domestic and international market demands (GDF, 2023).

Large manufactures include Akca plywood and Turkish plywood. Both deliver an array of plywood types as well including birch, poplar, pine beech and combined. (Akca, 2024; TurkishPlywood, 2024).

When it comes to CNC routing machinery in Turkey, there are several companies that supply the necessary equipment, but opportunities for outsourcing the routing process to these companies are quite limited. Within a 100 km radius of Istanbul, only two suitable options were identified (as per the Europages website: https://www.europages.nl/). Searching for it online yielded very little result as well. This highlights the limited availability of facilities offering CNC routing services in the region.

Given this scarcity, it becomes clear that for certain projects, especially those in disaster scenarios or remote areas, it would be essential to have the CNC machine provided directly on-site. However, this approach presents significant challenges, including high costs associated with transporting and setting up such equipment. Additionally, power outages, which are more common in disaster-stricken or remote locations, could further complicate operations, emphasizing the need for reliable power sources or backup systems to ensure uninterrupted functionality. As well as that, if the services are rare in the country the knowledge of how to operate the machinery might also not be available.

In terms of budget this is also not too high. A regular disposable income for Turkey was around 83,800 Turkish lira, equal to around 3300 euro in 2023 which gave people a mere 275 euro a month to spend (TUIK, 2023). Especially if you think that in turkey a cubic square meter of plywood is around 632.97 euros (IndexBox, 2024). Which is already almost 3 times as much as in the Netherlands but that also means that for a house that uses around 14.58 cubic meters of wood it would cost them close to 9.000 euros for material costs alone. So here the option to go for OSB which is only 256.68 euro would be a much better option (IndexBox, 2023a).

Regulations and Standards

Türkiye’s building regulations, particularly for seismic design, are among the most stringent globally due to the country’s seismic risk. The Turkish Earthquake Code (TEC) outlines critical requirements for structural design, such as load distribution, base isolation, and material selection. As for Eurocode the national regulations code for Türkiye is TS (e.g. TS EN1998-1).

Türkiye’s seismic building codes now emphasize lateral stability, lightweight construction, and materials that dissipate energy during earthquakes, ensuring buildings can better withstand such events. The AFAD is the government institute in Türkiye that handles disaster and emergency management.

In 2018, Türkiye also revised its building code to improve earthquake resilience, a significant advancement on paper. However, poor enforcement and widespread non-compliance undermined its impact. Developers, prioritizing cost and speed over safety, often ignored the updated standards. Compounding the issue were construction amnesties, legal exemptions allowing unsafe buildings to bypass safety certifications for a fee. At least 75,000 structures in the 2023 earthquake, and millions across the country, were affected by these amnesties (AFAD, 2018).

Turkey is also committed to sustainable forestry, with 8.1 million hectares of forests certified under the Forest Stewardship Council (FSC) standards, and additional certifications under the Program for the Endorsement of Forest Certification (PEFC) are in progress.

Building environment and urban context
What is unique about the city is, however, that it spans across two continents. To the west lies the European part and Asia to the east, divided by the Bosphorus strait connected only by three bridges and two tunnels.

Figure 113: Main zones and infrastructure
Source: Fitzgerald (2009)

Sultanahmet where the ‘old city’ or what in the past was known as Constantinople lies on the south side of the large estuary called the ‘golden horn’. This part of the city has been the main capital of many different Empires in the past including the Roman, Byzantine, and Ottoman empires. It makes it the historical heart of Istanbul and houses many of its iconic landmarks within the ancient city walls. It is home to iconic landmarks such as the Hagia Sophia, Blue Mosque, and Topkapi Palace, showcasing the city's Byzantine and Ottoman heritage.

Figure 114: View of old city center
Constantinople looking at the Fatih mosque
Source: Lescohier (2020)

The New City, including Taksim and Şişli, serves as Istanbul's commercial hub, bustling with shopping districts and vibrant nightlife. Along the European Bosphorus shore, scenic neighborhoods feature historic mansions, seafood restaurants, and stunning waterfront views. The Golden Horn area, encompassing Eyüp and other neighborhoods, highlights the city's religious and cultural history, while the Western Suburbs provide a glimpse into everyday life through their mix of traditional and modern settings. On the Asian Side, districts like Kadıköy and Üsküdar offer a relaxed atmosphere with lively markets and serene waterfronts. Finally, the Princes' Islands, a car-free archipelago in the Sea of Marmara, provide a peaceful retreat with historic architecture and tranquil landscapes.

Figure 115: A few impressions on the different districts
(Top left Takism, top right Western residential area, bottom left Bosporus shoreline, bottom right
Source: Maps (2024)

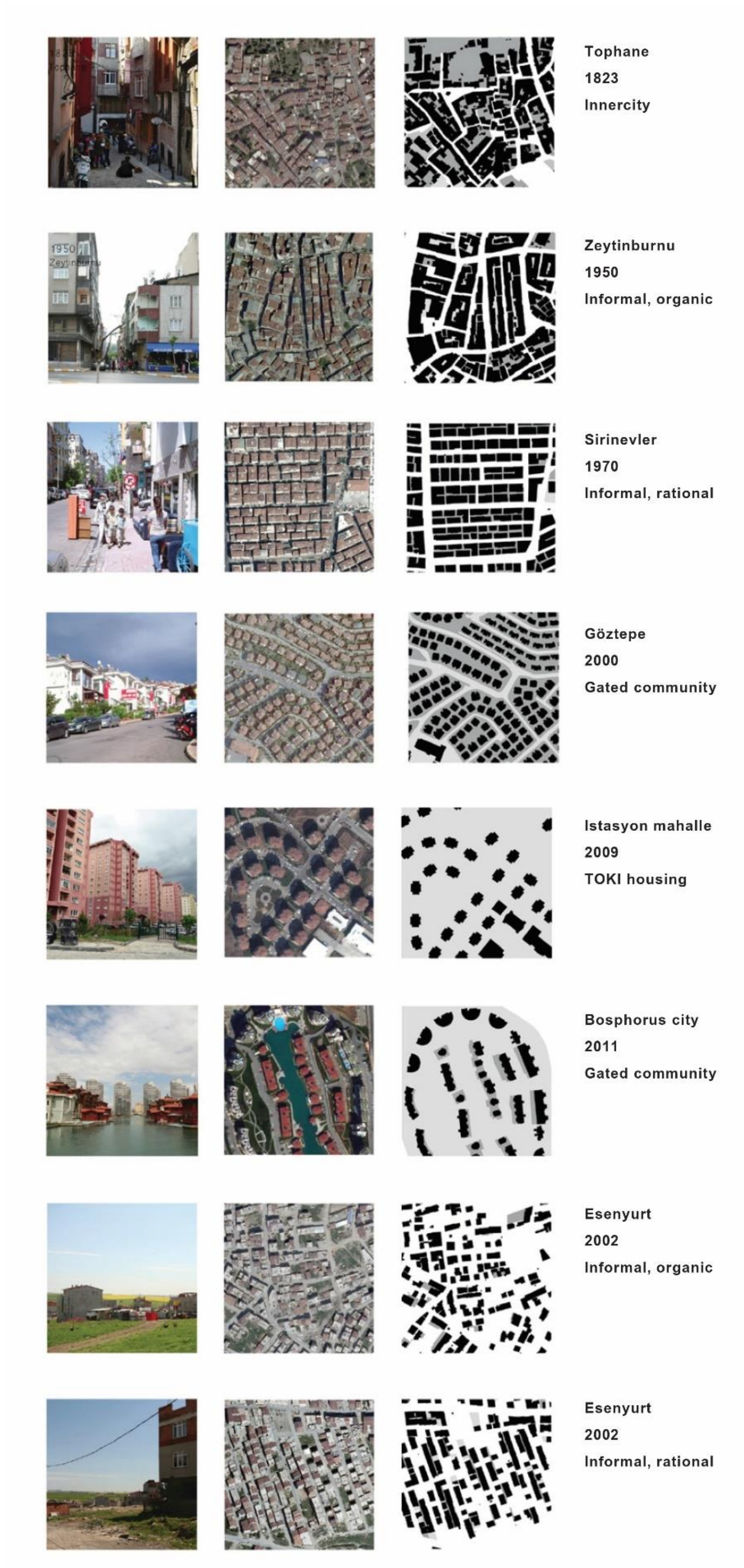
As for the urban layout, most buildings are very tightly knit partially due to the climate as spoken about in the previous paragraph. As Istanbul, Türkiye’s largest city, is home to over 16 million people (Turkish Government, 2024), making it significantly larger than a city like Delft, even on par with the entirety of the Netherlands, which has a population of around 18 million (CBS, 2025). The population is spread over just 1,539 square kilometers. Which means the city has a density of 2,523 people per square kilometer much higher than Türkiye itself with just 102 people per square meter (Turkish Government, 2024).

Istanbul's urban layout is a dynamic mix of building typologies and spatial arrangements that reflect its rich history and ongoing urbanization.

In the historic core, districts like Fatih and Eminönü feature dense, tightly knit, and organic layouts with narrow streets and irregular buildings, fostering intimate, community-focused neighborhoods. Newer areas, particularly on the city's outskirts, showcase a rise in high-rise residential complexes and mixed-use developments, offering more open layouts while maintaining high density.

The European side, with its historic and commercial hubs, is more densely developed, while the Asian side combines suburban sprawl with modern residential zones.

Despite the contrasts, Istanbul's tightly interwoven urban fabric remains a defining feature, blending tradition with modernity and adapting to the city's growing population and changing needs.



As for the specific site that is going to be looked at in this case study will be in Kartal Istanbul (40.902642 latitude, 29.211873 longitude). Near the D-100 and Kartal bridge. Where there is an open patch of land fixed between two larger roads. The area is surrounded by some midrise houses as well as some taller high rise apartment buildings to the south and on the other side of the road a shopping or business district.

Figure 116: Map of the area of Kartal
Source: Maps (2024)

Figure 117: Surrounding area impressions
Source: Maps (2024)

4.2 Design requirements

The design requirements have been separated into the different categories mentioned before in the research, on top of those there has been made a distinction between soft and hard criteria. The soft criteria consist of requirements that are not too easily measured or quantifiable and the hard criteria are.

4.2.1 Social cultural:

Soft criteria:

- Visually pleasing
- Culturally acceptable
- At least have separate rooms or dividers to create privacy
- Is customizable in: Layout, and materials
- No high craftsmanship needed, people should be able to design, fabricate and build it without the interference of experts (within their own community)
- Make sure joints never fit 'wrong' (make it easy for someone to assemble the structure right)

Hard criteria:

- Social cultural criteria are often hard to 'measure' so in this case there are no hard criteria in this category.

4.2.2 Physical technical:

Soft criteria:

- Construction ease and speed:
    - No specialized tools needed to assemble
    - Easy to assemble (not too complicated puzzle like structure)
    - Easy to disassemble
    - Connections without mechanical or adhesive connections (no need for bolts, screws or glue, all based on friction-fit or interlocking joints)
- Should be upgradable (more units should be able to be connected to the first one in the x and y direction)
- Should be accessible to anyone (also people in wheelchairs or less able people)
- Every member should be planarly craftable (since the proposal is to create as much as possible with CNC for the ease of production)
- Outside layer is watertight (can be any water-resistant sheet material/ cloth available)
- Easily disassembled and relocatable (so when deconstructed or when just fabricated the packet should be compact, enough to fit in a truck or even van if needed)
- Gabled or hip roof (for the possibility of passive heating, cooling and ventilation through the roof as well as resistance to wind- see climate design and daylight)
- Should be in compliance with EN 1995-1-1 Eurocode 5: Design of timber structures - Part 1-1: General - Common rules and rules for buildings
- Should be in compliance with safety and health regulations in the country it is being built in

Hard criteria:

- Spatial requirements:
    - Has at least a private bathroom (including toilet), a kitchen block, storage space, bedroom and a semiprivate outdoor area
    - People should have at least 8 square meters of indoor living space (10 for wheelchair users)
    - The plan is rectangular or square with at least 3:2 or 1:1 length, width ratio (1:1 for wheelchair users).
    - Smallest unit 16 square meters (for one or two people)
    - Ceiling at lowest point is at least 2 meter (2.1 meters in the Netherlands)
- Ease and rapidness of construction:
    - Should be able to be erected by 2 or 3 people.
    - The weight of one component should not exceed 25kg (then it's still carriable by a single individual)
- Structural:
    - Structurally sound (Does not exceed the ULS Ultimate limit state, and SLS serviceability limit state)
    - Roof needs slope around 30 degrees if the area is prone to large wind forces and hurricanes

4.2.1 Environmental:

Soft criteria:

- Enough daylight
- Protected against the weather conditions
- The shelter components should be reusable (so materials can be reused or sold, or it can be stored away again for later use or be usable in a different orientation)
- Structure needs to be structurally sound using as little material as possible
- Production should lead to as little as possible waste (saw fibers could be used again as for something like a fire)
- Use passive climate strategies to create comfortable indoor environment (e.g. openable windows, overhangs, insulation wind tunnel, solar chimney, etc.)
- Insulation can be added later or is already included
- Roof is as low as possible in cold climates, as high as possible in warmer climates (If mixed like a continental climate also make it higher but make sure to keep the sun's path in mind so that in both cold and warm situations the shelter is comfortable)
- Structure is made from wood composites, type and rest of the materials are up to local availability
- Materials can be recycled, reused or sold at the end of life.
- House should be optimally oriented in accordance with the sun and main wind direction

Hard criteria:

- Thermal comfort:
    - Around 21 degrees inside
    - At least 15 degrees in cold climates/ winter
    - At least 5 to 7 degrees difference between the in and outside in warm climates/ summer however not over 30 degrees (so if it's 30 degrees outside max 25 inside)

4.2.3 Economical:

Soft criteria:

- Keep production and material costs as low as possible (Looking at disposable income)

Hard criteria:

- Initial costs of materials are between 500 and 1500 euros (if possible lower)

4.2.4 Organizational:

Soft criteria:

- Materials should fit in a regular size van/ small truck to get it to site
- A manual should be given of how to place and build the structure (or any additional information should be given to inform the user)
- Makerspaces or something similar that provides the necessary machinery should be provided or located in the vicinity so people do not have to drive hours, or it must be transported from a long distance away
- Make the production process as easy as possible so people have the chance to produce it themselves

Hard criteria:

- Shelter should be built within 1 or 2 days

4.3 The overall concept

The overall architectural concept of the structure (hopefully) ties all these criteria into one. Creating an affordable modular wooden frame structure that is upgradable, can be expanded, easily transported, set up and broken down again. Something universal yet customizable enough that it is ethically, culturally and socially sustainable as well as comfortable to live inside. A CNC machined wooden frame 'Lego' kit produced for the users, by the users within their own community and with locally sources materials keeping the footprint low.

4.3.1 Geometry, modularity and expandability:

The concept is to create a shape and outlook of a place in which everyone would be able to feel at home in. Something universally seen as 'home' or a symbol like it, that anyone would be able to recognize, or draw is the shape seen to the left here. A simple 'box' with a triangular prism as the roof. It might be a simple geometry, but it has a lot of opportunity to be adapted in many ways and with the project dealing with a lot of factors at the same time having a simple design does help to see what works and what does not. Also, a square or rectangular layout is proven to be the most efficient in the use of space.

Figure 118: Icon of a house
Source: TheNounProject (2024) by Sherrinford

The shape also opens ways to easily adapt, add onto or expand in the width, length and height. A simple grid system would suffice in this case, which is also beneficiary when translating everything to an adaptable digital model. All you do is add to x y or z and you can divide or expand. The idea is to use portal frames connected by beams. This is something the user is not able to change but is done at the hand of optimization, the forces in the structure are calculated and the optimal 'grid' or rather number of frames and beams in x and y are found.

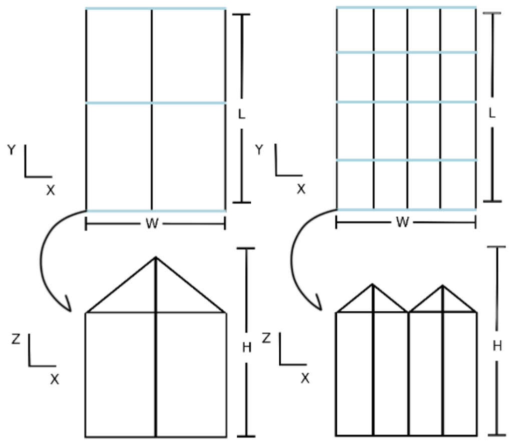


Figure 120: Layout grid and expansion

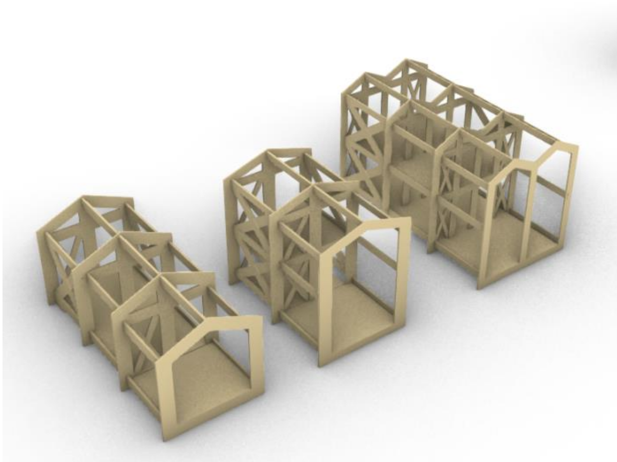


Figure 119: Variations on the structure with different grid patterns

However, what the user can adapt is that they are able to add onto the existing structure in all three dimensions. Once they have created a first design and built it up on site the idea is for them to be able to add another unit against it or on top of it once their situation changes or they have a little more budget to extend if they are looking to be stuck in a temporary situation for a while. About how this and the structure itself works in more detail will be discussed in chapter 5.

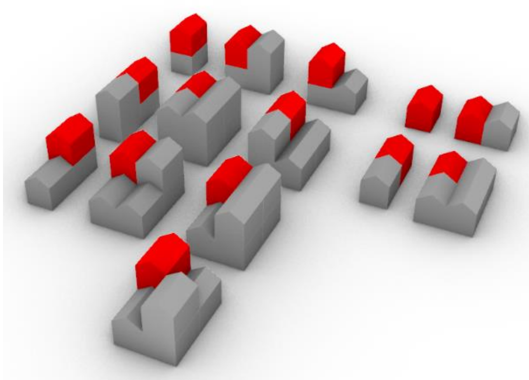


Figure 121: Different additions (original unit in red)

4.3.2 Custom layout:

Talking about the layout, due to the setup of the structural system as a grid they are also easily dived. Depending on how many frames there are and where colums are situated in x and y direction will determines the set up, however the user is free to choose how to interperate these spaces themselves and can be adapted to whatever the user would like. The only things that are fixed are the position, bathroom and the addition of the outside area to the shorter side of the building. The inclusion of a kitchen in the shelter design is flexible, as in some cultures cooking is traditionally done outdoors. In such cases, the space typically allocated for a kitchen could be repurposed for a living area, additional bedroom space, or other functional needs. To accommodate this variability, users will be able to specify their preferences through the application. The application will allow them to indicate whether they want a kitchen included. If requested, the design will account for necessary features such as plumbing and ventilation etc.

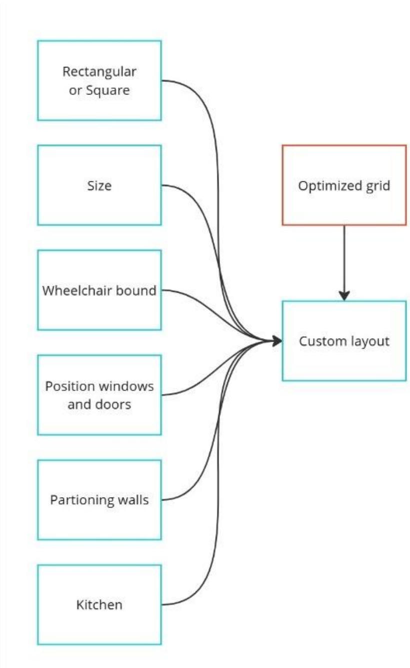


Figure 122: Customizable factors in the layout

Another thing they are able to adapt besides the layout itself is the general size, rectangular or square floorplan, indicate if they are wheelchair reliant or not, where they want doors and windows (taking into consideration that the areas where bracing is situated this cannot be done) and if and where they would like extra partitioning.

Down below I worked out a couple of examples for different layouts. I took 8 square meters per person as the very minimum, a length width ratio of either 1:1 (square) or 2:3 (rectangle), 3 frames where there is 1 column in the center of the space and worked out 4 options. And a few options for elevation as well.

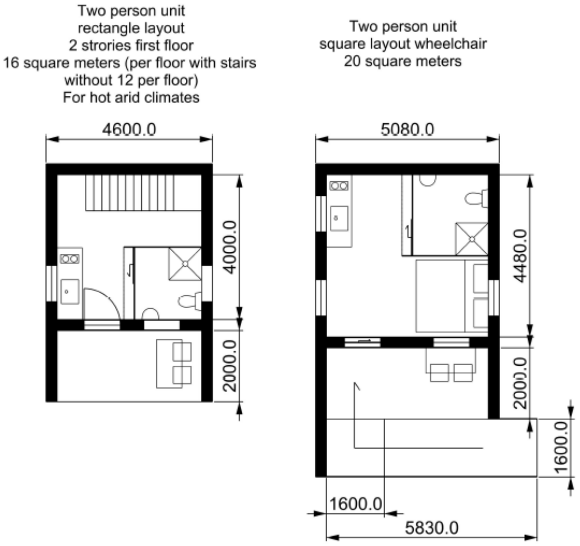


Figure 123: Floorplans of different units

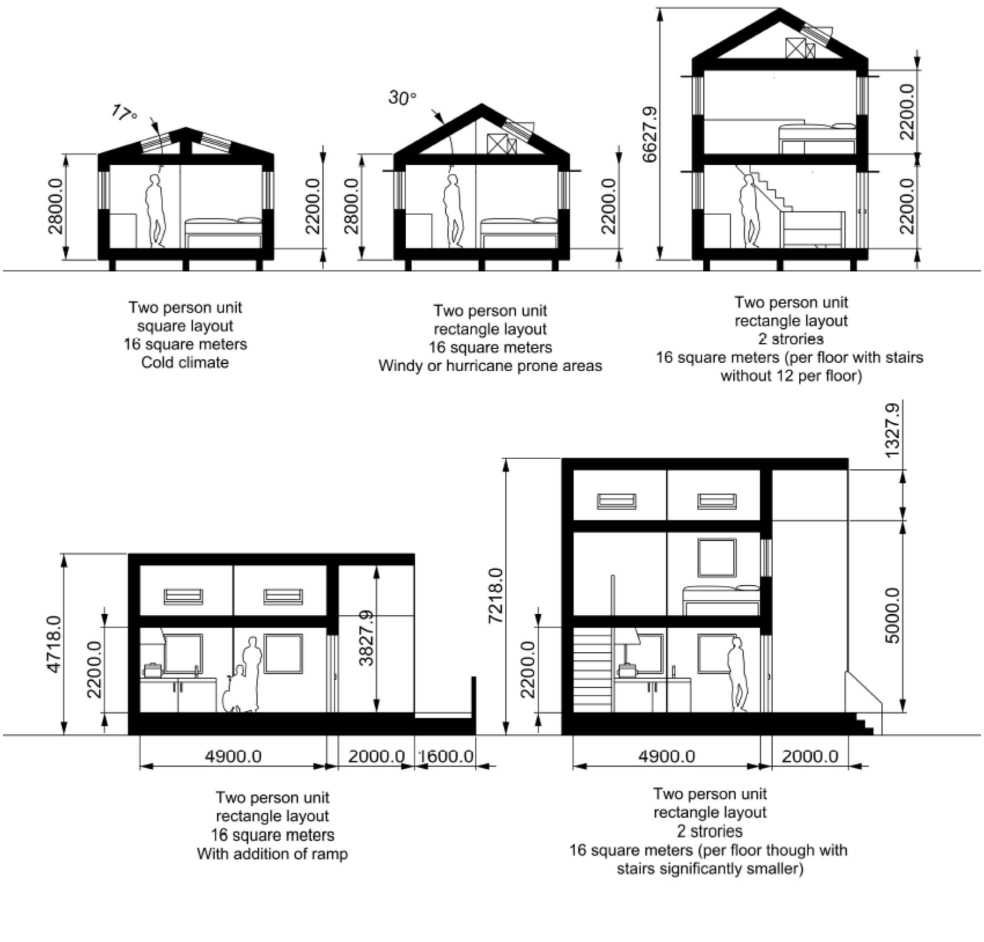


Figure 124: Sections of the different units

Two square layouts, one with an extra floor and stairs, the other adapted to a wheelchair user by increasing the minimum area size per person to 10 and adding a ramp so there is enough space for them to move around. And two rectangular ones, one with a set up that is more open, the other more divided when for example the user prefers separate bedrooms in terms of gender segregation or privacy. Also moving the door to the side if people prefer a more private outside space so that instead of a porch-like outside area it turns into something like a backyard.

The sections will also be different in each case, however some of the factors are predetermined based on the local climate like height of the gable roof with space for storage between the rafters (not a walkable area but enough to leave some of people's belongings, see paragraph 4.3.4). Each option has at least 2200 mm of headspace on each (walkable) floor and a roofed semiprivate outdoor space either reachable by stairs or ramp as the entire structure is raised from the terrain by wooden beams and the foundation (for example concrete or brick) holing them up to keep the wood from being affected by groundwater that in turn are connected to the foundation.

People can of course, if their budget allows for it, choose a larger area than the examples here. Which is what I have done for a unit for 4 people (for the impressions see 4.3.6).

Figure 125: 4-person unit (left 2 bedrooms, right one bedroom and larger living area)

On the left is the standard unit with 2 bedrooms where 4 people would reside using the minimal amount of area needed (32 square meters). Instead on the right, one of the bedrooms is used as part of the living space or kitchen.

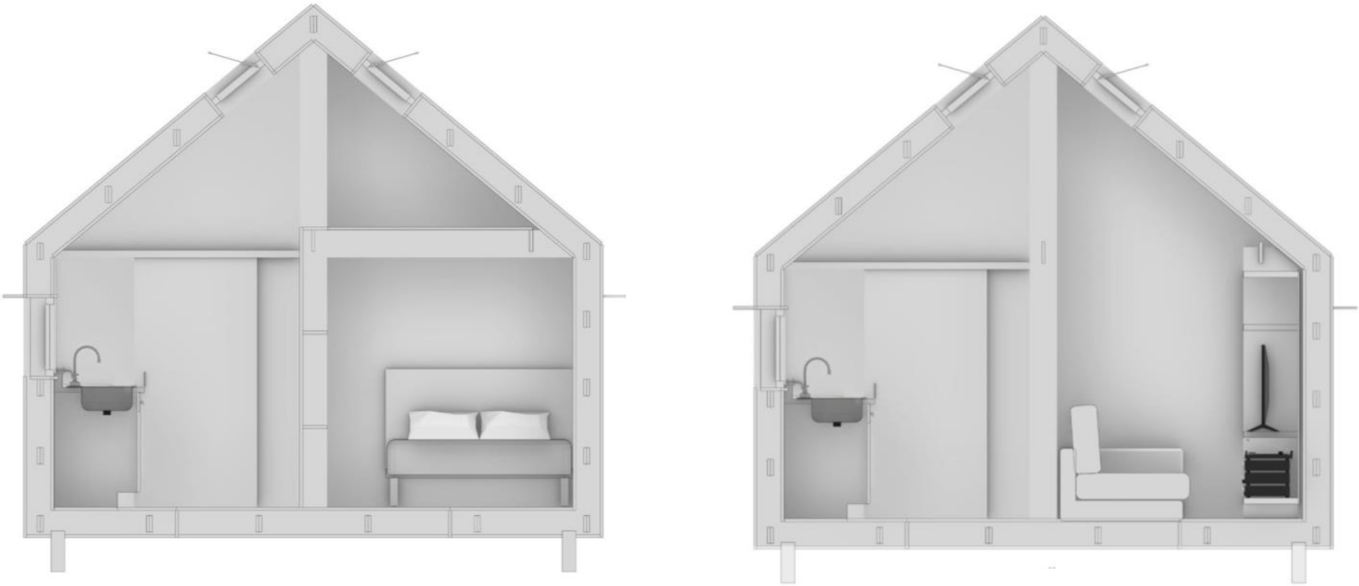


Figure 126: Section over the width in 3D model for 4-person unit
(Left 2-bedroom version with storage up top – Right 1 bedroom and larger living space)

Figure 127: Sections over the length
(Top 2-bedroom version - Bottom 1 bedroom and larger living space unit)

4.3.3 Materiality and resources:

As for the material to use, a few things are important. Supply, costs, locality and sustainability. Making sure the products are as local as possible, while not affecting the local economy or permanent housing construction too much. Keeping costs low and making sure that the resources are sustainably produced or gathered.

In any situation, the availability of materials can vary greatly; one region may face scarcity while another has an abundance. Different countries also have unique regulations and standards. To address this, the material selection process is designed to prioritize locally available, sustainable, and environmentally friendly options.

The idea is that when a disaster occurs, companies capable of supplying sufficient materials without significantly impacting the local environment or economy can submit their information. We check their stocks' quality and when passed this information is used to update a database of available materials, including their properties and stock levels. Using this database, an application enables users to input their location and receive a list of material options available in their area. The application provides details about each material, allowing users to make informed decisions based on their budget, aesthetic preferences, and familiarity with the materials.

The process is straightforward: users access the application, specify where they plan to build, and browse the available materials. Once they select their preferred material, the application gathers the necessary information, such as material properties, and uses it to perform safety checks and optimize the structural design. The system then generates a model, along with the files needed for production These include a detailed "shopping list" of the required materials and quantities or, alternatively, the option to directly place an order for the necessary components (this process is further discussed in chapter 5 and 6).

This streamlined approach ensures that material selection is both efficient and adaptable, balancing user preferences with local constraints while minimizing the environmental impact.

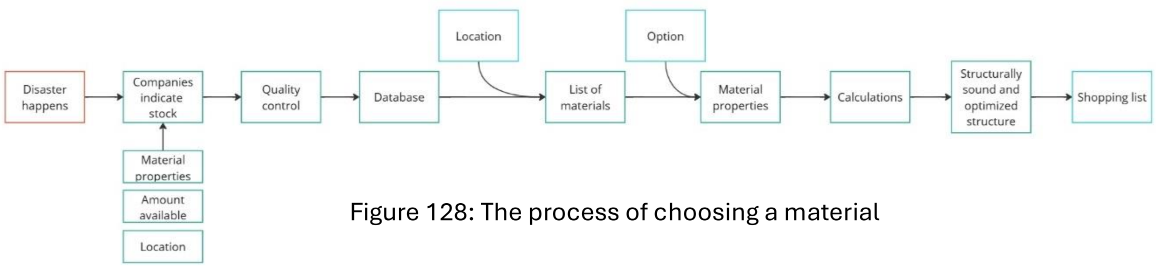


Figure 128: The process of choosing a material

Though for the construction of the walls, floors and roofing there should be a certain 'template' to go by. The frames and beams and wall structures are to be cut out of a composite wood plating material. For this thesis I looked at two options, OSB (for a cheaper but less performant material) and Plywood (more expensive higher performance material). Making sure both are produced with WBP glue (water and boil proof) so they are able to be used in an outside setting. As well as an FSC label or something similar, to ensure a sustainable choice and trying to source them as locally as possible (also looking into where the wood itself came from).

Additionally, there should be at least an outside finishing layer keeping the rain out, though the plywood and OBS itself should be resistant to the weather conditions, it does last longer when it is more protected. Something like correlated sheets, who will run from top to bottom on the longer sides of the building. The short ends will just show the plywood, one of them is mostly protected under the roof of the outside area so perhaps the back should have some extra protection.

Insulation can be added between two the two sheets of wood or left out and left open if this fits more with the local climate or in case of difficulties with budget and added later. As the entire structure should be able to be taken apart if the shelter needs to be relocated or if parts need to be repaired. Every joint and connection is friction fit without adhesives so should (perhaps by hammering it out or some additional force) be taken apart again or ‘unlocked’ (see key joints in structural design).

The inside should also have some sort of finish, for example gypsum plate or other plates to protect against fire.

All the outer walls and roof will be set up like this. Inner walls will consist of a similar set up though not insulated (unless the user would want that for acoustics) and gypsum plate or something similar as finish to but on either side of the wood. Some inner walls, however, will only consist of a single sheet of plywood simply to divide the room and save space.

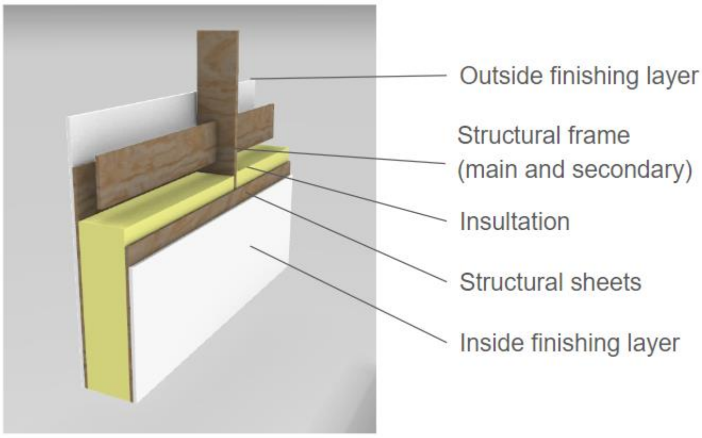


Figure 129: Buildup of an outer wall

4.3.4 Climate:

Climate-responsive design varies based on the specific environmental conditions of a region, but the underlying principles remain consistent. In colder climates, characterized by extended periods with temperatures below 10°C or weeks of freezing weather, the roof is typically lower to reduce the volume of space that needs heating. This compact design makes it easier to retain warmth, aided by windows positioned to capture solar radiation for passive heating. Effective insulation is essential to maintain internal temperatures, and roofs are slightly angled to allow snow and rain to slide off efficiently.

For warmer climates, roof designs often incorporate openings to allow hot air to escape, creating natural ventilation. In regions with colder winters, these openings can be sealed during the winter months to retain heat. Overhangs are a common feature, designed to block the intense summer sun while allowing the lower-angled winter sun to penetrate and warm the interior.

In areas prone to high winds, roofs are typically angled at 30 degrees to reduce wind resistance. Additionally, the shelter's front area often acts as a buffer zone, casting shadows on the rear façade. This design allows for larger windows and openings without overheating the interior. Cross-ventilation is achieved by strategically placing windows opposite each other or incorporating filter strips above them, enabling air to flow efficiently through the structure.

Elevating the structure slightly off the ground also enhances airflow underneath, helping to cool the building as wind passes beneath it.

As well as protect against potential smaller floodings during rainstorms etc.

Furthermore, orientation plays a critical role in climate design as well; the building should face the direction that maximizes exposure to sunlight, with most windows situated on this side to optimize natural light and heat gain.

As for orientation and context in the case of Kartal in Istanbul the layout of the shelters does not have to be too formal.

The surrounding area also does spread quite informally and most oriented in the north south orientation.

This can also be done for the shelter, Having the different buildings close together and informally spread though with their longest wall shoulder to shoulder.

This ensures that in the summer shadows are cast between the houses keeping it cool. The porch would probably be turned towards the back and not on the street side unless people want to.

For the Netherlands there is not to much space at the Green village so only a few would be able to stand next to each other but most likely facing south, with the porch towards the street instead and perhaps a little more formal (for example grouped into the different sizes and larger areas in between for enough space for, cars bikes and pedestrians.

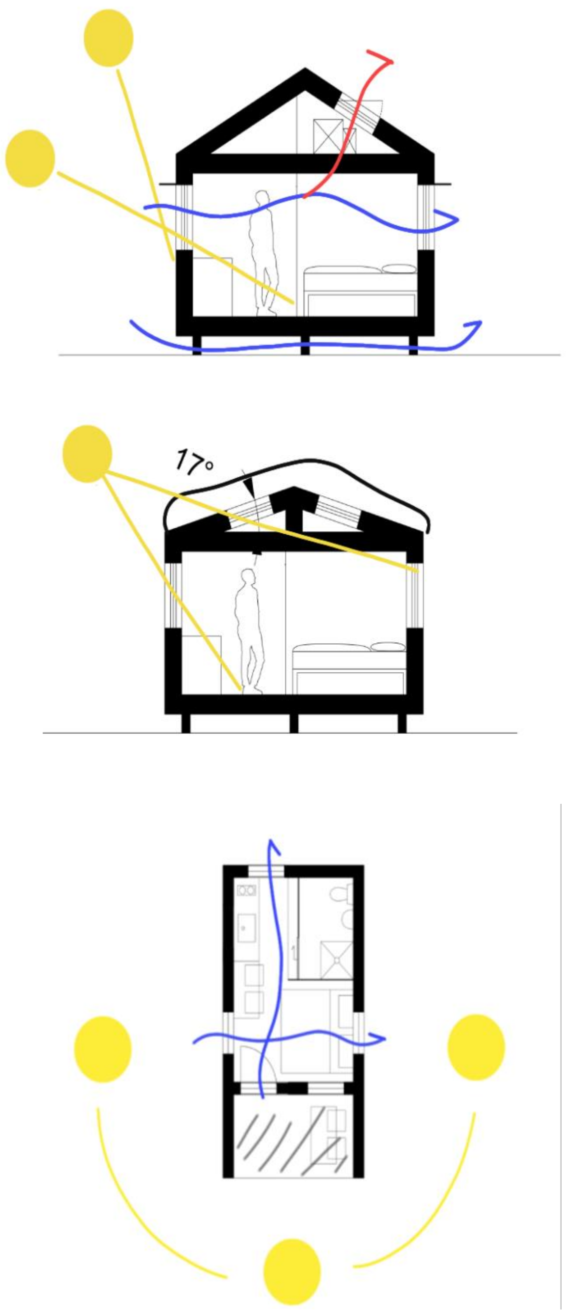


Figure 130: Climate design principals

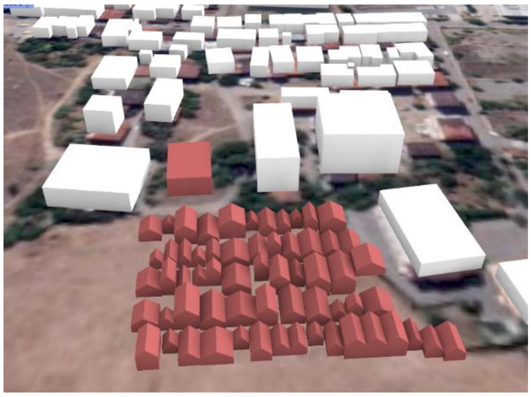


Figure 131: Urban layout Turkey

4.3.5 Impressions of 3D model:

4.3.6 Summary of key features:

1. Modular and Expandable Design
   The shelter's wooden frame structure is based on a modular grid system, allowing for easy expansion or reconfiguration. Individual modules can serve as standalone units or be combined to create larger spaces, accommodating changing needs such as growing families, additional storage, or community spaces. The structure is also designed to support up to two stories, maximizing utility in limited spaces.

2. Structural Materials
   The primary load-bearing components are constructed from structural plywood or oriented strand board (OSB), depending on what is locally available. These engineered wood products are chosen for their high strength-to-weight ratio, sustainability, and compatibility with CNC milling for precision and efficiency. The flexibility of using locally sourced materials reduces costs and environmental impact while promoting local economies.

3. Customizable Layouts
   The modular system enables diverse configurations, ranging from simple single room shelters to multi-room or multi-story layouts. The shelter can be adapted for various functions, such as living spaces, community halls, or clinics. Internal partitions can be added or removed as needed to suit privacy or communal requirements.

4. Sustainability and Local Adaptability
   The design emphasizes the use of renewable and recyclable materials. The wooden frame construction aligns with circular economic principles, enabling reuse or reassembly as circumstances change. Roof overhangs and wall cladding can be adapted to local climates, providing shade in hot regions or increased insulation in colder environments.

5. Ease of Assembly
   The shelter is designed for assembly with minimal tools and expertise, making it accessible for local communities to build themselves. Prefabricated components can be CNC-milled for precision and efficiency, and interlocking joints ensure stability without the need for heavy machinery.

6. Natural Ventilation and Daylight
   Openings and ventilation gaps are included in the design to ensure airflow and reduce reliance on artificial cooling. Skylights or translucent panels are added for natural lighting.

7. Thermal Performance:
   Insulation materials can be added to walls and roofs to enhance thermal comfort, particularly in extreme climates.

8. Cultural and Aesthetic Flexibility
   The modular system allows for integration of culturally significant elements, such as specific roof shapes or decorative facades, ensuring the design resonates with local traditions and preferences.

5. Structural design of the temporary shelter

In this chapter the structural design will be worked out. The general concept, load cases and design values are necessary to calculate the size of the members and make sure the shelter is structurally sound and know what I need for the application.

5.1 General concept

The design utilizes portal frames as the primary structural components. As discussed in the previous chapter, the user defines a layout, and the application generates a grid based on that layout to determine the placement of frames and their connective elements.

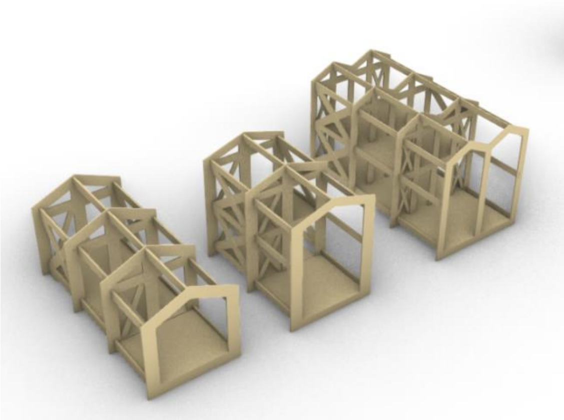


Figure 132: Frame structure for different options
Source: own model

Two types of portal frames are employed: one for the interior space (shown on the left) and another for the exterior porch area (on the right, see Figure 133). Initially, only the first option was included, but introducing a middle column enhanced the structural stability and provided greater flexibility for interior divisions. This adjustment allows users to fully utilize the open space if desired or easily partition it to suit their specific needs.

The roof and walls will be connected to the frames directly, the floors to the connective elements in between who in turn area carries by the frames as seen in the diagram below.

Figure 133: General shape of the portal frames
Source: Own drawing

To create lateral stability at least 2/5th of each side has bracing, there will always be braces in either corner but the rest of them are able to be moved if the user wants to put a window in a certain spot.

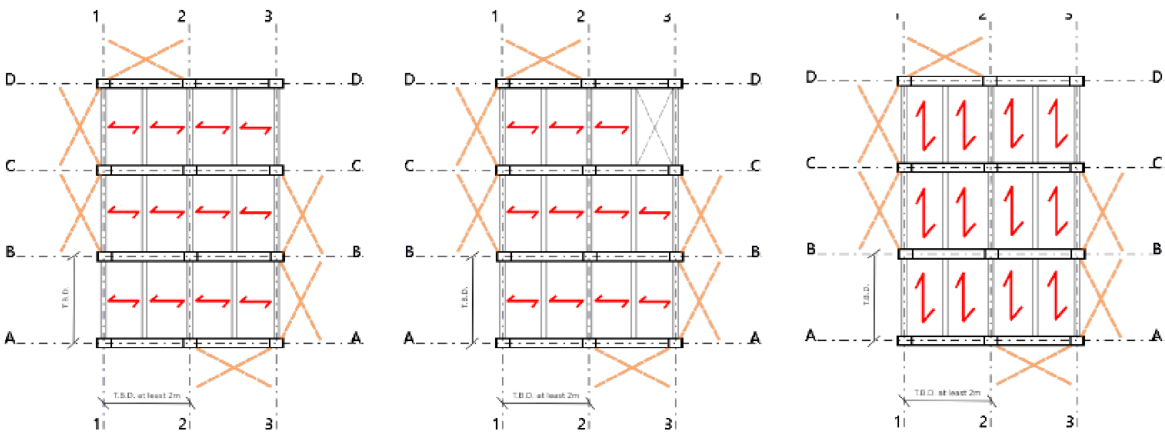


Figure 134: Structural diagram
Source: Own drawing

5.1.1 Materiality and production

The structure of the shelter consists entirely of either Plywood or OSB based on what the user chooses. Both wooden plate materials can be CNC machined in a 3-axis CNC machine. They will be cut from standard sizes sheet (typically around 1220 by 2440 mm). They should at least have an FSC label to make sure they are sustainably fetched and produced.

Since the CNC machine can only mill from the top to the bottom of the material, creating elements with two opposing faces or differing geometries on each side can be quite challenging. This process requires precise alignment, as the material must first be drilled from one side, then flipped and positioned exactly mirrored to mill the other side accurately. To simplify production, I aimed to minimize the use of such designs as much as possible. However, despite these efforts, a few components with opposing geometries were still necessary in the final design.

There are however guides on how to do this, more easily like drilling holes in the corners of the material that can when mirrored exactly align again and since these files are created by the application, the user only had to be learned, when/ how to flip it a what file to hand in. Yet it is something to improve upon in the future.

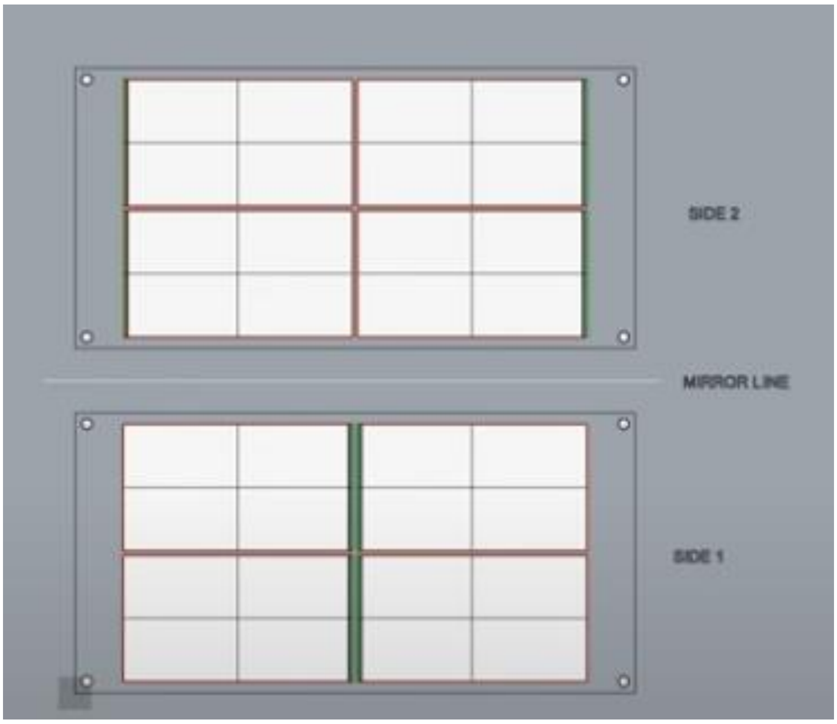


Figure 135: Example of a 2 faced geometry and set up for CNC machining
Source: CNCprojects (2022)

Though I have tried it myself with the scale model, and it was quite possible to do it even when this was the first time using my own CNC machine.

5.1.2 Joinery and ease of construction.

As for how all the cut elements then slot together, there are a few types of joints used in the structure to get the final geometry:

- Key
- Dowel
- Finger tenon
- Lapped dovetail
- Snap fit

Each chosen for their own strengths in the main direction the forces are expected to work on them. Every joint friction-fit and there is no need for glue or any other type of adhesive to bring everything together. Joined in such a way there the structure is sound yet if needed fully deconstructable or upgradable. As Key slots are nice to join two surfaces slender surfaces together, dowels are nice to use when you want something preventing to slide out like the bracings, finger tenons are nice to join two surfaces on an angle and the dove tail to join larger surfaces together (edge to edge). Snap fits are nice just like the keys to 'snap' things in place but then at an angle instead of two parallel surfaces like the more lapped joints of the keys. All coming together like in the example model down below.

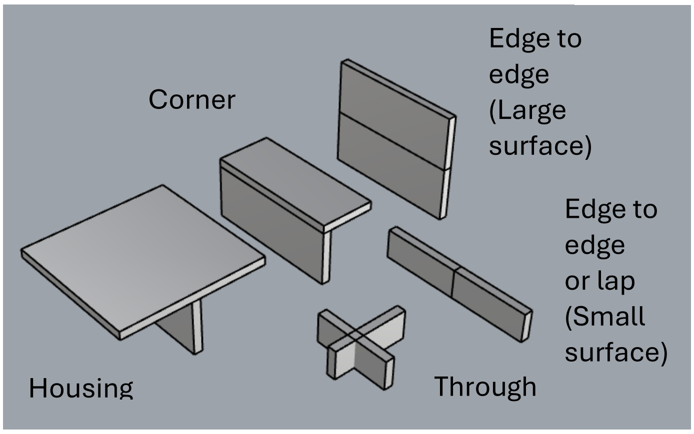


Figure 136: Different orientations of elements meeting each other
Source: Own diagram

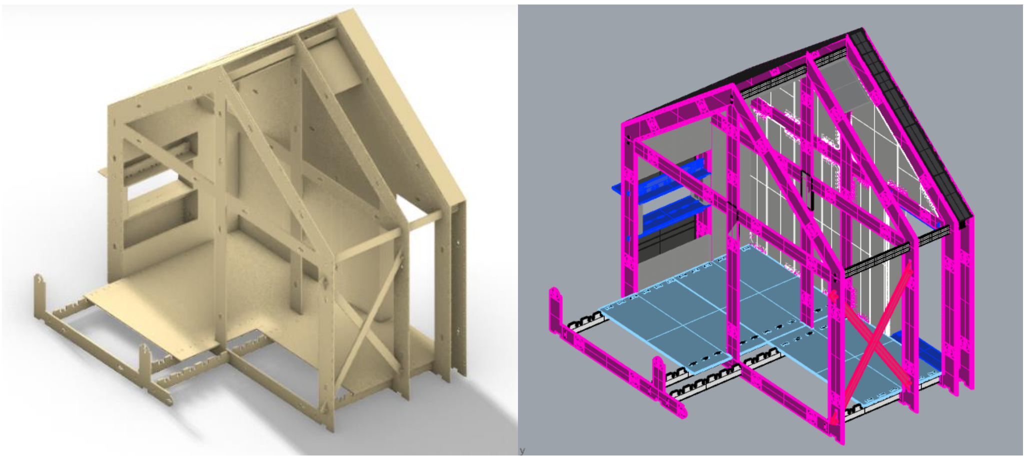


Figure 137: Detailed model of the construction
Source: Own model

So, to get into a little bit more detail, starting with the frames, they are built up from 17 different pieces (though a few of them are merely mirrored versions of the other). They are slotted together with so called key joints where the two members overlap and though the hole in the middle a key is inserted and twisted until 'locked'.

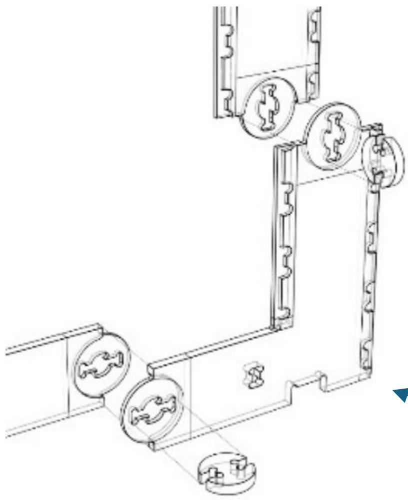


Figure 138: Key joint in the frame
Source: Own drawing

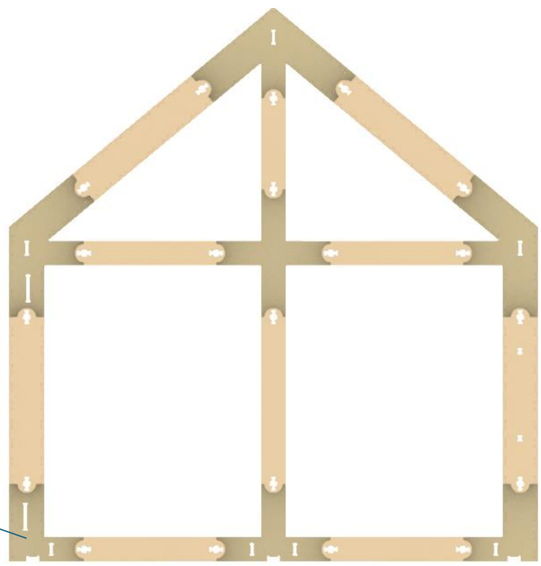


Figure 139: Frame build up
Source: Own drawing

Another point why I chose these types of joints in the primary structure is that they can be locked and unlocked, which gives the opportunity to also when repairs are needed to get pieces out and change them instead of forsaking the whole thing. Additionally, this gives the opportunity for people to upgrade their structure if needed in both x, y and z direction. Want to add more frames to the sides, you can change the columns with ones with keys to lock two together.

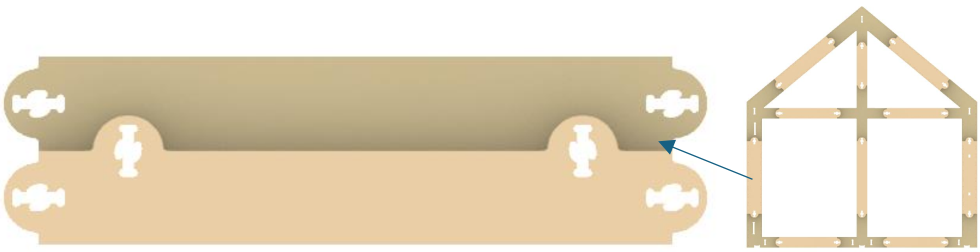


Figure 140: Element that joins two frames together
Source: Own model

And adding more frames to the front and back is also not too much of a problem either, again you can remove the most outer frame (this one has a slightly different set up from the rest see the next part), insert any new ones and place back the old one at the end.

The frames also hold the walls and roof, this is done using a hidden finger joint. This is however where the double-faced geometries come in as each face of the ridge is on either side of the frame to hold both the left and right wall element (except for the most outer ones these only have the slots on one side, though in some cases the keyed joint is also on the other side of the face.

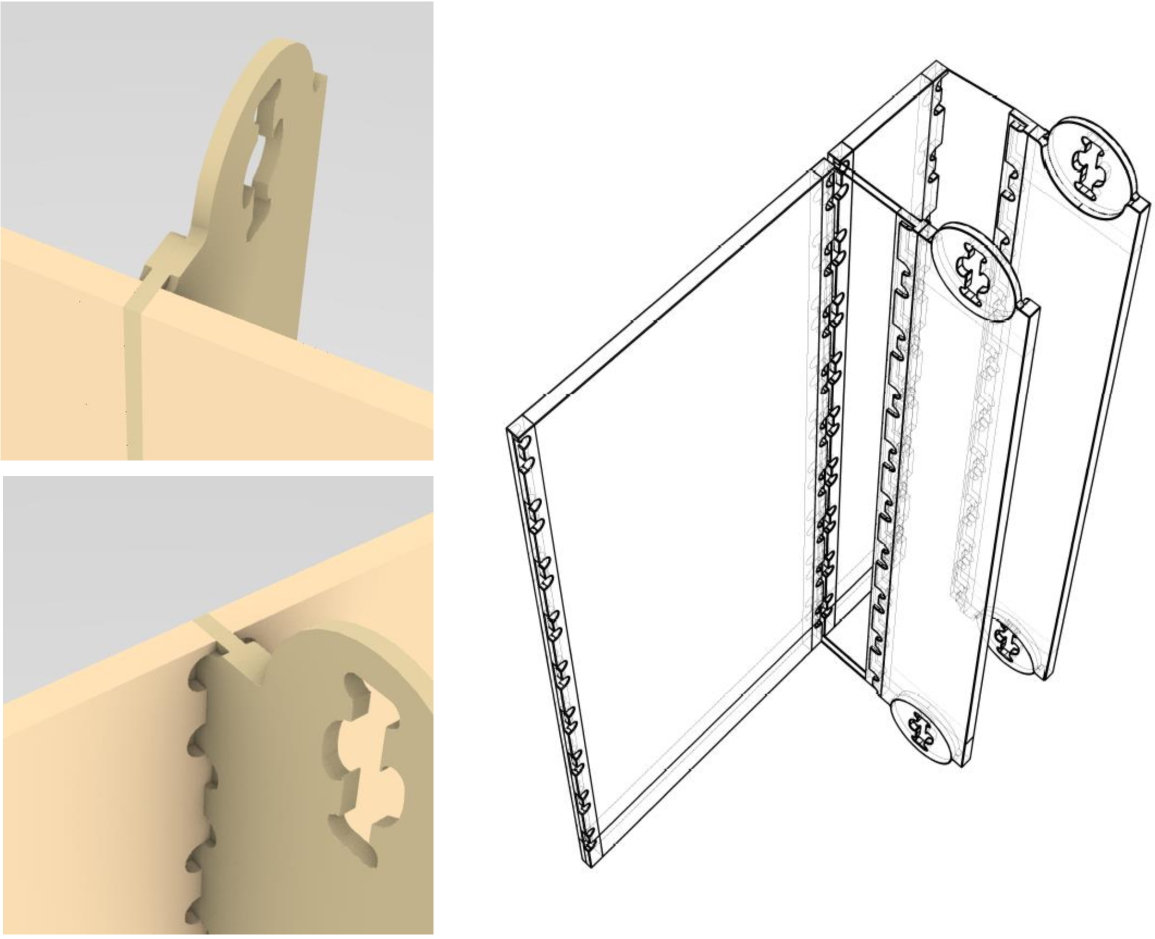


Figure 141: Example of frame to wall sheeting joint (hidden finger joint, can't or hard to be seen from the outside)
Source: Own drawings

The frames themselves are connected by horizontal elements that run from the front to the back, connected by a single dovetail joint and 'locked' by both the frames they run trough as well as the end point who are set up as snap fit joints, again in case people would want to expand. The floor joists also have finger joints to be able to connect the floor plates. The frames for the windows are similarly done as to the floorplates.

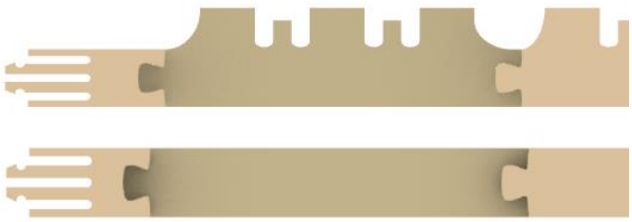


Figure 142: Connecting pieces of the frames
Source: Own drawing

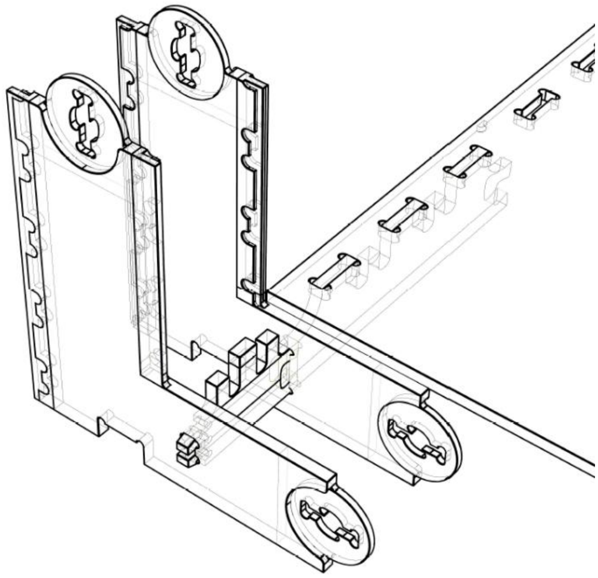


Figure 143: Joint from outer frame to joining element to floor
Source: Own drawing

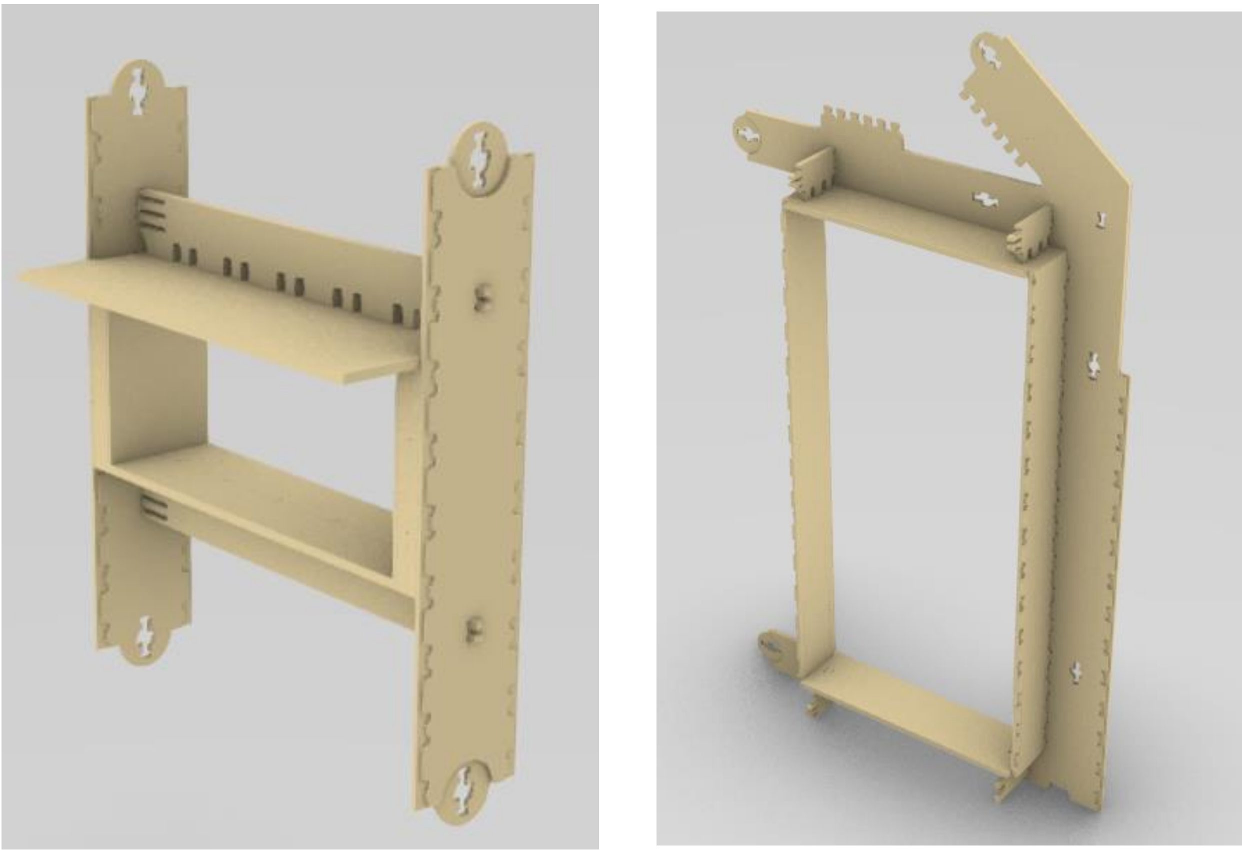


Figure 144: Window and door detail
Source: Own model

The bracings are simply doweled from both sides to resist both compressive and tensive forces.

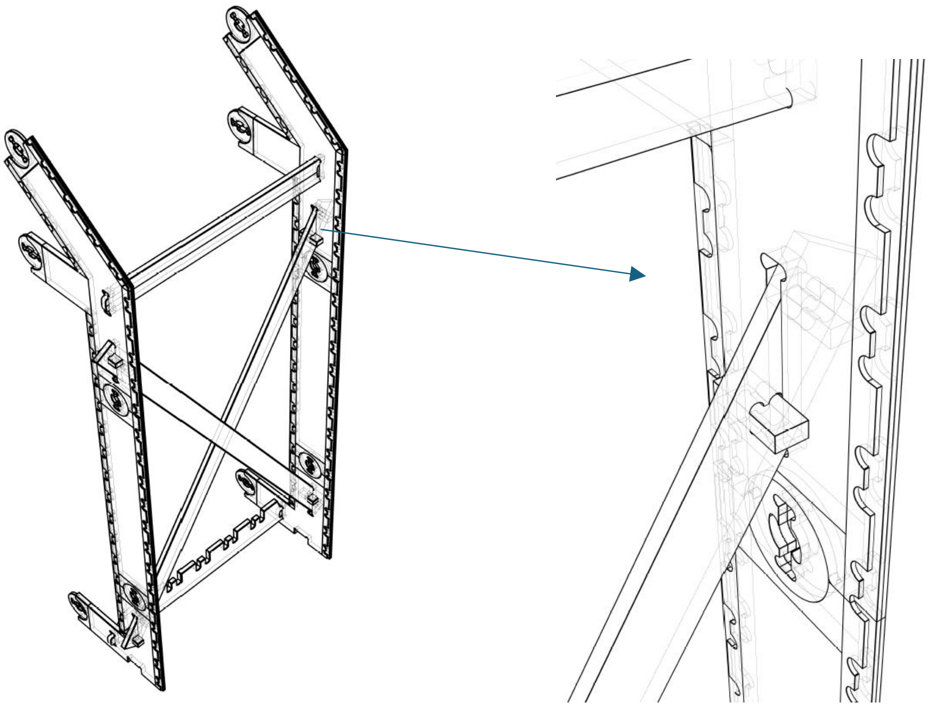


Figure 145: Bracing joints
Source: Own drawings

The final joint to address is the one that closes the frame, effectively uniting it into a single cohesive sheet. This joint uses a double-layered dovetail design and can only be inserted in one direction. The insertion direction is perpendicular to the anticipated forces, such as wind pressure from the exterior. This ensures that the sheets are securely locked in place, minimizing the risk of separation or displacement under external forces.

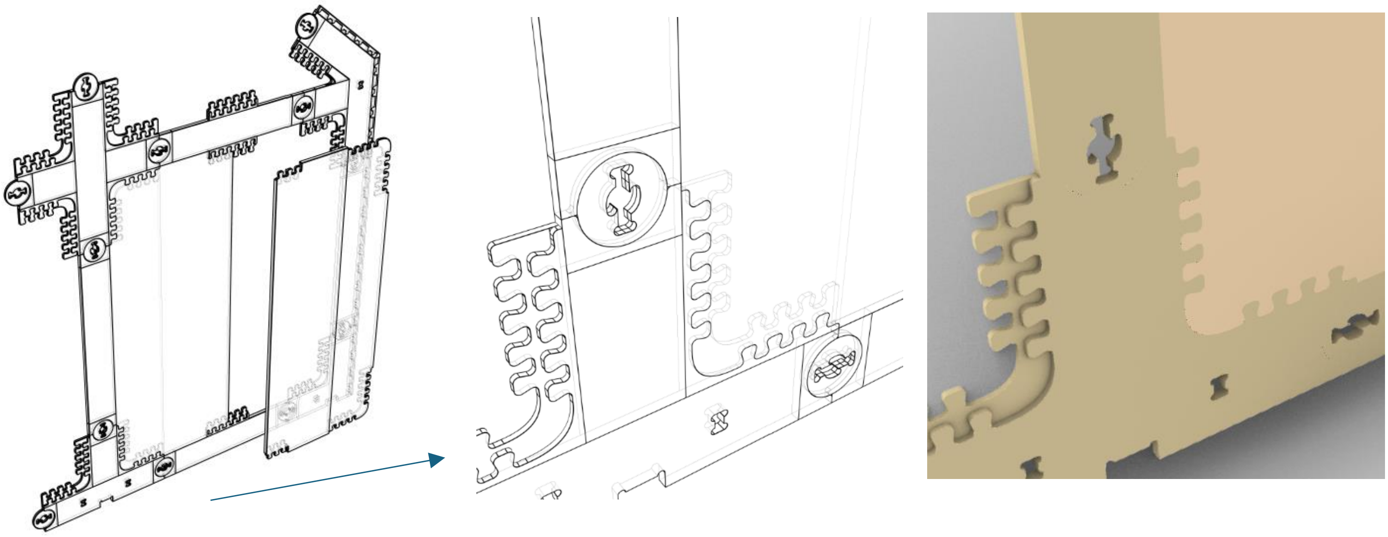
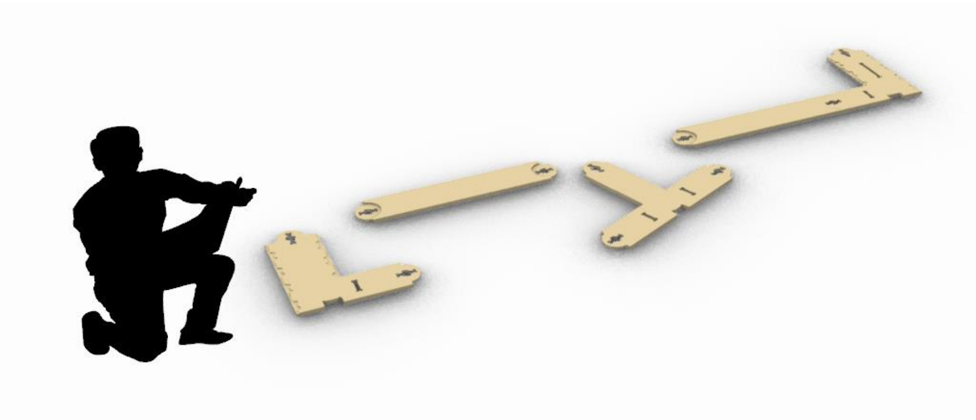


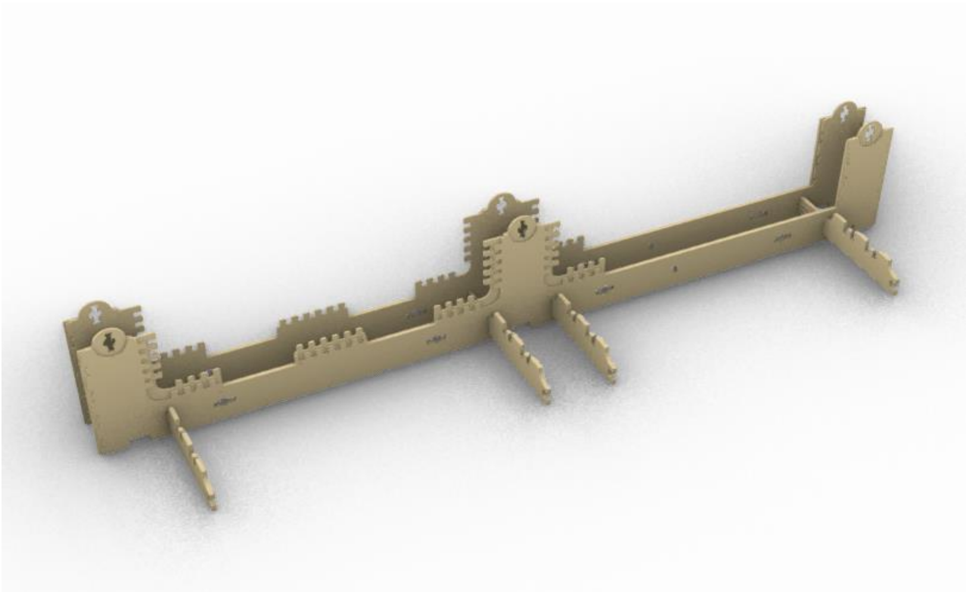
Figure 146: Edge joints between wall plate and frames
Source: Own drawing

5.1.3 Building sequence

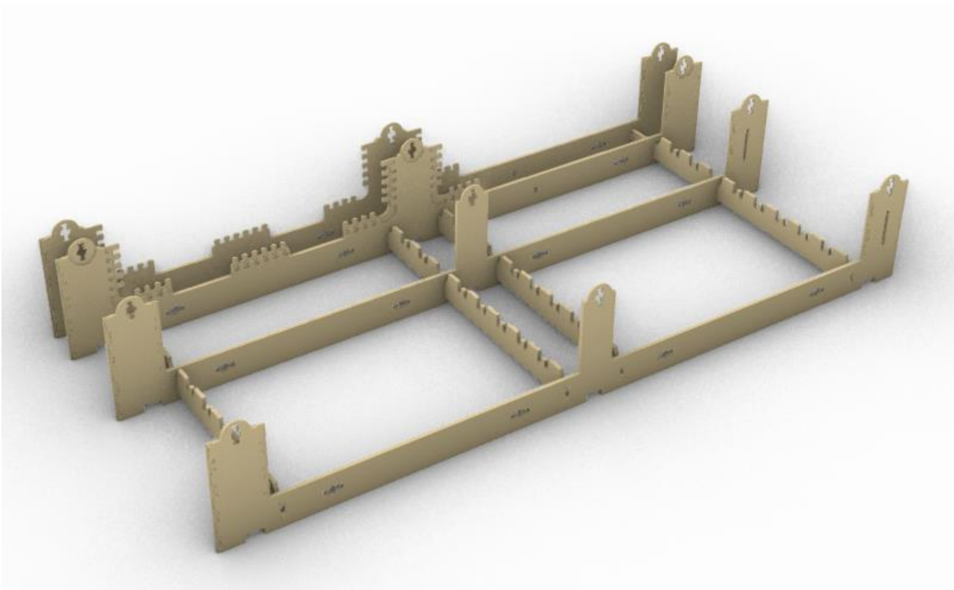
So how do all of them go together? In what order should people build the structure?



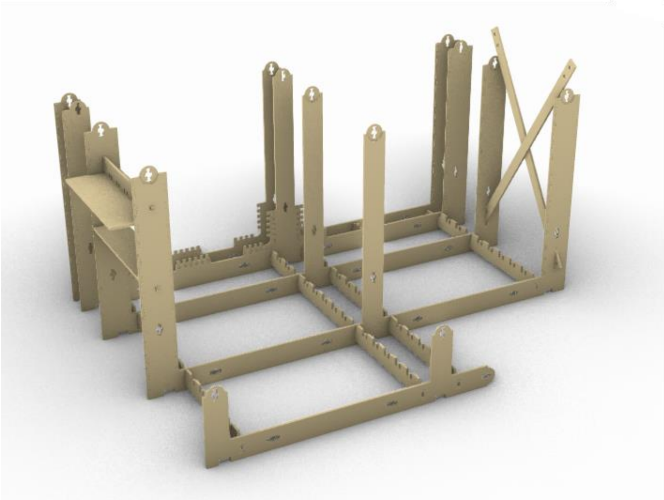
1. Connect the bottom parts of the frames



2. Raise the joint bottoms and connect with connector pieces.

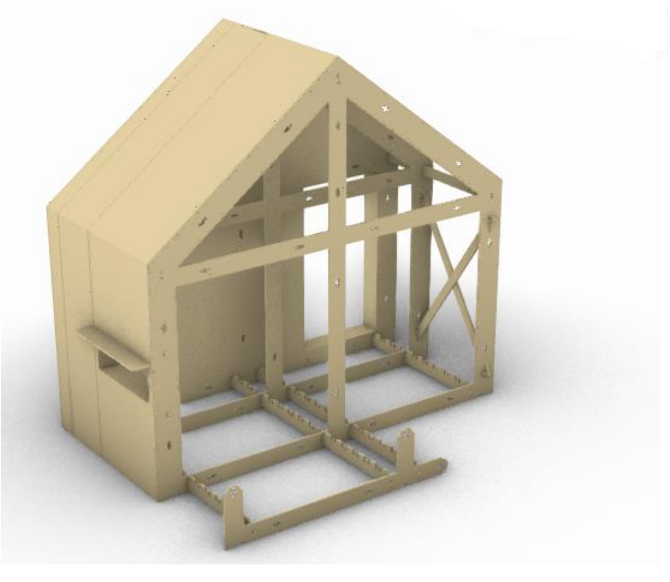


3. Repeat step 2 until the construction of the floor is there. (Don't forget possible connections for the doors)

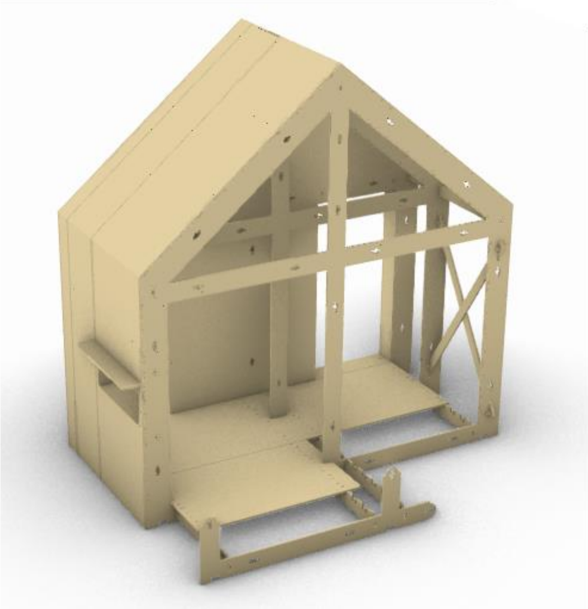


4. Then continue adding the columns, windows and bracing.

5. Add the rest of the frames and connections in the same manner until you have a structure standing



6. Add the walls (first inside then insulate then outside)



7. Lastly add the floors, the outside and inside finishing layer and doors as wel as actual windows

5.2 Load cases

As for the load cases, the following cases will be considered in the calculations:

Table 2: Load cases

LC1	Permanent load
LC2	Snow centric
LC3	Snow excentric
LC4	Wind loads left side
LC5	Wind loads front side
LC6	Wind under pressure
LC7	Wind overpressure
LC8	Floor load distributed
LC9	Floor load concentrated
LC10	Seismic load horizontal
LC11	Seismic load vertical

5.2.1 Permanent load

The permanent load are the forces that work on the structure that like the name are permanent. Like floors walls beams etc. otherwise called dead load (Gk).

It consists of the weight of the members themselves (qeg in kN/m) and the weight of everything else permanently resting upon it (things like floors, installations, lights etc. qr in kN/m^2).

For qeg the area of the cross section (width * height) is needed to determine the load based on the material density (kN/m^3).

For the qr the thickness of the materials the floor and other elements resting upon it permanently is needed.

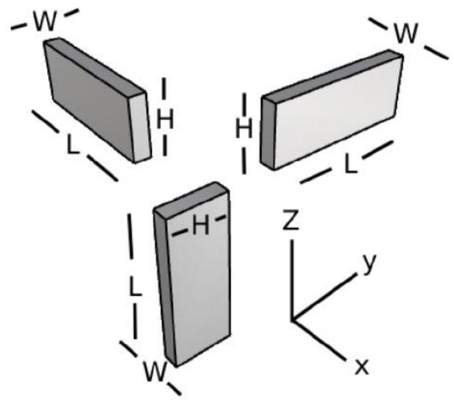


Figure 147: With and height in of the load baring elements in different orientations
Source: Own diagram

The density in both cases will come from the datasheet of the various materials used and chosen by the user, or a standard value would be used for things such as lights and installations to determine the loads. The thickness (width) is also based on what the user chooses. Do they choose to go with 18mm plywood then this will be their thickness or width (W) of the cross section. The height (H) will be determined first by rule of thumb. Later after checking failure criteria, the height will be adapted and optimized (see 5.4 failure criteria).

The formulas would be as follows:

- qeg = density * area
- qr = density * thickness (W)
- Gk = qeg + qr

Beams floor	1/12 l
Beams roof (not walkable)	1/20 l
Column	1/20 l

Table 3: Rule of thumb determination for H
Source: Arends (2017)

5.2.2 Snow loads

Both, Turkey as well as the Netherlands occasionally have to deal with snow. Turkey more so than the Netherlands but it is still important to take into account.

According to EN1991-1-3 where the snow loads are discussed, the structure should at least calculate snow load as a centric or unified snow load and one in case that the snow will shift because of wind or other factors (eccentric or drifted snow loads).

A few other factors named for the calculation are:

- The shape of the roof
- Thermal properties
- Roughness
- Amount of heat generation under the roof
- Proximity of other buildings
- Surrounding terrain
- And local climate (wind, temperature variations and likelihood of additional snow or rain)

The snow load on the roof can then be calculated as follows:

$$s = \mu_i \; C_e \; C_t \; s_k$$

Where:
Sk = Characteristic value of snow on the ground
μi = Snow load shape coefficient
Ce = exposure coefficient
Ct = Thermal coefficient

In this case Ct can be set to 1, as the roof will always have insulation in colder climates and thus the heat conduction will be < 1W/m^2K.

Ce depends on the surroundings, if the wind can easily get to the snow or not and move it. In case of the Netherlands, this could be definite factor on the chosen site. It is sheltered by trees but also near some open water and not too many high buildings so this can conservatively be set as 0.8. For Turkey where in most cases there are higher buildings in the close proximity, but the site itself might me more open a value of 1.0 could be used.

Table 4: Recommended values for Ce
Source: Table 5.1 in EN1991-1-3:2003

Topography	C_e
Windswept [a]	0,8
Normal [b]	1,0
Sheltered [c]	1,2

[a] *Windswept topography*: flat unobstructed areas exposed on all sides without, or little shelter afforded by terrain, higher construction works or trees.

[b] *Normal topography*: areas where there is no significant removal of snow by wind on construction work, because of terrain, other construction works or trees.

[c] *Sheltered topography*: areas in which the construction work being considered is considerably lower than the surrounding terrain or surrounded by high trees and/or surrounded by higher construction works.

As for the μi this value depends on the angle, and shape of the roof. The shelter will have a pitched roof either with a slope lower than 30 or exactly 30, in case of respectively colder climates and hurricane or high wind force prone areas. Higher than 30 will also be used in more tropical or warmer climates but for this case study, only the category in the table below is applicable (0 < a < 30). μ1(0) is set as 0.8 unless otherwise specified in national regulations.

Table 5: Snow load shape coefficient
Source: NEN1991-1-3+C1+A1:2019

Hoek van het dak α	**$0° \leq \alpha \leq 30°$**	**$30° < \alpha < 60°$**	**$\alpha \geq 60°$**
$\mu_1(\alpha)$	$\mu_1(0°) \geq 0{,}8$	$\mu_1(0°) \times (60° - \alpha) / 30°$	0,0
$\mu_2(\alpha)$	0,8	$0{,}8 \times (60° - \alpha) / 30°$	0,0
$\mu_3(\alpha)$	$0{,}8 + 0{,}8\ \alpha / 30$	1,6	--

As for the shape, there are two options, a single span pitched roof or multi span roofs.

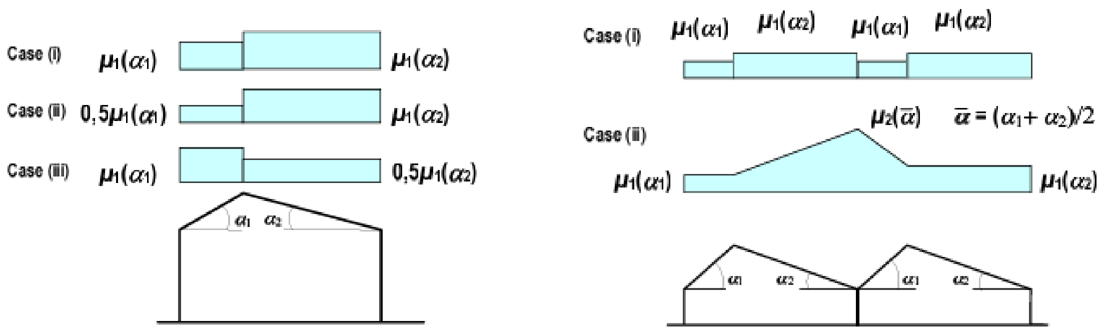


Figure 148: Diagram for determining the μi
Source: EN1991-1-3:2003

The Sk value is based on set national standards, for Istanbul the Sk is 0.75 kN/m^2 for the Netherlands it’s 0.7 kN/m^2 (Dlubal, 2024).

5.2.3 Wind loads

The wind loads on the structure are dependent on the surrounding terrain and height of the building and the amount of wind in the area.

Table 6: Terrain categories for wind and their parameters
Source: EN 1991-1-4:2005

	Terrain category	z_0 m	z_{min} m
0	Sea or coastal area exposed to the open sea	0,003	1
I	Lakes or flat and horizontal area with negligible vegetation and without obstacles	0,01	1
II	Area with low vegetation such as grass and isolated obstacles (trees, buildings) with separations of at least 20 obstacle heights	0,05	2
III	Area with regular cover of vegetation or buildings or with isolated obstacles with separations of maximum 20 obstacle heights (such as villages, suburban terrain, permanent forest)	0,3	5
IV	Area in which at least 15 % of the surface is covered with buildings and their average height exceeds 15 m	1,0	10
NOTE: The terrain categories are illustrated in A.1.			

Mean wind velocity

Before the wind load can be calculated we first need a few more basic values like the mean wind velocity. Which is in this case gathered by the plugin in Grasshopper called Ladybug. Here you can, based on EWP files, gather meteorological data of the location and analyze them. One of the components can thus with the input of the height (default 10 meters) and the type of terrain as discussed above here determine the mean wind velocity.

The mean wind velocity is dependent on the height it sits at and the tomography of the surrounding terrain and the Vb0 and could be calculated by hand as well with this formula (EN-1991-1-4:2005):

$$v_m(z) = c_r(z) \cdot c_o(z) \cdot v_b$$

The Vb0, is the characteristic 10 minutes mean wind velocity irrespective of the wind direction, or time of year 10 meters above ground level in a terrain like II in the table above. For the Netherlands, delft this is 27.0 m/s (NEN EN-1991-1-4, wind zone II). For Türkiye this is set as 28.0 m/s (TS-EN 1991-4). The others are factors incorporating the terrain roughness (Cr) and the orography factor (Co).

Wind turbulence

Another value we need is the wind turbulence intensity which can be determined as follows:

$$I_v(z) = \frac{\sigma_v}{v_m(z)} = \frac{k_l}{c_o(z) \cdot \ln(z/z_0)} \quad \text{for} \quad z_{min} \leq z \leq z_{max}$$

$$I_v(z) = I_v(z_{min}) \quad \text{for} \quad z < z_{min}$$

Where:

Kl = Turbulence factor (recommended to set to 1)

C0 = Orography factor (is 1 unless otherwise specified)

Z0 =roughness length (in Table 6)

Peak velocityTable 6: Terrain categories for wind and their parameters

Next to that we also need the Peak velocity pressure (qp(z)) which is calculated like so:

$$q_p(z) = \left[1 + 7 \cdot I_v(z)\right] \cdot \tfrac{1}{2} \cdot \rho \cdot v_m^2(z) = c_e(z) \cdot q_b \quad \text{and} \quad c_e(z) = \frac{q_p(z)}{q_b}$$

Where:

p = air density

Ce(z) = exposure factor

qb = basic velocity pressure

With qb for the Netherlands being 0.46 kN/m^2 and 0.49 kN/m^2 for Türkiye. The value 7 comes from a peak factor of 3.5.

Wind pressure on surfaces

Another value is the wind pressure the wind creates. The external pressure (We) and internal pressure (Wi) are calculated with the next formulas:

$$w_e = q_p(z_e) \cdot c_{pe} \qquad w_i = q_p(z_i) \cdot c_{pi}$$

Where:

Cpe/Cpi = the pressure coefficient

Who in turn can be determined by determining the geometric shape and gathering the right values from the tables (Section 7 in EN 1991-1-4).

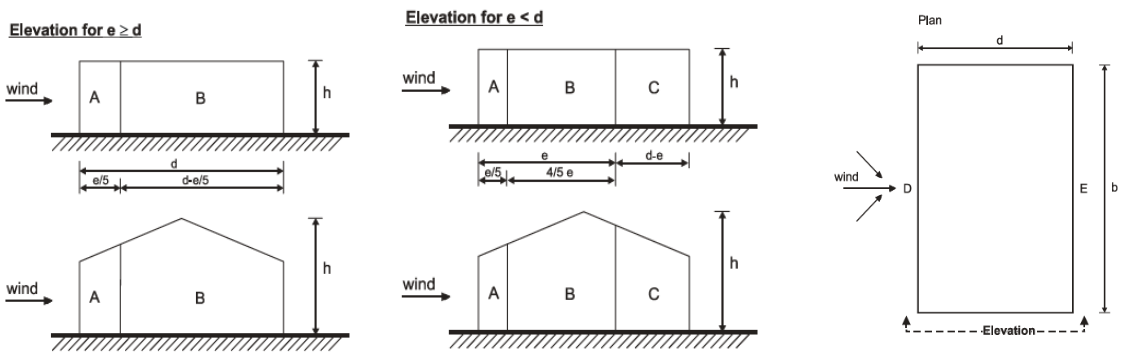


Figure 149: Zones of the wall's sections

Source: EN 1991-1-4

Table 7: Recommended values of external pressure
coefficient of vertical walls in each zone as seen above
Source: EN-1991-1-4

Zone	A		B		C		D		E	
h/*d*	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$
5	-1,2	-1,4	-0,8	-1,1	-0,5		+0,8	+1,0	-0,7	
1	-1,2	-1,4	-0,8	-1,1	-0,5		+0,8	+1,0	-0,5	
≤ 0,25	-1,2	-1,4	-0,8	-1,1	-0,5		+0,7	+1,0	-0,3	

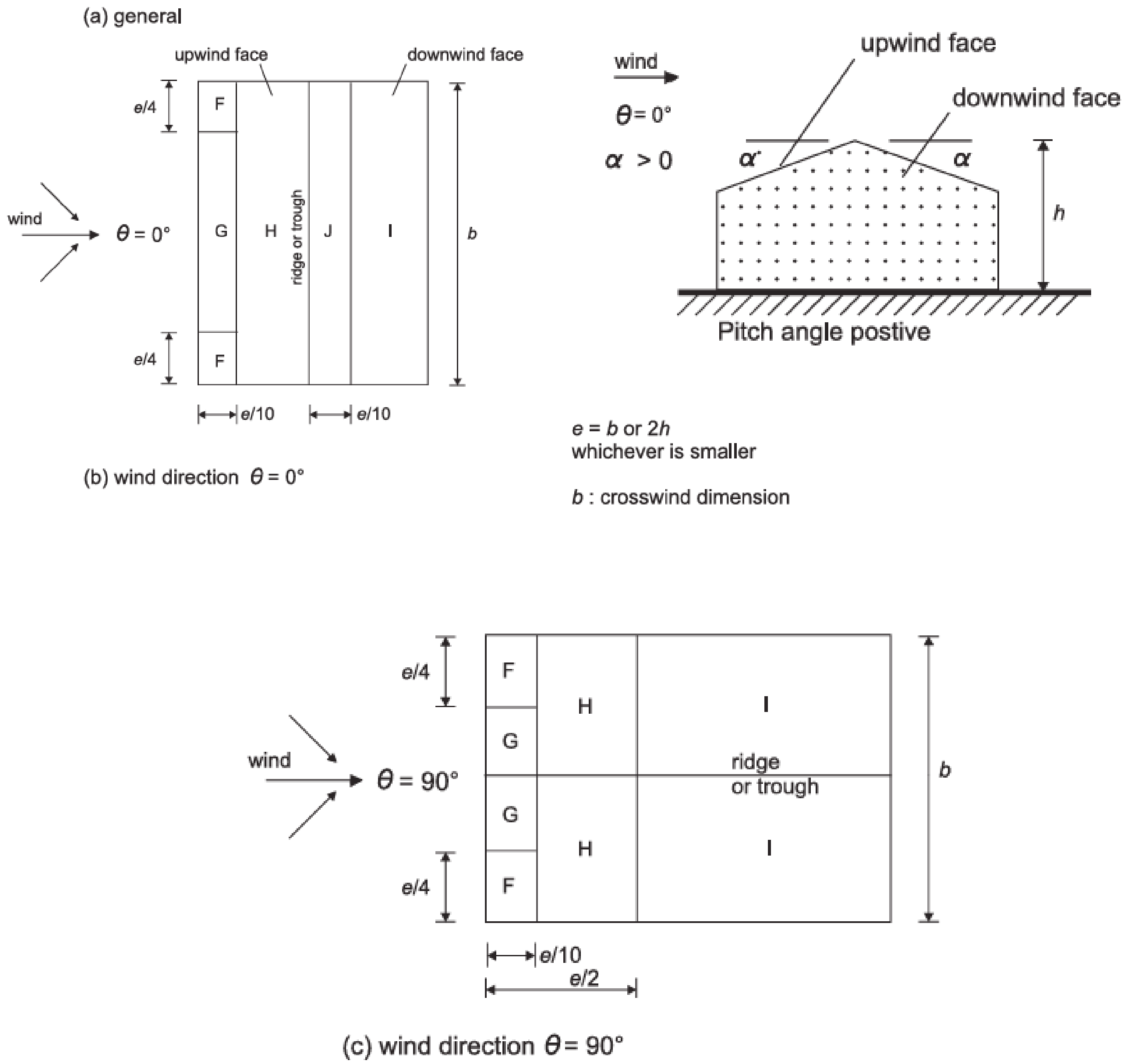


Figure 150: Duo pitched roof zoning for pressure coefficient
Source: EN 1991-1-4

Pitch Angle α	Zone for wind direction $\theta = 0°$									
	F		G		H		I		J	
	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$
-45°	-0,6		-0,6		-0,8		-0,7		-1,0	-1,5
-30°	-1,1	-2,0	-0,8	-1,5	-0,8		-0,6		-0,8	-1,4
-15°	-2,5	-2,8	-1,3	-2,0	-0,9	-1,2	-0,5		-0,7	-1,2
-5°	-2,3	-2,5	-1,2	-2,0	-0,8	-1,2	+0,2		+0,2	
							-0,6		-0,6	
5°	-1,7	-2,5	-1,2	-2,0	-0,6	-1,2	-0,6		+0,2	
	+0,0		+0,0		+0,0				-0,6	
15°	-0,9	-2,0	-0,8	-1,5	-0,3		-0,4		-1,0	-1,5
	+0,2		+0,2		+0,2		+0,0		+0,0	+0,0
30°	-0,5	-1,5	-0,5	-1,5	-0,2		-0,4		-0,5	
	+0,7		+0,7		+0,4		+0,0		+0,0	
45°	-0,0		-0,0		-0,0		-0,2		-0,3	
	+0,7		+0,7		+0,6		+0,0		+0,0	
60°	+0,7		+0,7		+0,7		-0,2		-0,3	
75°	+0,8		+0,8		+0,8		-0,2		-0,3	

NOTE 1 At $\theta = 0°$ the pressure changes rapidly between positive and negative values on the windward face around a pitch angle of $\alpha = -5°$ to $+45°$, so both positive and negative values are given. For those roofs, four cases should be considered where the largest or smallest values of all areas F, G and H are combined with the largest or smallest values in areas I and J. No mixing of positive and negative values is allowed on the same face.

NOTE 2 Linear interpolation for intermediate pitch angles of the same sign may be used between values of the same sign. (Do not interpolate between $\alpha = +5°$ and $\alpha = -5°$, but use the data for flat roofs in 7.2.3). The values equal to 0,0 are given for interpolation purposes

Table 8: External pressure coefficient duo pitch roof
Source: EN 1991-1-4

Table 9: External pressure coefficient duo pitch roof
Source: EN 1991-1-4

Pitch angle α	Zone for wind direction $\theta = 90°$							
	F		G		H		I	
	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$
-45°	-1,4	-2,0	-1,2	-2,0	-1,0	-1,3	-0,9	-1,2
-30°	-1,5	-2,1	-1,2	-2,0	-1,0	-1,3	-0,9	-1,2
-15°	-1,9	-2,5	-1,2	-2,0	-0,8	-1,2	-0,8	-1,2
-5°	-1,8	-2,5	-1,2	-2,0	-0,7	-1,2	-0,6	-1,2
5°	-1,6	-2,2	-1,3	-2,0	-0,7	-1,2	-0,6	
15°	-1,3	-2,0	-1,3	-2,0	-0,6	-1,2	-0,5	
30°	-1,1	-1,5	-1,4	-2,0	-0,8	-1,2	-0,5	
45°	-1,1	-1,5	-1,4	-2,0	-0,9	-1,2	-0,5	
60°	-1,1	-1,5	-1,2	-2,0	-0,8	-1,0	-0,5	
75°	-1,1	-1,5	-1,2	-2,0	-0,8	-1,0	-0,5	

Or when there are multiple units together:

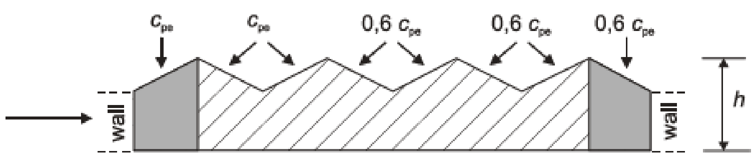


Figure 151: Pressure coefficient in multi span roofs
Source: EN 1991-1-4

With those the wind force can be calculated in two ways, one by simply using force coefficients or what I adapted here by using the surface pressures. Where the summation of Few, Fwi and Ffr are calculated. For this the area of the surface (Aref) is needed. Ffr is disregarded in this case as the ratio of width to length is always 2:3 or 1:1 by the same height of 2200mm. So, the area of the surfaces perpendicular to the wind is always less than 4 times the total area perpendicular to the wind.

external forces:

$$F_{w,e} = c_s c_d \cdot \sum_{\text{surfaces}} w_e \cdot A_{ref}$$

internal forces:

$$F_{w,i} = \sum_{\text{surfaces}} w_i \cdot A_{ref}$$

friction forces:

$$F_{fr} = c_{fr} \cdot q_p(z_e) \cdot A_{fr}$$

CsCd here is the structural factor which can be set as 1 as the building's height is always less than 15 meters.

5.2.4 Floor loads

The floor loads or loads that are variable, things like people walking around furniture etc. These can be distributed (qk) or focused on one point (Qk). In the national annex of each country in the Eurocode they have fixed values for these based on how the building is used.

Table 10: Variable floor loads

Source: NB.1+2 – 6.2+6.4 in E

Klasse van belaste oppervlakte	q_k [kN/m2]	Q_k [kN] [a]
Klasse A (wonen en huishoudelijk gebruik)		
A-vloeren	1,75	3
A-trappen	2,0	3
A-balkons	2,5	3
Klasse B (kantoorruimten)		
B-kantoorruimten	2,5	3
Klasse C (bijeenkomstruimten)		
C1-tafels: ruimten in scholen, cafés, restaurants, eetzalen, leeszalen, ontvangstruimten	4,0 [b]	7
C2-vaste zitplaatsen: ruimten in kerken, theaters of bioscopen, conferentiezalen, collegezalen, vergaderzalen, wachtkamers, wachtkamers/ -lokalen in stations	4,0 [b]	7
C3-zonder obstakels voor rondlopende mensen: ruimten in musea, tentoonstellingsruimten enz. en toegangsruimten in openbare gebouwen en kantoren, hotels, ziekenhuizen, stationshallen.	5,0	7
C4-fysieke activiteiten: danszalen, gymnastiekzalen, toneel-/balletpodia enz.	5,0	7
C5-grote mensenmassa's: gebouwen voor openbare evenementen, zoals concertzalen, sporthallen met inbegrip van tribunes, bordessen en toegangsruimten, stationsperrons	5,0	7
Klasse D (winkelruimten)		
D1-kleinhandel	4,0 b	7
D2-warenhuizen / supermarkten	4,0 b	7
Klasse D (opslag en industrieel gebruik)		
E1-winkels	≥ 5	≥ 7
E1-bibliotheken	≥ 2,5 [c]	≥ 3
E1-overige	≥ 5	≥ 10
E2-industrieel gebruik	≥ 3 [d]	≥ 7 [d]
Klasse F (garages en voertuigverkeersruimten)		
F- lichte voertuigen lichter dan 25 kN	2	10
Klasse G (garages en voertuigverkeersruimten)		
G1-middelzware voertuigen 25 kN tot 120 kN	5	40
G2-voertuigen zwaarder dan 120 kN	G_v/A_v [e]	2 × max. krikbel.
Klasse H (daken niet toegankelijk)		
H1-dakhelling α: $0 \geq \alpha < 15°$	1,0 [f]	1,5
H2-dakhelling α: $15 \geq \alpha < 20°$	$4 - 0{,}2 \times \{\alpha\}$ [f]	
H3-dakhelling α: $\alpha \geq 20°$	0	
Daken van onder het maaiveld gelegen ruimten		
geen verkeersbelasting	4 [f]	7

[a] De puntlasten moeten zijn aangebracht op een oppervlakte van 100 mm × 100 mm; de gegeven waarden moeten ook zijn gebruikt voor constructies van ondergeschikte betekenis.

[b] Voor *schoolgebouwen* volstaat een vloerbelasting van 2,5 kN/m².

[c] Waarde toe te passen voor de ruimten tussen de stellingen; voor het oppervlak met de stellingen geldt het totaal gewicht van de stelling met boeken (6 kN/m²): $A_{st} \times h_{st} \times 6$ kN.

[d] Afhankelijk van het bedoelde gebruik.

[e] G_v is het gewicht per voertuig in kN en A_v is de door het voertuig ingenomen oppervlak in m².

[f] De belasting q_k werkt op een oppervlakte A van 10 m², binnen de grenzen van nul tot het hele dakoppervlak.

5.2.5 Seismic loads

In the case of Istanbul, it is also good to look at possible seismic loads. The forces and stresses that these loads bring with are determined by a couple of things, like ground conditions and the stiffness of the structure.

For this I'll be using a linear-elastic analysis, using lateral force for the method of analysis. For this I need the location of the shelter, the soil type, the building's geometry and set up (mainly the story heights, dead loads per story and the plan including the walls in the direction of the force).

Table 11: Soil types and parameters
Source: NEN-EN 1998-1:2005

Ground type	Description of stratigraphic profile	Parameters		
		$v_{s,30}$ (m/s)	N_{SPT} (blows/30cm)	c_u (kPa)
A	Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface.	> 800	_	_
B	Deposits of very dense sand, gravel, or very stiff clay, at least several tens of metres in thickness, characterised by a gradual increase of mechanical properties with depth.	360 – 800	> 50	> 250
C	Deep deposits of dense or medium-dense sand, gravel or stiff clay with thickness from several tens to many hundreds of metres.	180 – 360	15 - 50	70 - 250
D	Deposits of loose-to-medium cohesionless soil (with or without some soft cohesive layers), or of predominantly soft-to-firm cohesive soil.	< 180	< 15	< 70
E	A soil profile consisting of a surface alluvium layer with v_s values of type C or D and thickness varying between about 5 m and 20 m, underlain by stiffer material with v_s > 800 m/s.			
S_1	Deposits consisting, or containing a layer at least 10 m thick, of soft clays/silts with a high plasticity index (PI > 40) and high water content	< 100 (indicative)	_	10 - 20
S_2	Deposits of liquefiable soils, of sensitive clays, or any other soil profile not included in types A – E or S_1			

With that the base shear force can be calculated by the following formula:

$$F_b = S_d(T_1) \cdot m \cdot \lambda$$

Where:
Fb = Base shear force
Sd = Ordinate of design spectrum at T1
T1 = the fundamental period of vibration of the building for considering lateral motion
m = Total mass of the building above foundation
λ = Correction factor

The correction factor being 0,85 if T1 is smaller or equal to 2 Tc or higher than 2 stories otherwise this can be set to 1.

T1 can be calculated by (for stories up to 40 stories):

$$T_1 = C_t \cdot H^{3/4}$$

Where:
Ct = All structures except a few exceptions this number is 0.050
H = Height of the building starting from just above the foundation.

Then check the value of T1 with the values down below here and calculate Sd(T1) with the following formulas for horizontal elastic response:

$$0 \le T \le T_B : S_e(T) = a_g \cdot S \cdot \left[1 + \frac{T}{T_B} \cdot (\eta \cdot 2{,}5 - 1)\right]$$

$$T_B \le T \le T_C : S_e(T) = a_g \cdot S \cdot \eta \cdot 2{,}5$$

$$T_C \le T \le T_D : S_e(T) = a_g \cdot S \cdot \eta \cdot 2{,}5\left[\frac{T_C}{T}\right]$$

$$T_D \le T \le 4\text{s} : S_e(T) = a_g \cdot S \cdot \eta \cdot 2{,}5\left[\frac{T_C T_D}{T^2}\right]$$

Where:
n = Dampening correction factor (n=1 means 5% viscous dampening)
ag = design ground acceleration (listed in the national annex or from the Dlubal (2024) database)

Table 12: Values of parameters describing the recommended type 1 elastic response spectra
Source: NEN-EN 1998-1:2005 en

Ground type	S	T_B (s)	T_C (s)	T_D (s)
A	1,0	0,15	0,4	2,0
B	1,2	0,15	0,5	2,0
C	1,15	0,20	0,6	2,0
D	1,35	0,20	0,8	2,0
E	1,4	0,15	0,5	2,0

For the vertical response these are the formulas and spectra to check against.

$$0 \le T \le T_B : S_{ve}(T) = a_{vg} \cdot \left[1 + \frac{T}{T_B} \cdot (\eta \cdot 3{,}0 - 1)\right]$$

$$T_B \le T \le T_C : S_{ve}(T) = a_{vg} \cdot \eta \cdot 3{,}0$$

$$T_C \le T \le T_D : S_{ve}(T) = a_{vg} \cdot \eta \cdot 3{,}0\left[\frac{T_C}{T}\right]$$

$$T_D \le T \le 4s : S_{ve}(T) = a_{vg} \cdot \eta \cdot 3{,}0\left[\frac{T_C . T_D}{T^2}\right]$$

Table 13: Advised spectra for type 1
Source: NEN-EN 1998-1:2005 en

Spectrum	a_{vg}/a_g	T_B (s)	T_C (s)	T_D (s)
Type 1	0,90	0,05	0,15	1,0

For elastic analysis the following formulas are used for both, ag being av in vertical response:

$$0 \le T \le T_B : S_d(T) = a_g \cdot S \cdot \left[\frac{2}{3} + \frac{T}{T_B} \cdot \left(\frac{2{,}5}{q} - \frac{2}{3}\right)\right]$$

$$T_B \le T \le T_C : S_d(T) = a_g \cdot S \cdot \frac{2{,}5}{q}$$

$$T_C \le T \le T_D : S_d(T) \begin{cases} = a_g \cdot S \cdot \frac{2{,}5}{q} \cdot \left[\frac{T_C}{T}\right] \\ \ge \beta \cdot a_g \end{cases}$$

$$T_D \le T : \quad S_d(T) \begin{cases} = a_g \cdot S \cdot \frac{2{,}5}{q} \cdot \left[\frac{T_C T_D}{T^2}\right] \\ \ge \beta \cdot a_g \end{cases}$$

Table 14: Behavior factor
Source: NEN-EN 1998-1:2005 en

Design concept and ductility class	q	Examples of structures
Low capacity to dissipate energy - DCL	1,5	Cantilevers; Beams; Arches with two or three pinned joints; Trusses joined with connectors.
Medium capacity to dissipate energy - DCM	2	Glued wall panels with glued diaphragms, connected with nails and bolts; Trusses with doweled and bolted joints; Mixed structures consisting of timber framing (resisting the horizontal forces) and non-load bearing infill.
	2,5	Hyperstatic portal frames with doweled and bolted joints (see 8.1.3(3)P).
High capacity to dissipate energy - DCH	3	Nailed wall panels with glued diaphragms, connected with nails and bolts; Trusses with nailed joints.
	4	Hyperstatic portal frames with doweled and bolted joints (see 8.1.3(3)P).
	5	Nailed wall panels with nailed diaphragms, connected with nails and bolts.

Where:

q = is the behavior factor
B = Lower factor of the horizontal design spectrum

Gravity in Karamba3D applies to all active elements in the model that have a specific weight ("gamma") greater than zero. The gravity vector specifies the direction in which gravity acts, with a vector of length one representing the normal gravitational force on Earth. So the Fd does not have to be divided up, Karamba does that for us.

The Turkish Earthquake Code (TEC-2018) provides specific guidelines for soil classification, considering factors like shear wave velocity, standard penetration test (SPT) results, and soil bearing capacity.

5.2.6 Load combinations

The different loads of course can coexist at the same time. To ensure buildings and structures can withstand extreme storms, accidental events, and combined loading scenarios, engineers apply safety factors to the loads and combine them in what are known as load combinations. This approach ensures the structure remains stable and does not collapse under the most critical conditions.

For the consequence class CC2 is applicable (medium consequence for loss of human life, like residential buildings with under 3 stories)

Loas combinations for permanent or variable design situations

For the ULS (ultimate limit state, see next chapter for more information) the loads that are applicable are the ones that cause bending shear and buckling. In this case things like dead load (permanent load) and live load (variable load, like floor loads, snow and wind). When approaching the limit state based on the failure or deformation of a certain part (STR/GEO), the load combinations can be determined as follows (EN-1990-1 6.10a and b):

6.10a) $$\sum_{j\geq1} \gamma_{G,j} G_{k,j} \text{"+"} \gamma_P P \text{"+"} \gamma_{Q,1} \psi_{0,1} Q_{k,1} \text{"+"} \sum_{i>1} \gamma_{Q,i} \psi_{0,i} Q_{k,i}$$

6.10b) $$\sum_{j\geq1} \xi_j \gamma_{G,j} G_{k,j} \text{"+"} \gamma_P P \text{"+"} \gamma_{Q,1} Q_{k,1} \text{"+"} \sum_{i>1} \gamma_{Q,i} \psi_{0,i} Q_{k,i}$$

Where:
yg,j = Partial factor of the dead load (permanent load)
ξ,j= Reduction factor
Gk,j = Dead load (permanent load)
Yp = Partial factor for prestressing loads
P = Prestressing loads
Qk,1 = Most prominent live load (variable load)
Qk,i = Live load (variable load) of the rest of the loads
yQ1 = Partial factor for leading live load (variable load)
yQi = Partial factor for live load (variable load) of the rest of the loads
Ψ01 = Psi factor for most prominent loads
Ψ0i = Psi factor for accompanying loads

The value used is the one that is least favorable out of these two equations. To determine the 'right' combination of loads the following table can be used to fill in the top equation.

Table 15: Partial safety factors for (STR/GEO) actions
Source: NEN-EN1990:2002 Table A1.2(B)

Persistent and transient design situations	Permanent actions		Leading variable action (*)	Accompanying variable actions (*)	
	Unfavourable	Favourable	Action	Main	Others
(Eq. 6.10a)	$\gamma_{Gj,sup} G_{kj,sup}$	$\gamma_{Gj,inf} G_{kj,inf}$		$\gamma_{Q,1} \psi_{0,1} Q_{k,1}$	$\gamma_{Q,i} \psi_{0,i} Q_{k,i}$
(Eq. 6.10b)	$\xi\gamma_{Gj,sup} G_{kj,sup}$	$\gamma_{Gj,inf} G_{kj,inf}$	$\gamma_{Q,1} Q_{k,1}$		$\gamma_{Q,i} \psi_{0,i} Q_{k,i}$

In the Netherlands this mean that in CC2 that the partial factors can be determined like this:

Blijvende en tijdelijke ontwerpsituaties	Blijvende belastingen		Overheersende veranderlijke belasting	Veranderlijke belastingen gelijktijdig met de overheersende	
	Ongunstig	Gunstig		Belangrijkste (indien aanwezig)	Andere
(Vgl. 6.10a)	1,35 $G_{k,j,sup}$ [a]	0,9 $G_{k,j,inf}$		1,5 $\psi_{0,1} Q_{k,1}$	1,5 $\psi_{0,i} Q_{k,i}$ (i >1)
(Vgl. 6.10b)	1,2 $G_{k,j,sup}$ [b]	0,9 $G_{k,j,inf}$	1,5 $Q_{k,1}$		1,5 $\psi_{0,i} Q_{k,i}$ (i >1)

[a] Bij vloeistofdrukken met een fysiek beperkte waarde mag zijn volstaan met 1,2 $G_{k,j,sup}$.

[b] Deze waarde is berekend met ξ = 0,89.

Belasting	ψ_0	ψ_1	ψ_2
Voorgeschreven belastingen in gebouwen, categorie			
Categorie A: woon- en verblijfsruimtes	0,4	0,5	0,3
Categorie B: kantoorruimtes	0,5	0,5	0,3
Categorie C: bijeenkomstruimtes	0,6/0,4 [a]	0,7	0,6
Categorie D: winkelruimtes	0,4	0,7	0,6
Categorie E: opslagruimtes	1,0	0,9	0,8
Categorie F: verkeersruimte, voertuiggewicht ≤ 25 kN	0,7	0,7	0,6
Categorie G: verkeersruimte [b], 25 kN < voertuiggewicht ≤ 160 kN	0,7	0,5	0,3
Categorie H: daken	0	0	0
Industrieel gebruik waarbij de veranderlijke belasting:			
— niet langdurig aanwezig is	0,5	0,5	0,3
— langdurig aanwezig is	1,0	0,9	0,8
Sneeuwbelasting	0	0,2	0
Belasting door regenwater	0	0	0
Windbelasting	0	0,2	0
Temperatuur (geen brand)	0	0,5	0

[a] De waarde 0,6 geldt voor delen van het gebouw die in geval van een calamiteit zwaar kunnen worden belast door een mensenmenigte (vluchtroutes, trappen enz.); de waarde 0,4 geldt in overige gevallen.

[b] Met verkeersruimte wordt in dit geval een ruimte bedoeld waar voertuigen kunnen rijden, bijvoorbeeld parkeergarages.

Table 16: Partial and psi factors
Source: NEN-EN 1990 NB:2019

The Ψ0 factor can be derived from the table here. Ψ1 and 2 are for accidental load combinations (see next part), like fire or sudden impacts.

For Türkiye this is slightly different, I could not access the NB (TS EN 1990), so I took the advised values in EN 1990:2002, with:

yg,sup = 1.35
yg, inf = 1.00
yQ,1 = 1.50
(or 0 when favorable)
yQ,I = 1.50
(or 0 when favorable)
Ɛ,j = 0.85

And the values in the table to the left here:

Table 17: Psi factors
Source: EN 1990:2002

Action	ψ_0	ψ_1	ψ_2
Imposed loads in buildings, category (see EN 1991-1-1)			
Category A : domestic, residential areas	0,7	0,5	0,3
Category B : office areas	0,7	0,5	0,3
Category C : congregation areas	0,7	0,7	0,6
Category D : shopping areas	0,7	0,7	0,6
Category E : storage areas	0,1	0,9	0,8
Category F : traffic area, vehicle weight ≤ 30kN	0,7	0,7	0,6
Category G : traffic area, 30kN < vehicle weight ≤ 160kN	0,7	0,5	0,3
Category H : roofs	0	0	0
Snow loads on buildings (see EN 1991-1-3)*			
Finland, Iceland, Norway, Sweden	0,70	0,50	0,20
Remainder of CEN Member States, for sites located at altitude H > 1000 m a.s.l.	0,70	0,50	0,20
Remainder of CEN Member States, for sites located at altitude H ≤ 1000 m a.s.l.	0,50	0,20	0
Wind loads on buildings (see EN 1991-1-4)	0,6	0,2	0
Temperature (non-fire) in buildings (see EN 1991-1-5)	0,6	0,5	0

NOTE
The Ψ values may be set by the National annex.

* For countries not mentioned below, see relevant local conditions.

Loas combinations for accidental and seismic combinations:

For accidental actions (something hit the structure) or seismic combinations the load values can be taken as follows:

Table 18: Partial factors of accidental or seismic combinations
Source: EN 1990:2002

Design situation	Permanent actions		Leading accidental or seismic action	Accompanying variable actions (**)	
	Unfavourable	Favourable		Main (if any)	Others
Accidental (*) (Eq. 6.11a/b)	$G_{kj,sup}$	$G_{kj,inf}$	A_d	ψ_{11} or $\psi_{21} Q_{k1}$	$\psi_{2,i}\ Q_{k,i}$
Seismic (Eq. 6.12a/b)	$G_{kj,sup}$	$G_{kj,inf}$	$\gamma_I A_{Ek}$ or A_{Ed}		$\psi_{2,i}\ Q_{k,i}$

(*) In the case of accidental design situations, the main variable action may be taken with its frequent or, as in seismic combinations of actions, its quasi-permanent values. The choice will be in the National annex, depending on the accidental action under consideration. See also EN 1991-1-2.

(**) Variable actions are those considered in Table A1.1.

Loas combinations for Serviceability limit state:

Additionally, ones for the limit state are as these using the psi values listed in the previous paragraphs.

Table 19: Serviceability limit state design values
Source EN 1990:2002

Combination	Permanent actions G_d		Variable actions Q_d	
	Unfavourable	Favourable	Leading	Others
Characteristic	$G_{kj,sup}$	$G_{kj,inf}$	$Q_{k,1}$	$\psi_{0,i} Q_{k,i}$
Frequent	$G_{kj,sup}$	$G_{kj,inf}$	$\psi_{1,1} Q_{k,1}$	$\psi_{2,i} Q_{k,i}$
Quasi-permanent	$G_{kj,sup}$	$G_{kj,inf}$	$\psi_{2,1} Q_{k,1}$	$\psi_{2,i} Q_{k,i}$

5.3 Member design values

The strength of timber is sensitive to a lot of factors. Which is why design strength is used to determine the strength of the member incorporating different modification factors to incorporate these variables. In the Eurocode (EN 1995-1-1) the formulas as well as these factors are given.

The general formula to determine the design strength is:

$$X_d = k_{mod} \frac{X_k}{\gamma_m} k_{various}$$

Where:
Xd = Design value
Xk = Characteristic value
Ym = Partial factor for material properties
Kmod = Modification factor for load duration
Kvarious = Factors accounting for size, buckling, load sharing etc. (which in normal circumstances is generally 1)

For design stiffness these are:

$$E_d = \frac{E_{mean}}{\gamma_M} \qquad G_d = \frac{G_{mean}}{\gamma_M}$$

Where:
Emean = Average value of elasticity (modulus of elasticity)
Gmean = Average value of shear (modulus of shear)

According to Eurocode (EN 1995-1-1, table 2.3), LVL, plywood and OSB the Ym factor is 1.2.

The Kmod factor is based on a couple of things such as the service class, material and load duration. In EN 1995-1-1 (table 2.1) the load duration is stated as follows:

Load-duration class	Order of accumulated duration of characteristic load
Permanent	more than 10 years
Long-term	6 months – 10 years
Medium-term	1 week – 6 months
Short-term	less than one week
Instantaneous	

The table for Kmod itself is found in table 3.2 of the same document shown below is a shortened version showing Plywood and OSB:

Material	Standard	Service class	Load-duration class				
			Permanent action	Long term action	Medium term action	Short term action	Instanta-neous action
Plywood	EN 636						
	Part 1, Part 2, Part 3	1	0,60	0,70	0,80	0,90	1,10
	Part 2, Part 3	2	0,60	0,70	0,80	0,90	1,10
	Part 3	3	0,50	0,55	0,65	0,70	0,90
OSB	EN 300						
	OSB/2	1	0,30	0,45	0,65	0,85	1,10
	OSB/3, OSB/4	1	0,40	0,50	0,70	0,90	1,10
	OSB/3, OSB/4	2	0,30	0,40	0,55	0,70	0,90

5.4 Failure criteria

The failure criteria that are considered for the structure are based on two 'states' the ULS (ultimate limit state) and the SLS (Serviceability limit state) (EN1995-1-1 section 6 and 7).

5.4.1 Ultimate limit state (ULS):

The ultimate limit state considers the elastic behavior of the material. The state to where if it fails the structure collapses or deforms permanently as a result of the loads. Hence why the maximum occurring stress may not exceed the design strength of the material. Since wood differs from strength with the grain direction, in plywood grain direction is chosen as the direction of the grain on the top and bottom plates, same for OSB.

Which gives the following conditions:

- Tension parallel to the grain (same for perpendicular just using prefix 90 instead of 0)

  $$\sigma_{t,0,d} \leq f_{t,0,d}$$

  Where in perpendicular member size is incorporated
- Compressive strength parallel to the grain:

  $$\sigma_{c,0,d} \leq f_{c,0,d}$$

- Compressive strength perpendicular to the grain:

  $$\sigma_{c,90,d} \leq k_{c,90} f_{c,90,d}$$

  Where Kc,90 can be taken as 1 unless it falls under one of the 7 situations mentioned in EN-1995-1-1 section 6.
- Bending

  $$\frac{\sigma_{m,y,d}}{f_{m,y,d}} + k_m \frac{\sigma_{m,z,d}}{f_{m,z,d}} \leq 1$$

  $$k_m \frac{\sigma_{m,y,d}}{f_{m,y,d}} + \frac{\sigma_{m,z,d}}{f_{m,z,d}} \leq 1$$

  Where Km = 1
  And instability is considered
- Shear

  $$\tau_d \leq f_{v,d}$$

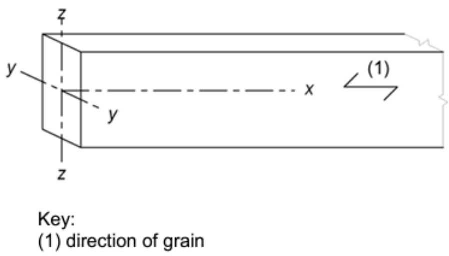


Figure 152: Member axis
Source: EN 1995-1-1:2004

5.4.2 Serviceability limit state (SLS):

The serviceability limit state considers the plastic nature of the material. Mainly looking at deflections. How much a member deflects without permanently deforming.

The shear modulus of timber is low so deflections due to sheer should be considered here just like creep. So total deflections would be (Overend, 2022):

$$w_{fin} = (w_{bend} + w_{shear}) \times (1 + k_{def})$$

Load type		Instantaneous deflection at mid-span	
Full span UDL		Bending	$\frac{5p_d l^4}{384EI}$
		Shear	$\frac{k_{form} p_d l^2}{8Gbh}$
Partial span UDL	$k \leqslant 0.5$	Bending	$\frac{p_d l^4(12k^2-8k^4)}{384EI}$
		Shear	$\frac{k_{form} p_d l^2 k^2}{4Gbh}$
	$0.5 < k \leqslant 1$	Bending	$\frac{p_d l^4(1-8k+36k^2-32k^3+8k^4)}{384EI}$
		Shear	$\frac{k_{form} p_d l^2(-0.5+2k-k^2)}{4Gbh}$
Point load	$k \leqslant 0.5$	Bending	$\frac{F_d l^3(3k-4k^3)}{48EI}$
		Shear	$\frac{k_{form} F_d lk}{2Gbh}$

k_{form} = 1.0 for solid timber sections; k_{form} = 1.2 for timber I-beams

Figure 153: Deflection from different sources
Source: Overend (2022)

Where Wbend (deflection from bending) and Wshear (deflection from sheer) are in the Eurocode combined as Winst (instant deflection) and Kdef is there to account for creep.

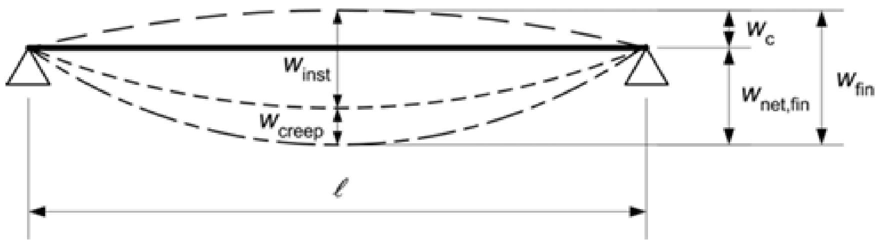


Figure 154: Components of deflection
Source: EN 1995-1-1 figure 1.7

Material	Standard	Service class 1	Service class 2	Service class 3
Plywood	EN 636			
	Part 1	0,80	–	–
	Part 2	0,80	1,00	–
	Part 3	0,80	1,00	2,50
OSB	EN 300			
	OSB/2	2,25	–	–
	OSB/3, OSB/4	1,50	2,25	–

Table 20: Kdef
Source: EN1995-1-1

As for the maximal deflection (Wmax) those are given in the table below and should not be exceeded.

Table 21: Maximal deflection
Source: (EN 1995-1-1)

	w_{inst}	$w_{net,fin}$	w_{fin}
Beam on two supports	$\ell/300$ to $\ell/500$	$\ell/250$ to $\ell/350$	$\ell/150$ to $\ell/300$
Cantilevering beams	$\ell/150$ to $\ell/250$	$\ell/125$ to $\ell/175$	$\ell/75$ to $\ell/150$

5.4.3 Optimization

As for the optimization of the structure, I want to be able to get as close to still not failing the failure criteria while trying to keep the members their weight as low as possible and in turn the material usage low as well.

Using Galapagos in Rhino grasshopper there are a few parameters that can be adjusted and thus lower the volume of the material used.

- Number of frames in y direction
- Number of columns in x direction
- Height of the cross section

Changing these within a set dimension respectively:

- 3 to 10 (int, making sure there is at least 1.6m in between each)
- 3 to 10 (int, odd numbers, at least 1.6 meters in between each)
- 200 to 500 (int, in mm)

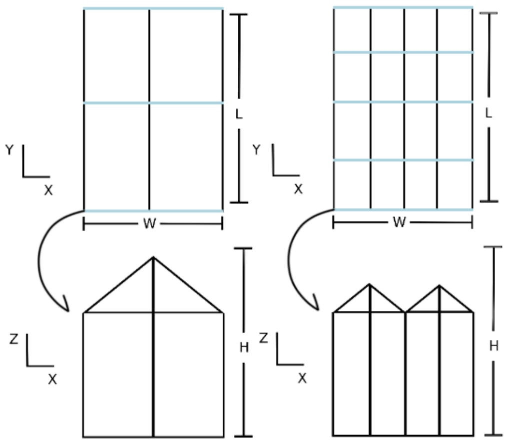


Figure 155: Structural grid system
Source: Own diagram

Galapagos iterates through various design options using these, aiming to approach the failure criteria as closely as possible while maintaining structural safety. By dividing the design strength by the actual stresses in the material for all discussed cases, a value between 0 and 1 can be obtained, with values exceeding 1 indicating failure. The goal is to set a constraint that brings this value as close to 1 as possible, for example 0.8, ensuring the structure remains both safe and sound.

Another optimization that is done has more to do with the eventual production of each part trying to keep the amount of waste and use of material as low as possible when CNC routing by nesting the geometries as packed as possible. More about this in the next chapter.

6. Design of the digital environment

In this chapter the design process of the digital model and the user interface or application will be handled. Showing how all the factors and parameters mentioned in the previous chapters have come together into one parametric digital design and how from there it is translated into something a CNC machine can read to eventually fall on the user's lap.

6.1 Concept design

Main question in the design of the digital model is to get from the user's interface (UI), the digital model, to code readable for CNC machines. What software to use for each step and how to make them communicate. The latter often being the hardest step.

6.1.1 Used software:

The programs environments and software I choose to try out were:

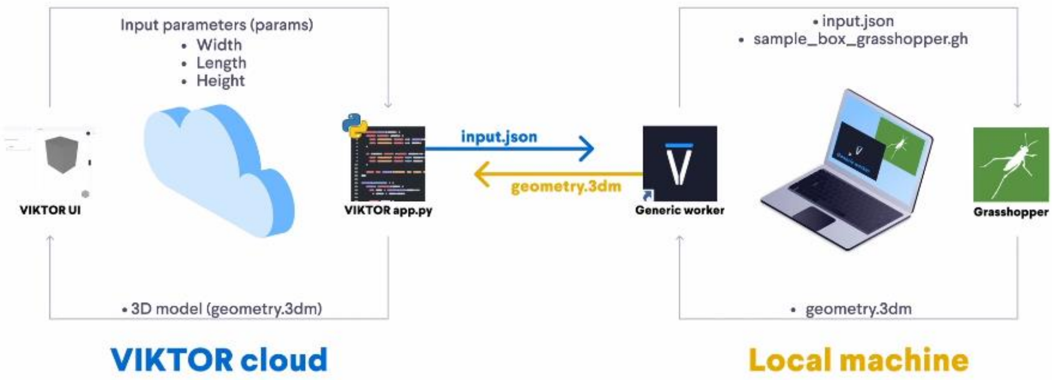
- Interface:
    - VIKTOR SDK v14.15.2 (set up and communication between Grasshopper and the UI)
    - Python 3.10.3
    - Hops (for communication with Grasshopper)
- Database: Excel
- Calculations and parametric model:
    - Grasshopper: Parametric model
    - Karamba3D 2.2.0.15: Structural analysis
    - Ladybug 1.8.0: Weather data (e.g. wind and temperature)
    - Python 2.7: Custom scripting
- Optimization: Galapagos/ Octopus (plugin in Grasshopper)
- Check: FEM-Modeling software Dlubal

I chose Grasshopper and the plugins above here due to familiarity as I had worked with them before. Same for Galapagos, Octopus I was not familiar with but works similar as Galapagos but can handle multicriteria data.

VIKTOR was also new. It is a platform that offers the opportunity to create web applications. There are a couple of these environments like this but what I liked about VIKTOR was the ease of using it. There were many tutorials online, with videos to learn from, too for the integration of the Grasshopper functionalities into an application as well as an active community to reach out to if stuck. I am not too familiar with coding applications; I do have a base knowledge of python but that really is as far as it goes so this was nice to have. Additionally with the free version you still have all the software tools the platform offers available to you, create unlimited applications and publish up to 5. So, VIKTOR provided the opportunity for me to learn as well as create a simpler solution to connect a UI with Grasshopper.

But how does it work? How does Viktor communicate with Rhino Grasshopper? VIKTOR offered two ways to integrate them. Virtually and locally. Both connecting the two, one (locally) needing Rhino Grasshopper to be installed and open for it to work, though the user would not need an understanding of Grasshopper or Rhino for them to make use of it in both situations.

Locally the VIKTOR UI gathers the parameters the user inputs and sends them over to the python script which in turn sends it to a worker as a .json file. The worker is the one that handles the calculations and sends back the results over to the python script either in the terminal or and can then visualize it in the UI. The worker only needs the .gh file with your script to gather how it needs to translate the inputs into the wanted output and only needs Grasshopper to be 'open' the script itself does not.



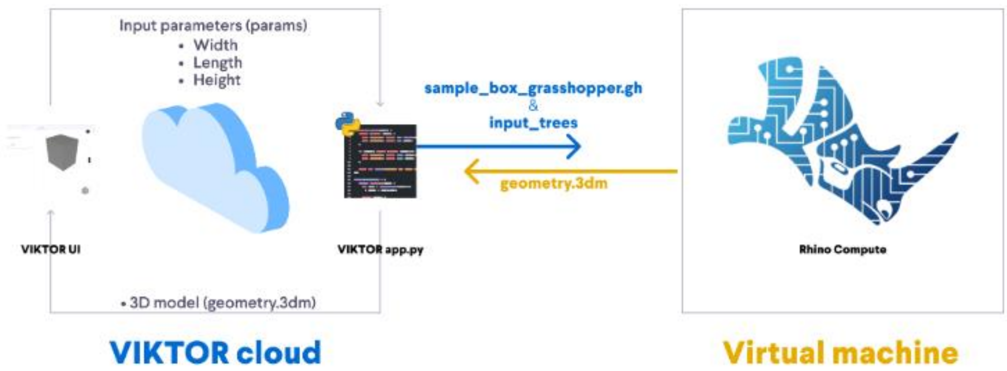


Figure 156: Flowcharts of communication process between Viktor and Grasshopper
Source: VIKTOR (2024)

Virtually it needs the .gh script to work and the inputs but here Grasshopper does not have to be running or installed to work. Instead, it uses Rhino Compute, a virtual environment with the same functionalities as Rhino and Grasshopper in a virtual environment. However, this demanded the setup of a Rhino Compute Server, and this was something I was not familiar with how to do as well as the fact this needs an API key which again is something I was not familiar with on how to acquire and after some research could not figure out. Additionally, to host such a server you pay er core per hour of it running. So, I stuck with the local approach especially in a development stage like this.

Returning to the local approach, for the Viktor worker to know where to use the UI input and what the results are, it uses the Hops plugin in Grasshopper to communicate with the script.

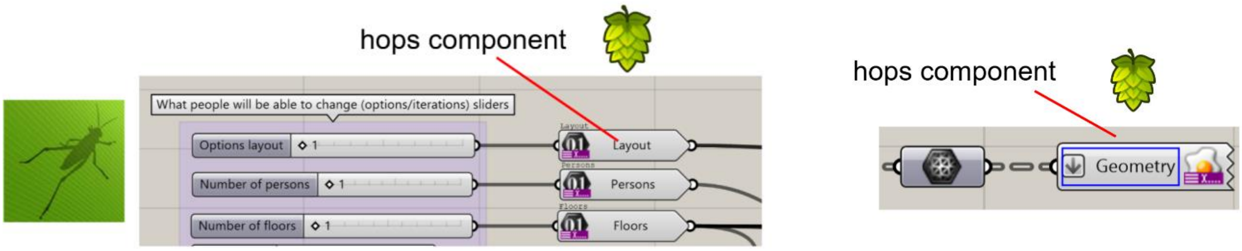


Figure 157: Hops components, left input, right output

```
# Input fields
Layout = vkt.NumberField('Layout', default=1, max=2, min=1)
Persons = vkt.NumberField('Persons', default=1, max=12, min=1)
Floors = vkt.NumberField('Floors', default=1, max=2, min=1)
```

Figure 158: Input parameters in python app.py script

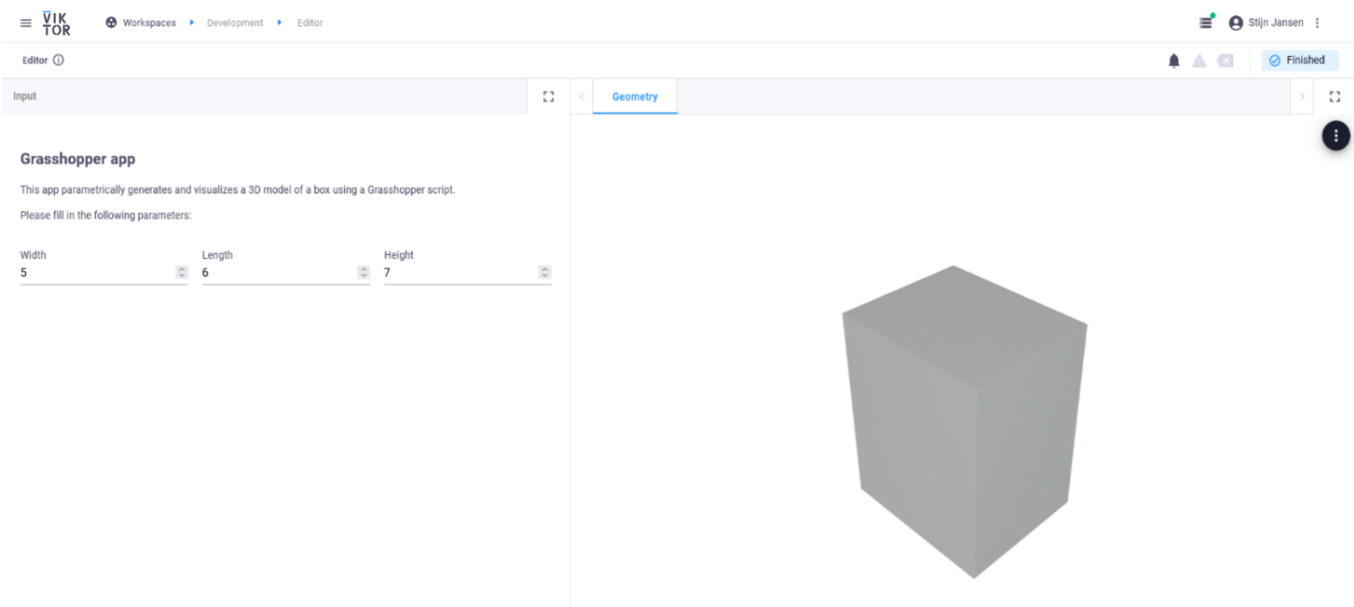


Figure 159: Example of VIKTOR UI
Source: VIKTOR (2024)

Knowing all of this, how will the process look like from UI to the necessary files for CNC?

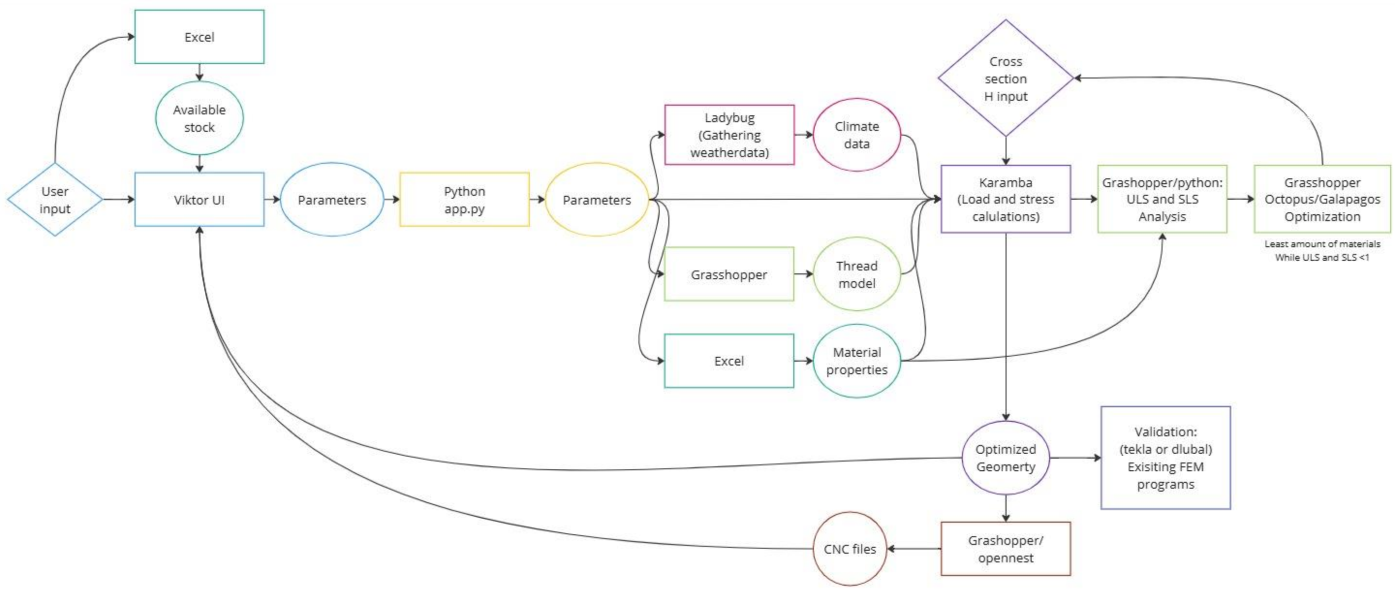


Figure 160: Overview of process

Everything starts with the UI, where people add in their custom parameters for the design. This creates a thread model in grasshopper, a set of climate data points in Ladybug and gives Karamba3D the necessary material and load values needed to calculate the forces and stresses in the structure. This gives a solution of stresses in the material and with a python script the ULS and SLS are checked. This gives a value either between 0 and 1 (passes) or higher (fails) Galapagos then takes the mass of the structure and iterates between possible options received from the constraints of the optimizable variables and tries to get that number as low as possible. With the optimal H the digital model is made (one simple for the UI, and one detailed for CNC). The simple model is sent to the UI directly and shown on screen. The other one is first nested within a 1220 by 2440 mm square (the boundary of the material plates), or, if vector lines are needed, first translated to 2D linework and then nested. These are saved in the right format and sent back over to the UI where the user is able to download these as well as a shopping list or the materials could directly be bought from the site and brought to site directly and instructions or a manual for producing and building.

As for what the exact inputs and parameters are and how they influence other components will be discussed on the next parts but to give a short overview of what is going to be discussed, the following categories are named:

- User input: Location
- Set up of the parametric model

6.1.2 User input: Location

One of the main inputs the user will have to give is their location. Based on that alone 4 different types or data are determined:

1. Weather data to for example the average wind velocity
2. To determine the local constraints of the shelter due to regulations in the area or certain safety factors or thing addressed in NBs of the Eurocode.
3. To see what materials are available
4. To see what machines are available and what their constraints/ limitations are (for example file type).

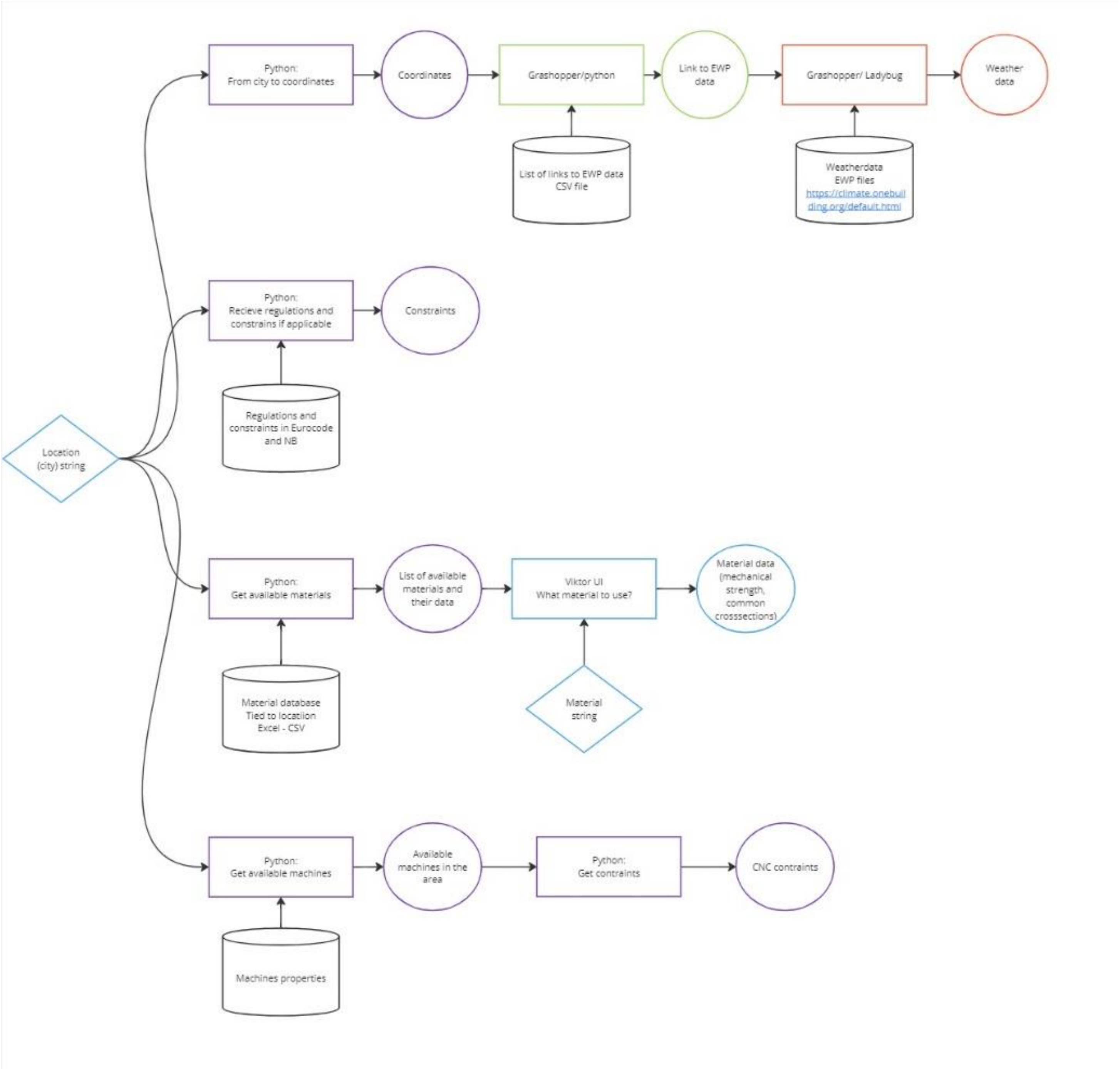


Figure 161: Location based data
Source: own diagram

6.1.2 Set up of the parametric model and Karamba 3D

User input: Layout

The user can also change the layout however they want in a certain set of constraints as follows:

- Size (min 16 square meters, max 96 square meters in steps of 8): int from 1 to 12
- Type of floorplan (rectangular or square): int 1 or 2
- Position bracing: int 1 to 10
- Position windows: int 1 to 10
- Position doors: int 1 to 10
- If they are wheelchair dependent: bool True or False
- Stories: Int 1 or 2

This creates the dimensions of the layout. In Grasshopper itself the rest is generated with a fixed height for the levels (2200 mm) as well as fixed height of the roof based on the climate data from Ladybug and the EWP files.

User input: Material

Based on what the input was on their location people will get to see what materials are available. They can then choose one of these materials and the script will send the necessary characteristic values of the material over to the material component in Karamba3D or any other part where they are needed (such as thickness, compression, tension and bending strength etc.).

User input location: data used

The data received from the location the user gave are as follows:

- Weather data
- Material data
- Load combinations
- Regulations and Eurocode checks
- Machine data

Parametric input: Optimization

In Grasshopper itself there are also quite a few parameters that can be optimized with Galapagos:

- Number of portals: int 1 to 10
- Number of columns: int 1 to 10
- Height of the cross section: int 200 to 500 (in mm)

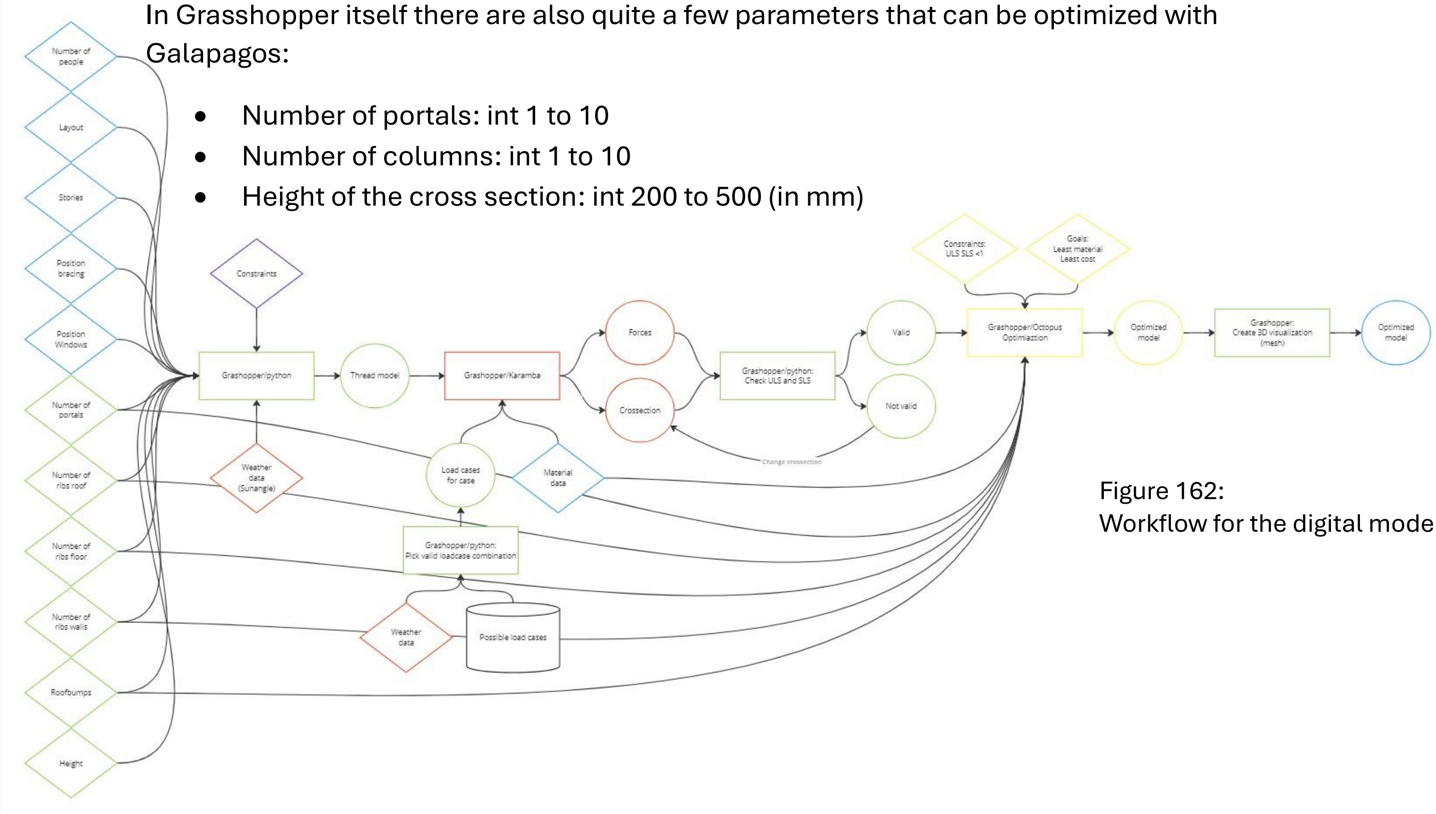


Figure 162:
Workflow for the digital model

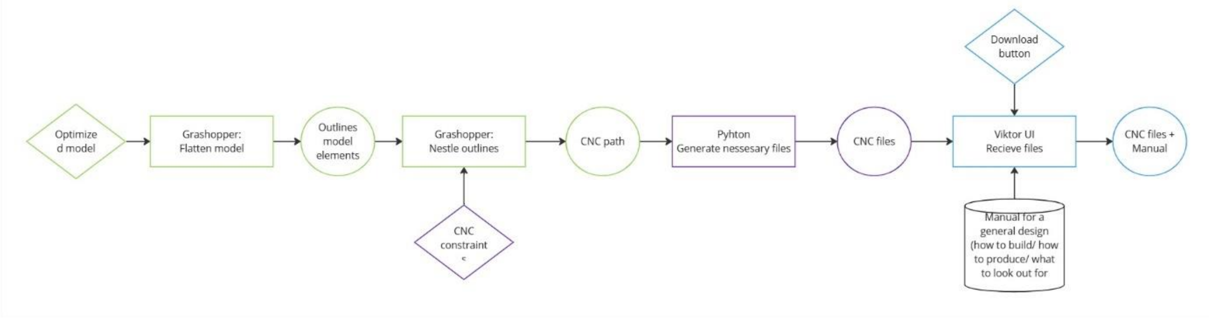


Figure 163: Workflow of translation to CNC
Source: own diagram

What is left to do is to create the necessary steps to translate the optimized model into something a CNC machine could read. And getting that back to the UI for the user to download by the simple click of a button.

6.2 Workflow of the entire process

So how did this all come together? What did I use and where did I have to differ from the original ideas? What did I use to reach the product I wanted?

6.2.1 Users location to weather data

Ladybug is a tool in grasshopper that based on EPW (Energy plus weather) files gathers weather data and can visualize them. Which is ideal here as for the structural analysis I need the mean wind velocity at a height of 10m and to determine the Service Class based on the relative humidity to define Kmod (See chapter 5).

The problem with EWP files is that not every location has these available, so I wrote a script that looks for the nearest one instead based the proximity of on longitude and latitude the user inputs and what is listed in the data of the EWP. Inspired from a similar component made by a user that used outdated links to EWP files (seanmoo, 2017). My own script uses a list of updated links in an excel sheet from: Climate.OneBuilding.Org (2024)

I also attempted to use your standard address format and then turn them into coordinates with a python script as well, but this was not doable without an API as you are then dealing with sensitive information and kept it to longitude and latitude values.

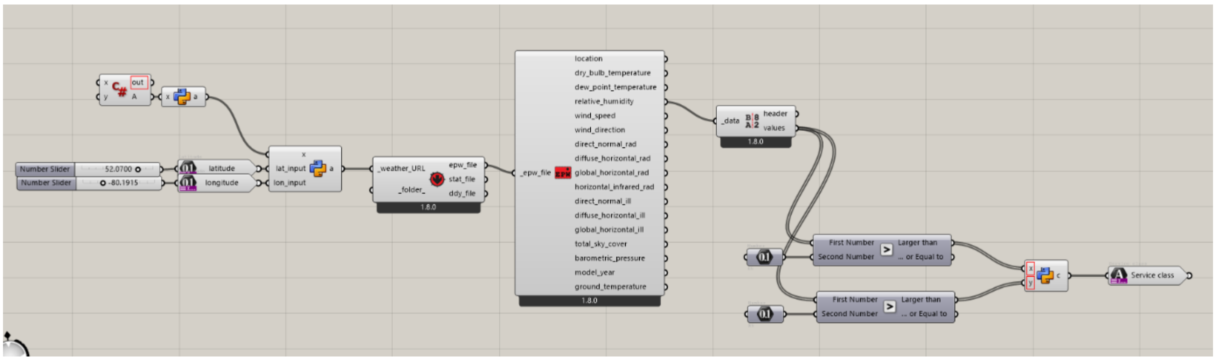


Figure 164: Grasshopper script of the gathering of weather data

The wind is much simpler as this is a component existent in Ladybug. Where just like Eurocode based on height and terrain type the average wind velocity is gathered.

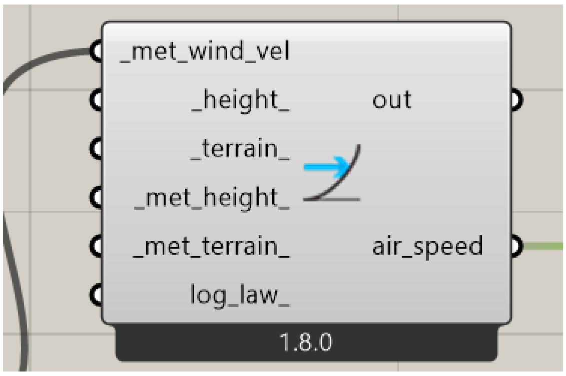


Figure 165: Wind velocity component

6.2.2 Parametric model

The parametric model is set up using a combination of python scripts in grasshopper and the usual grasshopper components.

During the final weeks of another course I was completing alongside my thesis, I shifted my focus temporarily to prioritize successfully earning my remaining credits. This required setting aside my thesis work for a short period to ensure I could fully dedicate my attention to completing the course requirements. When I returned to my Grasshopper script after the break, I found it challenging to comprehend the logic and structure of what I had previously developed. The script had become disorganized and complex, resembling what is often referred to as "spaghetti code," making it difficult to navigate and continue building upon.

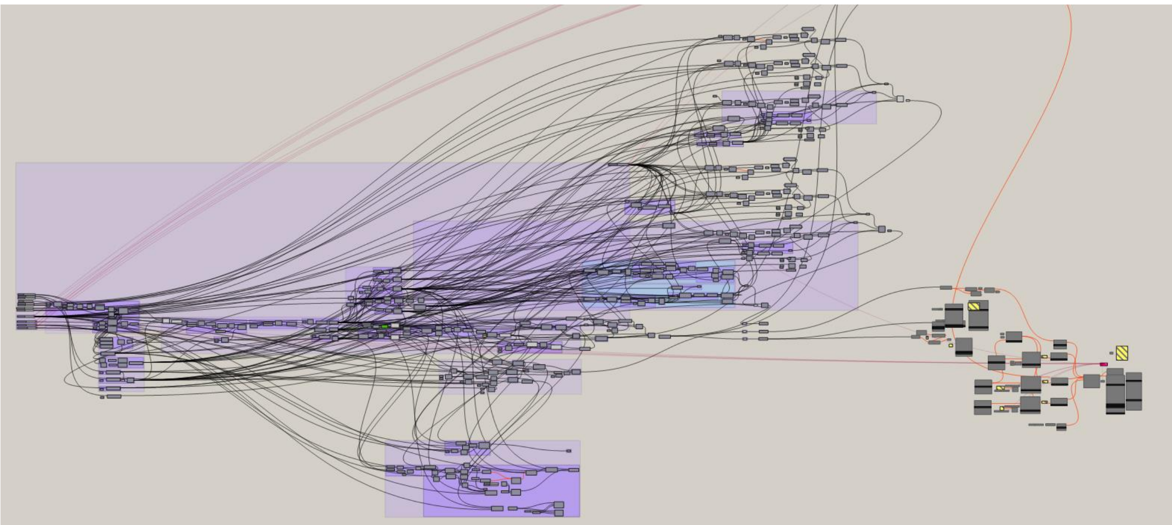


Figure 166: Spaghetti code

So, the first thing I did was clean it up to something more tangible, grouping properly and reducing the number of steps as there were quite a lot of repeating components.

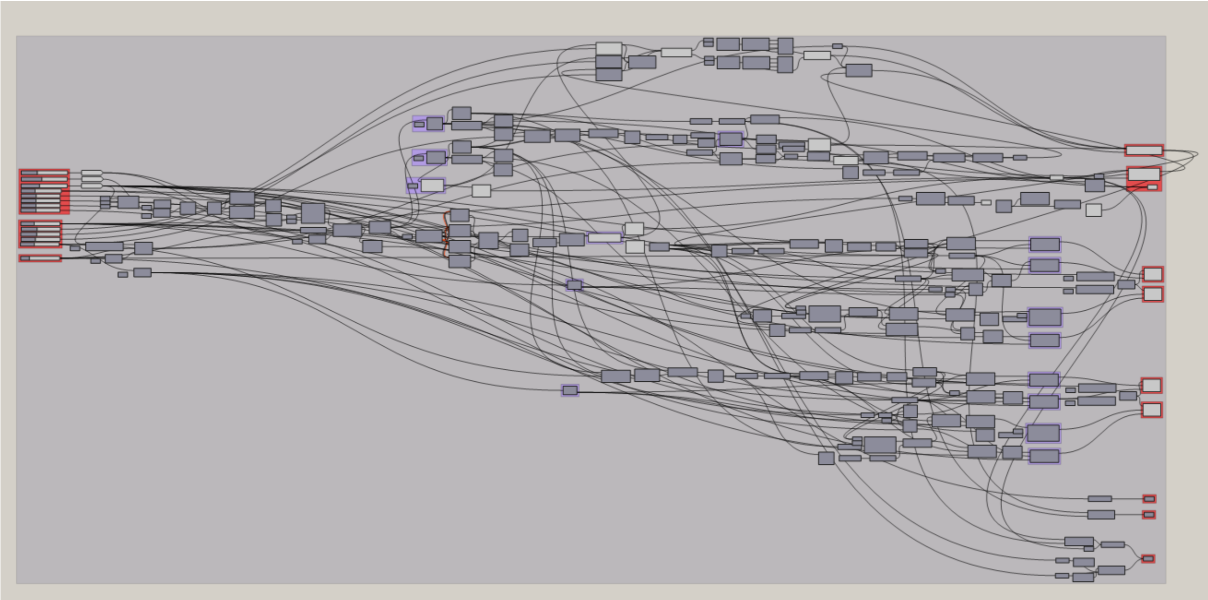
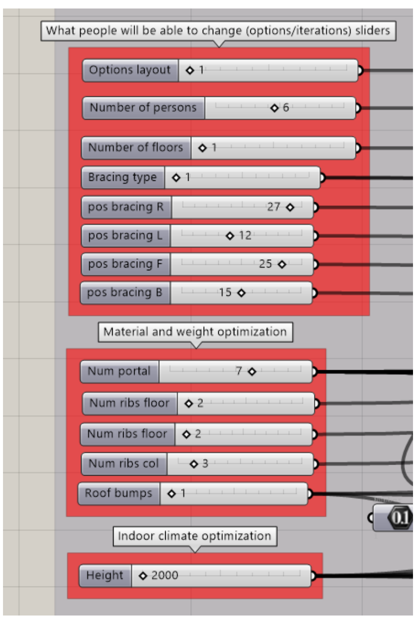
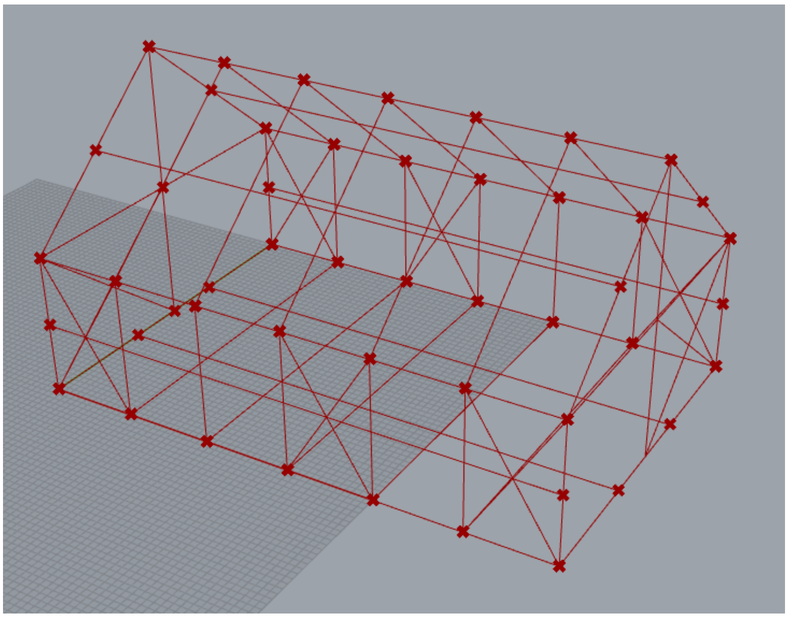


Figure 168: Inputs and result
Source: own screenshots

In Karamba the first steps are also taken. There were some problems at first where lines in the parametric model were intersecting with others without Karamba recognizing there was a joint there but after updating the script this worked fine. The only things left to do are add the load cases and write the script for their checks and do the optimization with Galapagos.





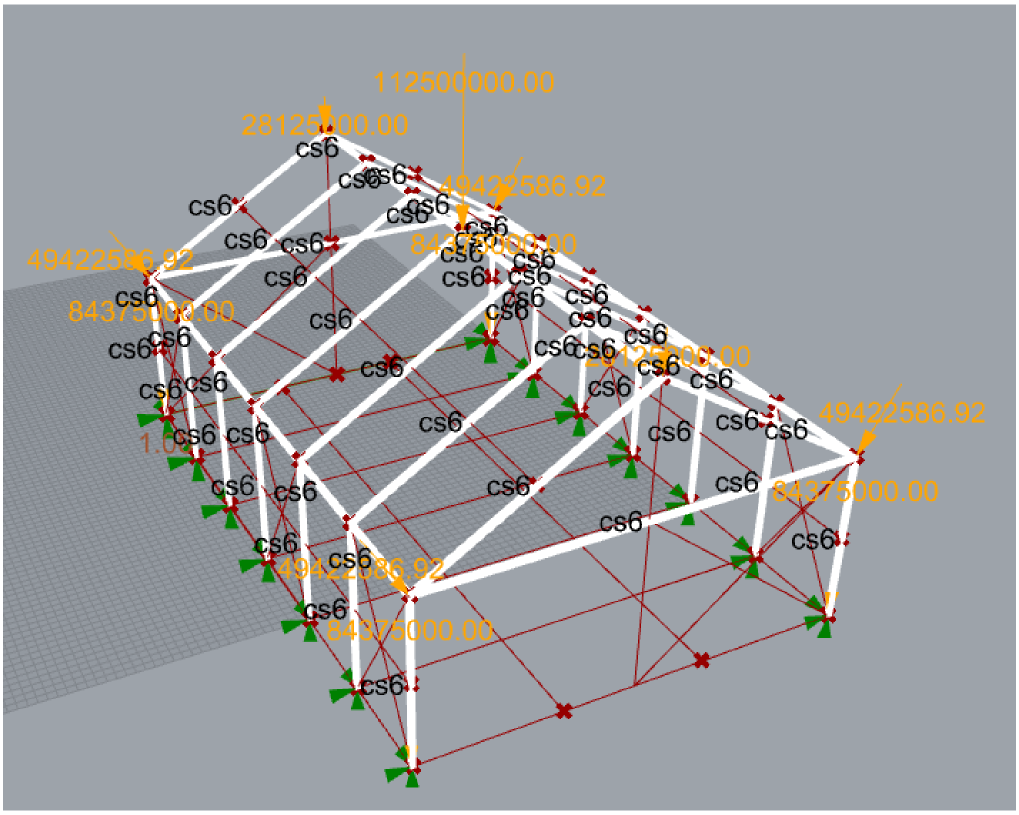


Figure 169: Karamba results

Here was a first ty of the Karamba model but the unities were quite off, this was due to the fact Kadamba's units were in cm and the rhino interface in mm, this caused very small values of which I thought I had added misplaced a factor 10 or 100 somewhere and started checking it on which I also found some problems in the generation of the structure so with a simpler model of just a floor on a beam I continued to try and find the kinks in the code.

Here is where I also switched from going back and forth between the excel sheet to calculate the loads. The first set up was the user chooses a material it is calculated in excel then send back over to the interface python script who then in turn would send it to Grasshopper which caused a lot of problems.

So now based on what material the user chooses it gathers the ID and material properties needed from excel and gathers it in grasshopper.

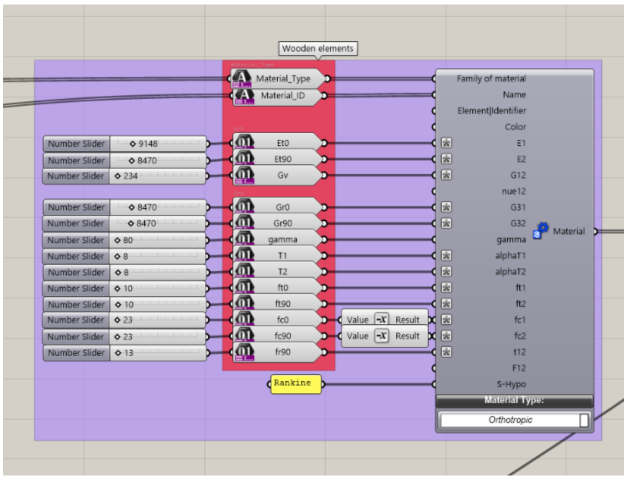


Figure 170: Material properties gathered in Grasshopper

For this to work, these values should also be available as parameters in grasshopper itself, thus also the strings of the ID which are gathered as seen in the picture below with the plugin spreadsheet.

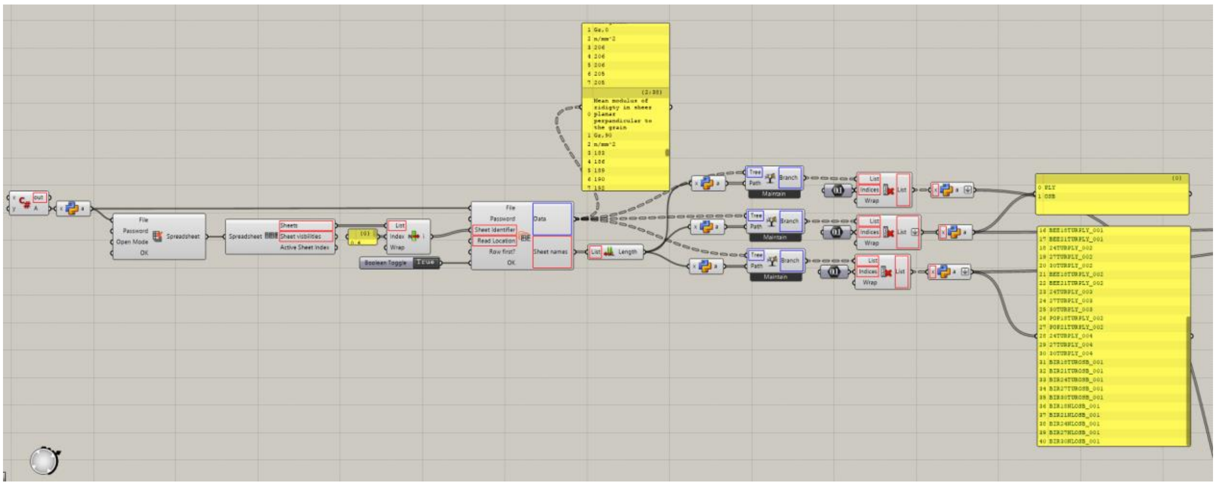
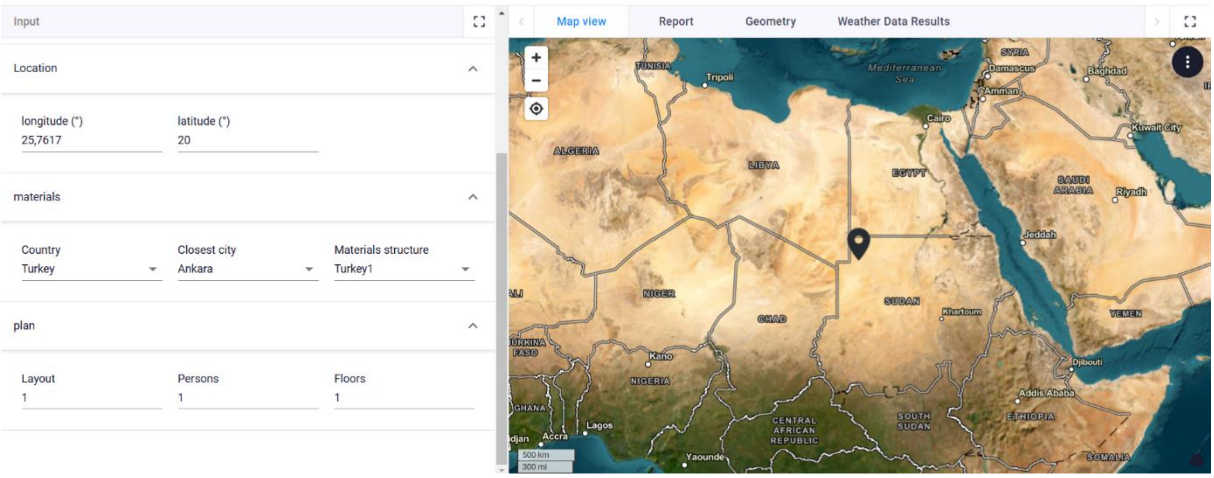


Figure 171: Gathering of ID materials

6.2.3 VIKTOR interface and communication

With this simpler model I was also able to get it visualized in the interface and changed depending on different values. So truthfully the application and grasshopper script are far from finished. I only have the permanent load cases in the calculations and the geometry you see on the screen is the one generated in grasshopper and not the optimized one.

Right now, the application that works is the one where the user can input their longitude and latitude and choose a type of material based on their location.



7. Discussions and limitations

7.1.1 Disaster management, the greater context

As mentioned before, shelter design is a large part of disaster management. Especially in the response and recovery phase after disaster. So, the question is whether this particular project falls into the same place in such a situation or if it can be part of the preparative stage as well.

As when disaster happens, and the damage has been done, the question is whether enough resources will be available to respond to the need for shelter. It might be the case that either the electricity has fallen out or locally no CNC machines will be available close by.

Figure 172: First concept
Source: own diagram

So, the first idea was to start early. Spanning the process into preparation as well, where every resource is still available, and time is not too much of the essence yet. To prepare everything beforehand, meaning that the user would design their shelter, produce the necessary elements to build their shelter and when disaster strikes make sure all components reach their destination, and the shelter can be erected on site quickly to serve as emergency shelter as well, to later transition into something more lasting until the permanent solution is met.

Though after consultation and further research this approach changed to the regular set of events where after disaster happens, shelter is produced and given to the people in need. To look more like a step between an emergency shelter and a permanent home. Something that might take a while to be set up as resources might not be available but would better fit the situation and thus might last longer. As has been said before, context is a large factor, and each disaster has its own. Calling for a different approach each time. Pushing the process to the response and recovery phase entirely. Adapting better to the local situation of the disaster itself. Fitting better with what people need at that moment. Though this brings its challenges. Where are machines available? Which companies can provide enough resources? How do we get shelter to the people the fastest?

This is where the concept WikiHouse adapted came to mind. Creating an environment for all actors in the design process to come together and let the user in on the design process that way.

So why not do that here as well? Create an environment not just for the user but where companies like material suppliers, or machine suppliers/ providers can come to and show what they have to offer. When disaster happens these companies provide information about what they still have available, what they have to offer and incorporate that information into the application. Give the user a list of what is still available and where, they choose what they want to use from that list, design their shelter and get the files necessary to produce it. Then build it up on site themselves and use it until it is no longer necessary. Then either dismantle the shelter for future use, sell the materials or use them for a different project.

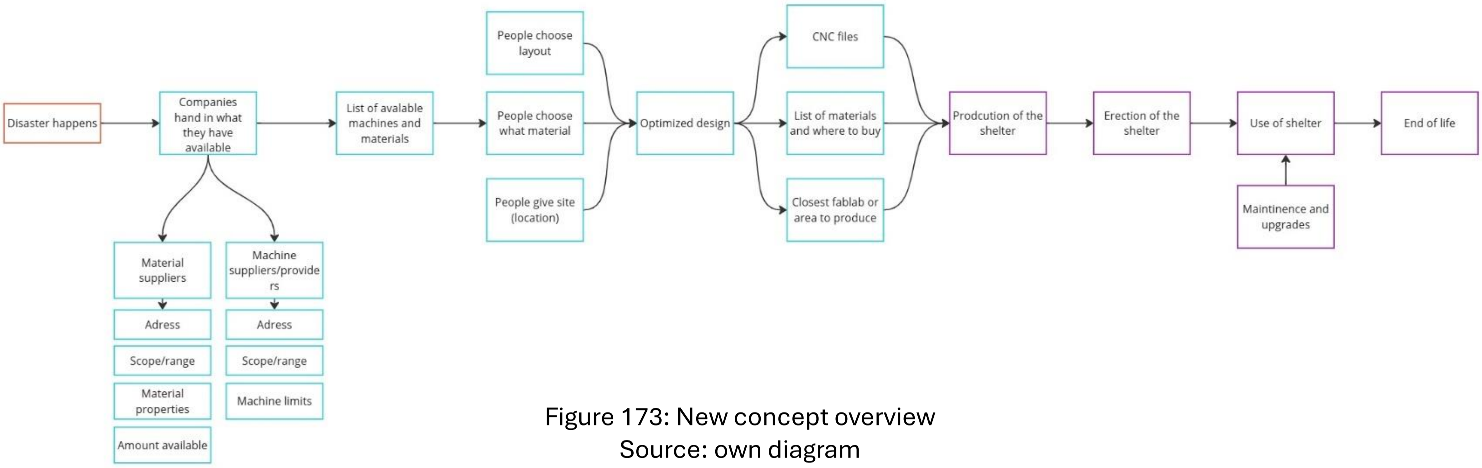


Figure 173: New concept overview
Source: own diagram

However, scarcity can still pose significant challenges, particularly regarding the availability of necessary machinery. In Türkiye, for instance, there is a limited number of services that provide access to such equipment. Additionally, the lack of widespread knowledge and expertise in operating these machines makes it difficult to find skilled individuals or to facilitate peer-to-peer training within communities.

7.1.2 Limitations

Flat roofs are particularly valuable in arid climates where they often serve as an extension of livable space. They provide practical functions such as cooling down at night, cooking, or sleeping under the open sky. Future iterations of the shelter design should integrate culturally appropriate flat roof options, ensuring that they remain structurally sound while accommodating these essential uses. Special attention should be given to designing roofs that are easy to assemble, durable under environmental stresses, and capable of supporting the additional weight and activities associated with these regions.

Ease of production is a critical focus for improving the feasibility of CNC-routed shelters. Currently, some components require flipping within the CNC-router to cut both sides, which introduces complexity, risks of inaccuracy, and potential alignment issues due to mirroring. Future research should prioritize simplifying the joinery to eliminate the need for flipping, thereby streamlining the production process. Simplified joints should maintain structural integrity while improving precision, reducing production time, and minimizing the potential for error. This approach would make the shelter design more accessible and scalable for local production in resource-constrained settings.

While digital models are powerful tools for simulating and designing structures, they are not infallible. They can contain inaccuracies, bugs, or errors in their setup that may result in discrepancies between the model and real-world performance. A digital model serves as a reflection of reality, but real-life scenarios may present unforeseen challenges or variations. Therefore, it is essential to recognize the limitations of computational tools and incorporate checks to ensure reliability.

To address these concerns, expert involvement remains a critical component of the process. Experts should be tasked with reviewing the underlying code and algorithms in the computational tools to verify their accuracy and adherence to safety standards. Additionally, a quality assurance process should be implemented to ensure that all components, fabrication outputs, and construction steps meet the requirements outlined in the instructions. This could involve both digital and physical checks, such as inspecting CNC-routed parts for precision and verifying structural assembly on-site. By combining the efficiency of computational tools with expert oversight, the risk of errors can be minimized, ensuring that the shelters are safe, functional, and meet the intended standards.

8. Conclusion and reflection

8.1 Conclusion

This thesis has laid the groundwork for developing a computational framework and design system aimed at empowering non-experts to create customizable wooden shelters that are structurally sound, sustainable, and culturally appropriate. While significant progress has been made, the project remains a work in progress, with ongoing refinements in the structural analysis, optimization and CNC integration. The groundwork has been laid out for these tasks and will be possible. The insights gained thus far are summarized below and will give answers to the main question:

How can CNC-routing and computational tools facilitate the design and local production of customizable wood-based shelters by non-experts in post-disaster contexts?

8.1.1 Temporary shelter design:

This research aimed to explore whether the design of a shelter could be simplified into an accessible application, focusing on the integration of regulations, guidelines, and shelter typologies into computational models. The findings from this study, grounded in the comprehensive analysis of UNHCR and Sphere guidebooks, provide clarity on how shelter design can align with global standards while remaining adaptable to diverse post-disaster contexts.

Main types of post-disaster shelters and differentiation

Post-disaster shelters are generally categorized based on their intended duration of use and construction methods or materials. The analysis identified the following terminology:

- Emergency shelters: Designed for immediate use, typically lasting a few days to weeks. These are low-cost and prioritize rapid deployment, often made with temporary materials like tarps or lightweight metals.
- Temporary shelters: Meant for months to years, offering greater durability and functionality. Materials often include timber, bamboo, or prefabricated panels. While designed for quick assembly, they must balance usability and cost.
- Transitional shelters: A bridge between temporary and permanent housing, these shelters can be upgraded, relocated, or repurposed. They emphasize flexibility, allowing occupants to adapt them over time to meet evolving needs.
- Permanent Housing: Constructed with robust materials like concrete or bricks, these are intended to last decades but require significant time and resources to implement.

Temporary shelters, as highlighted in this research, can be classified based on their manufacturing, materiality, and deployment approach. These categories address the diverse needs of disaster-stricken populations:

- Transportable shelters: Prefabricated off-site and shipped to the disaster area, such as container homes or flat-packed units (e.g., RHU by UNHCR). These are quick to deploy but often lack adaptability and are resource-intensive in terms of production and transport.
- Build-on-Site shelters: Constructed locally using available materials, these rely on community involvement and traditional methods. Examples include bamboo shelters in the Philippines or timber shelters in Aceh. These designs are sustainable and culturally relevant but require more time and coordination.
- Hybrid shelter kits: Combining aspects of both, shelter kits provide prefabricated components for local assembly, allowing for quicker deployment while leveraging local labor and resources.

However, the UNHCR (2016) also categorizes shelters based on their permanence and materiality. These include emergency shelters, which are temporary and quickly constructed; transitional shelters, which are more durable and designed to be modified, relocated, or upgraded; and durable shelters, which are intended as permanent structures made from robust materials like brick or concrete. Each type aligns with specific stages of disaster recovery, offering flexibility to address evolving community needs.

Each typology differs in terms of usability, adaptability, and sustainability:

- Usability: Transportable shelters offer rapid solutions but may not meet long-term needs. Build-on-site shelters excel in cultural fit and adaptability but require time and training.
- Adaptability: Transitional shelters are designed to evolve with user needs, making them ideal for contexts requiring flexibility.
- Sustainability: Build-on-site shelters and hybrid kits prioritize local resources and cultural integration, minimizing environmental impact.

Regulations and guidelines for designing Shelter

The UNHCR and Sphere handbooks serve as critical references for shelter design in post-disaster contexts. Both emphasize that adequate shelter must provide physical security, privacy, and protection from weather, while aligning with cultural norms and local contexts. Specific quantitative standards include:

- Minimum space requirements: 3.5 square meters per person in warm climates and 4.5–5.5 square meters in cold climates, accounting for additional needs like cooking and sanitation which is why in the design 8 square meters was chosen.
- Structural stability: Resistance to environmental stresses such as wind, snow, and seismic activity.
- Cultural sensitivity: Designs should respect local customs, such as providing internal divisions for privacy, especially in gender-sensitive contexts.
- Material sustainability: Preference for locally sourced, recyclable, or reusable materials to reduce environmental impact and support the local economy.

Incorporating regulations and guidelines into computational models

Integrating these guidelines into computational models requires a user-friendly interface that ensures adherence to these standards without requiring specialized expertise. Key considerations for the digital application include:

- Parametric design for flexibility: Computational tools like Grasshopper allows users to adjust shelter dimensions, layouts, and material selections while maintaining compliance with regulations.
- Cultural adaptability: The application incorporates localized parameters, such as materials available in the region and design templates reflecting cultural preferences.
- Automation for accessibility: By automating structural analyses and generating fabrication-ready files, the application reduces the barrier to entry for non-experts, enabling users to focus on customization within safe, pre-defined limits.

8.1.2 Structural design in wood:

Key principals

Wood is a versatile and renewable material, making it a preferred choice for sustainable shelter designs. Its structural performance is influenced by several key principles:

- Material properties: Wood is anisotropic, meaning its strength and stiffness vary based on grain direction. Longitudinal properties are significantly stronger than radial or tangential directions, which must be considered in load-bearing designs.
- Moisture sensitivity: As a hygroscopic material, wood absorbs and releases moisture depending on environmental conditions, causing expansion and contraction. Proper seasoning and drying are necessary to prevent deformation.
- Use of engineered wood products: Plywood, oriented strand board (OSB) are engineered products with enhanced strength, uniformity, and reduced variability. These are particularly suitable for CNC-routing due to their predictable mechanical properties. Plywood is more costly but stronger and aesthetically more pleasing though OSB is often loads cheaper.

Role of computational tools for structural stability and optimization

Computational tools play a vital role in designing structurally sound and resource-efficient wood-based shelters. They enable:

- Structural analysis and load optimization: Tools like Karamba3D and Rhino Grasshopper perform finite element analysis (FEM) to assess the stability of wooden components under loads. This ensures compliance with safety standards like Eurocode 5.
- Parametric customization: Computational models allow for iterative design, adjusting dimensions, materials, and joinery to optimize performance without compromising structural integrity.
- Material efficiency: Algorithms minimize waste by optimizing component layouts for CNC-routing, reducing offcuts and improving material utilization.

Influence if CNC-routing on structural integrity
CNC-routing transforms raw wood and engineered materials into precisely cut components, ensuring high structural performance:

- Precision and fit: CNC-routed joints (e.g., dovetail, lap joints, and tongue-and-groove) enhance structural integrity by providing tight fits without the need for adhesives or nails.
- Customization: CNC machinery enables the production of tailored components for unique designs, which is particularly beneficial in post-disaster contexts requiring adaptability to cultural and environmental factors.
- Potential weaknesses: While CNC-routing allows precise cuts, improper design or over-routing can weaken components, particularly at joints or thin sections.

Existing shelter designs using CNC-routing
Examples of CNC-routed shelters demonstrate the benefits and challenges of this approach:

- Benefits:
    - Rapid production: CNC-routing significantly reduces fabrication time compared to manual methods.
    - Ease of assembly: Components designed for CNC routing often use interlocking joints that simplify on-site assembly without heavy machinery.
    - Repeatability: Precision cutting ensures consistency across multiple units.
- Bottlenecks:
    - Access to machinery: CNC-routing requires access to specialized equipment, which may not always be feasible in remote disaster areas.
    - Material constraints: Engineered wood suitable for CNC routing may not always be locally available, increasing reliance on external supply chains.
    - Costs: The costs of operating and materials can become quite high

Properties of wooden plate materials for CNC-routing
Engineered wood products are well-suited for CNC routing due to their uniformity and enhanced strength. Key materials include:

- Plywood: Made from cross-laminated veneers, plywood is durable, dimensionally stable, and widely available.
- OSB (Oriented Strand Board): Composed of compressed wood strands, OSB is economical and structurally sound but less water-resistant than plywood.

Each material's performance is influenced by its adhesive bonding (e.g., phenol-formaldehyde for waterproofing) and grading standards, such as Eurocode 5 classifications for structural timber. For outside use WPB adhesives are the most useful.

Capabilities and limitations of CNC machinery

CNC machinery offers unparalleled precision and flexibility in wooden shelter design. However, its capabilities are bounded by certain limitations:

- Capabilities:
  - Precision cutting: CNC machines can achieve intricate geometries, enabling complex joinery and efficient use of material. As much as 0.01 mm accuracy can be achieved.
  - Scalability: CNC-routing supports batch production of identical components for large-scale deployment.
- Limitations:
  - Infrastructure requirements: CNC machines require electricity and trained operators, which may not be available in all post-disaster contexts.
  - Material thickness: Most 3-axis CNC machines handle limited thickness, necessitating design adjustments for thicker materials.

8.1.3 Web application and CAD Integration:

The integration of web applications with CAD tools in this thesis demonstrates how computational design can be made accessible to non-experts, enabling them to engage in designing structurally sound and culturally appropriate shelters. Below are the key insights addressing the questions posed:

Designing a User-Friendly Web Application for CAD Interaction

To ensure non-experts can effectively interact with CAD models, the web application was designed with an intuitive and guided user interface. The goal was to minimize technical barriers while maximizing user creativity and participation.

- Guided customization: Users were provided with predefined parameters and templates that align with cultural and structural requirements, ensuring designs remained feasible and functional.
- Visualization tools: The inclusion of 3D visualizations allowed users to see the real-time impact of their choices, such as layout adjustments or material selections, in an accessible and interactive environment.
- Error prevention: Constraints were embedded within the design platform to prevent users from creating structurally unsound models, maintaining safety and compliance with regulatory standards.

Technical requirements for Integrating computational design tools

The integration of tools like Grasshopper and Rhino with a web application required addressing several technical challenges to create a seamless and efficient system.

- Backend integration: The use of Viktor, a tool designed to bridge web interfaces with computational engines like Grasshopper and Rhino, enabled non-expert users to leverage the complex computational power of these tools without requiring direct installation or expertise.
- Data exchange: A robust pipeline was created to manage the transfer of user inputs (e.g., layouts, dimensions) from the web interface to the computational tools and back. Formats like CSV and APIs facilitated smooth communication, ensuring data accuracy and consistency.
- Scalability and accessibility: The application was developed with scalability in mind, allowing it to adapt to different user needs and local contexts. Offline or low-power options could be explored to increase accessibility in off-grid or disaster-affected areas.

Guiding users to create structurally sound and culturally appropriate designs

The application effectively combined computational intelligence with user-centric design principles to guide users in creating designs that adhere to cultural norms and structural standards.

- Cultural sensitivity: Templates were tailored to accommodate local cultural practices, such as avoiding flat roofs in regions where roofs are used for daily activities. Customization options allowed users to select layouts, materials, and features aligned with their traditions.
- Regulatory compliance: The system incorporated Eurocode 5 standards into the design process, automating structural checks to ensure stability and safety. Users were not required to have technical knowledge of these standards, as the platform handled the compliance verification in the background.
- Interactive learning: By providing real-time feedback and suggestions during the design process, the application acted as both a design tool and an educational platform, empowering users to make informed decisions.

8.1.4 User experience and accessibility

The design and implementation of the web application focused on making the shelter design process user-friendly, accessible, and empowering for non-experts. Key insights addressing the questions of user involvement, customization constraints, cost efficiency, and promoting creativity are summarized below:

Involving users into the design and fabrication phase

A participatory approach was central to involving users in both the design and fabrication phases:

- Design phase: The web application provided users with interactive tools to modify shelter layouts, materials, and features. By offering intuitive sliders, dropdowns, and real-time visual feedback, the platform ensured that users could actively shape their shelters without needing technical expertise.
- Fabrication phase: Outputs from the application included CNC-ready files and clear assembly instructions, enabling users to participate in fabrication. This involvement not only reduced reliance on external experts but also fostered a sense of ownership and pride in the construction process.

Constraints and customization options

To guide users in creating functional, safe, and culturally appropriate shelters, the platform incorporated a system of constraints:

- What users can customize: Users could adjust dimensions, layouts, and materials within predefined safety and cultural parameters. For instance, they could adapt the number of rooms, select materials suited to local availability, or modify the roof style to match cultural practices.
- What Users cannot customize: Critical structural elements, such as load-bearing components and joint configurations, were automatically calculated and locked by the system to ensure compliance with safety standards. This approach balanced user creativity with necessary design safeguards.

Ensuring user-friendly design

The application was designed to be as accessible as possible, catering to non-experts with limited technical knowledge:

- Simplified Interface: A clean, intuitive interface allowed users to make adjustments through drag-and-drop functionality and guided prompts. Complex computations, such as structural analysis, were handled entirely in the backend.
- Educational prompts: The platform provided contextual guidance and tips throughout the design process, helping users understand their choices without overwhelming them.
- Language and accessibility: To ensure inclusivity, the application supported multiple languages and incorporated visual aids for non-literate users.

Cost efficiency and structural integrity

The platform addressed cost constraints and structural safety through intelligent design and optimization:

- Material efficiency: Computational tools minimized material waste by optimizing component dimensions and configurations.
- Local sourcing: By encouraging the use of locally available materials, transportation costs were reduced while supporting the local economy.
- Predefined templates: Standardized yet flexible templates balanced affordability with user customization.
- Automated structural analysis: The integration of Eurocode standards ensured that all designs met structural requirements without the need for expert oversight.

Simplifying the design process for non-experts

The use of computational tools and web applications significantly lowered the barriers to entry for non-experts:

- Real-time feedback: Immediate visual updates and warnings (e.g., when a design choice might compromise safety) ensured that users remained within feasible parameters.
- Step-by-step guidance: The design process was broken into simple, sequential steps, making it easy for users to follow.
- Preset configurations: Default options for common requirements (e.g., family size, climate) allowed users to generate basic designs quickly while retaining the ability to customize further.

Empowering users locally

The application was built to empower users in designing and producing their shelters locally while promoting creativity and ownership:

- Encouraging creativity: By allowing users to personalize their designs within constraints, the platform balanced standardization with individuality.
- Promoting ownership: Direct involvement in both design and assembly fostered a sense of pride and responsibility, which is essential for long-term satisfaction and use.
- Strengthening community: The collaborative potential of the platform, especially in conjunction with Makerspaces, enabled communities to share knowledge and resources, further strengthening bonds and resilience.

8.1.6 Local production

The adoption of CNC-routed wood-based shelters offers significant benefits in terms of leveraging local resources and fostering sustainable, reusable, and culturally appropriate designs. The insights below address the questions on resource utilization, sustainability, and cultural alignment.

Contributing to local the use and reducing dependency on external supply chains

CNC-routed wood-based shelters are particularly effective in enabling local production and minimizing reliance on external supply chains:

- Utilization of locally sourced materials: By designing shelters to use materials readily available in the local context, such as plywood, or regionally abundant timber, the need for costly imports is reduced. This also ensures that the shelters are better suited to local climates and environmental conditions.
- Portable and accessible fabrication: The use of mobile Makerspaces or temporary workshops equipped with CNC machines can localize production in disaster-affected areas. This decentralization allows for rapid response and scalability, eliminating delays caused by transportation and logistical bottlenecks. Though these are costly and without electricity not usable.
- Economic empowerment: Engaging local communities in the production process not only reduces costs but also supports the local economy by creating jobs and fostering skill development.

Ensuring sustainability, reusability, and cultural Appropriateness

Several strategies were incorporated to align the shelters with principles of sustainability, adaptability, and cultural relevance:

- Sustainability:
    - Material efficiency: The CNC-routing process minimizes waste by precisely cutting components to fit the shelter's design specifications.
    - Renewable resources: The use of engineered wood products like plywood, sourced sustainably, reduces the environmental footprint compared to high-carbon materials like steel or concrete.
    - Circular design: Components are designed for disassembly and reuse, enabling shelters to be reconfigured or recycled as needs evolve.
- Reusability:
    - Modular construction: The modular design allows shelters to be adapted or expanded based on user needs, enhancing their long-term usability.
    - Durable connections: Traditional joinery techniques, integrated into CNC designs, ensure robustness while allowing easy disassembly and reassembly.
    - Longevity: Components are treated or finished to withstand environmental conditions, extending their usable lifespan.

- Cultural appropriateness:
  - Customization options: The digital platform ensures that users can adapt designs to align with cultural norms, such as roof styles, spatial layouts, or material aesthetics.
  - Incorporating local practices: By considering traditional building methods and cultural preferences, the shelters integrate seamlessly into the local community, fostering acceptance and use.
  - Community involvement: Encouraging local stakeholders to participate in design and construction helps ensure the final product respects cultural norms and traditions.

8.1.7 Final conclusion

CNC-routing and computational tools can empower non-experts in post-disaster contexts to design and locally produce customizable wood-based shelters by combining precision, adaptability, and user accessibility. Computational tools like Grasshopper and Rhino enable parametric modeling, ensuring that shelter designs adhere to structural standards (e.g., Eurocode) while remaining adaptable to local cultural and environmental needs. By embedding constraints and automating structural analyses, these tools allow users to customize shelters without requiring technical expertise. CNC-routing enhances production by precisely cutting components, minimizing waste, and ensuring tight fits with robust joinery techniques. The process supports local resource utilization by using materials like plywood or regionally sourced timber, reducing reliance on external supply chains. When paired with accessible web applications, users can design shelters interactively, receive fabrication-ready files, and engage directly in construction, fostering ownership and strengthening community resilience.

However, it is essential to acknowledge the limitations of these systems. Digital models, while powerful, can have inaccuracies, bugs, or errors in their setup that may lead to discrepancies between the design and real-world implementation. This underscores the need for expert involvement to verify the accuracy of the computational tools, inspect the code and program logic, and ensure that quality checks are performed to confirm all components meet the standards outlined in the instructions. Additionally, challenges such as access to CNC equipment, electricity, and skilled operators remain. Mobile Makerspaces and refined workflows offer scalable solutions to address these issues, but their implementation must also be carefully monitored to ensure the shelters are both practical and robust in real-world contexts.

9.2 Reflection

9.2.1 Relation between topic, track, and program

The project aligns closely with the Building Technology (BT) track of the MSc Architecture, Urbanism, and Building Sciences program. It combines structural design principles, computational modeling, and advanced fabrication techniques to address practical and societal challenges. By focusing on sustainable, adaptable shelter design, the project integrates technical innovation with the program's emphasis on architecture's role in addressing global and local issues, such as disaster resilience and resource utilization.

9.2.2 Academic and societal value

Academically, the project contributes to the exploration of computational and digital fabrication tools in humanitarian architecture, expanding the discourse on integrating advanced technologies into socially impactful design. Societally, it has the potential to empower communities by democratizing shelter design and fabrication, promoting self-reliance, and fostering local resource utilization. Ethical considerations, such as sustainability, inclusivity, and cultural appropriateness, have been central to the project, though further validation is required to assess its full impact.

9.2.3 Transferability of results

The principles and methods developed in this project are highly transferable. The computational framework and application can be adapted to various contexts, materials, and building types. The focus on modularity and scalability ensures that the system can be tailored to different cultural and environmental conditions. However, practical testing and refinement are necessary to confirm its broader applicability.

9.2.4 Looking ahead

Future research will focus on refining and expanding the capabilities of the digital design application to ensure it becomes a fully functional and user-friendly tool. The immediate goal is to improve the application by implementing comprehensive load analysis, such as wind, snow, and seismic forces, to guarantee structural reliability. Additionally, the platform will be enhanced to include detailed 3D visualizations of the shelters, allowing users to see precise representations of their designs. Automated generation of fabrication files, such as CNC-ready outputs and clear assembly instructions, will also be prioritized to streamline the transition from design to construction. Gathering user feedback is another critical step, involving real-world testing of the application and its designs to refine the user experience and ensure it meets the needs of non-experts. Building full-scale prototypes and engaging users in the design and assembly process will provide valuable insights, enabling iterative improvements based on their experiences and suggestions.

Further work will also focus on refining the joinery techniques used in the shelter designs. While the current joinery solutions are functional, future research will explore more robust and versatile methods, particularly those that ensure structural stability without relying on rigid connections. This includes analyzing how different wood types and engineered timber affect joint performance and testing these under various loads to ensure long-term durability. Expanding customization options is another key area, aiming to provide users with more material choices, architectural features like stairs or openings, and culturally adaptable layouts that align with local traditions and needs.

By addressing these aspects, the platform can evolve into a comprehensive tool that empowers users to design and build their shelters with confidence while maintaining cultural, structural, and environmental appropriateness. This iterative approach will ensure the system becomes a practical and widely applicable solution for shelter design and construction.

9.2.5 Personal experience

Throughout this project, one of the biggest challenges I faced was maintaining an effective plan and timeline. While I had initially developed a comprehensive plan, unforeseen personal challenges and some misjudgments in my planning caused delays. This led to adjustments, including extending my graduation timeline. Upon reflection, I realize that I attempted to address a very broad scope within a limited timeframe, which added complexity to the process. Despite these hurdles, I believe I maximized my efforts during the available time, though meeting all milestones on schedule proved challenging.

Another key learning point was recognizing the importance of consistent mentor engagement. Earlier in the process, I hesitated to reach out, whether due to uncertainty about the progress I had made or feeling that I did not yet have specific questions to address. In hindsight, seeking more frequent guidance during the initial phases could have helped keep the project more firmly on track. However, in the later stages of the thesis, I significantly improved my collaboration with mentors, and their input became invaluable in helping me refine the project’s direction and address outstanding issues.

These experiences have taught me the importance of better planning, defining a realistic scope, and proactively engaging with available resources. They will undoubtedly inform me of my approach to future projects and professional challenges.

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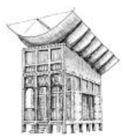
11. Appendix

11.1 Project analysis

Project	Photo	Pysical technical		Social cultural		Enviromental		Economical		Orginazational		Pro's	Con's
Pieter Stoutjesdijk Haiti shelter		Material	Reneable, CNC panels (fiberboard) from agricultural residues and made waterproof with a nano-coating	Safety and privacy	One room, multiple stories	Reusability	Good	Material costs	< 10.000 dollars	Transportability	Good	Sustainable local materials	High material costs
		Capacity	2 people	Expansion and flexibility	Not yet worked out (but no expandbility or flexability yet)	Protection against weather	Good			Assembly time	5 to 6 hours	Passive dimate sytem, including water collection, generating electricity and ventilation	
		Area	18 square meters	WASH facilities	No	Thermal comfort	Good					Short assembly time	
		Durability	aim for >5 years upto 20 years			Ventilation	Passive system roof ventilation						
		Conncections	6 types in the categories keyed, friction fit and snap joints			Energy supply	CSP system (solar power)						
						Daylight	Good						
Wikihouse		Material	Spruce Plywood or OSB	Safety and privacy	High	Reusability	Good	Material costs	15.000 dollars for 18 m2	Transportability	Produced on site/ DIY kit in smaller pieces	Created a community platform for anyone to share their designs as well as give acces for anyone to use (open source)	High material costs
		Capacity	Modular design (any number of people)	Expansion and flexibility	Fully deconstrucable and expandable, many design options	Protection against weather	Good			Assembly time	2 to 4 days for the chasis based on size, fully ready in 12 weeks	Very customizable (materials, floorplan, geometry, placement of windows etc.)	Is more a permanent solution
		Area	Largest example 103 square meters (can be any size).	WASH facilities	Yes	Thermal comfort	Good					Short assembly time	Need for expert involvement still large (They advise for architect, structural engineer etc.)
		Durability	60 years (with normal maintinance)			Ventilation	Depends on user (probably active)					Easy assembly	Nesting of the members for CNC create a lot of waste
		Conncections	S-joint and peg-in-slot connections			Energy supply	Regular house system (Solar panels can be added)						
						Daylight	Good						
IMBY kit		Material	Plywood	Safety and privacy	High	Reusability	High	Material costs	Smallest unit 10.000 dollars	Transportability	High, is dilivered as a flat packed kit, fully deconstructable and relocatable	Fully deconstructable and relocatable	Smaller units and width can't be extended
		Capacity	11 different options up to 3 or 4 people (quite small)	Expansion and flexibility	Modules can be added or removed and can be easily relocated	Protection against weather	High			Assembly time	3 people 2 days	Loacally produced	One space, no bathroom or kitchen
		Area	From 2.6 by 2.8 meters to 7.8 by 2.8 meters (extendable in length)	WASH facilities	No	Thermal comfort	No insulation and metal sheet roof however insualtion can be easily added					Easily constructed	High costs
		Durability	Not specified			Ventilation	Cross ventilation						
		Conncections	Wedged mortise and tenon joints			Energy supply	Not specified						
						Daylight	High because of window in the roof						

11.2 Symbols used for design strength

As for symbols that are used in the formulas as characteristic strengths they are as follows:

Tensile strength parallel to the grain	ft,0,k
Tensile strength perpendicular to the grain	ft,90,k
Compression strength parallel to the grain	fc,0,k
Compression strength perpendicular to the grain	fc,90,k
Bending strength parallel to the grain	fb,0,k
Bending strength perpendicular to the grain	fb,90,k
Sheer strength panel parallel to the grain	fv,0,k
Sheer strength panel perpendicular to the grain	fv,90,k
Sheer strength planar parallel to the grain	fr,0,k
Sheer strength planar perpendicular to the grain	fr,90,k
Mean modulus of elasticity parallel to the grain in bending	Eb,0,k
Mean modulus of elasticity perpendicular to the grain in bending	Eb,90,k
Mean modulus of elasticity parallel to the grain in tension	Et,0,k
Mean modulus of elasticity perpendicular to the grain in tension	Et,90,k
Mean modulus of elasticity parallel to the grain in compression	Ec,0,k
Mean modulus of elasticity perpendicular to the grain in compression	Ec,90,k
Mean modulus of rigidity in sheer panel parallel to the grain	Gv,0,k
Mean modules of rigidity in sheer panel perpendicular to the grain	Gv,90,k
Mean modulus of rigidity in sheer planar parallel to the grain	Gr,0,k
Mean modulus of rigidity in sheer planar perpendicular to the grain	Gr,90,k

11.2 Set up excel sheet data material

Plywood Türkiye							
Type of plywood							
Name			Birch plywood 18mm	Birch plywood 21mm	Birch plywood 24mm	Birch plywood 27mm	Birch plywood 30mm
Land			Türkiye	Türkiye	Türkiye	Türkiye	Türkiye
Company			Turkisch plywood	Turkisch	Turkisch	Turkisch	Turkisch
Type of wood			Birch	Birch	Birch	Birch	Birch
Grade			BB/CP (or higher)	BB/CP (or highe	BB/CP (or highe	BB/CP (or highe	BB/CP (or highe
Glue type			WBP	WBP	WBP	WBP	WBP
Price	*excl. transport	euro per m3	696	696	696	696	696
Length	l	mm	2500	2500	2500	2500	2500
Width	b	mm	1250	1250	1250	1250	1250
Thickness	t	mm	18	21	24	27	30
Number of layers	n		13	15	17	19	21
ID_type			PLY	PLY	PLY	PLY	PLY
ID_land			TUR	TUR	TUR	TUR	TUR
ID_name			BIR18TURPLY	BIR21TURPLY	BIR24TURPLY	BIR27TURPLY	BIR30TURPLY
ID_number			001	001	001	001	001
ID			BIR18TURPLY_001	BIR21TURPLY_0	BIR24TURPLY_0	BIR27TURPLY_0	BIR30TURPLY_0
Materialproperties - Strength and Stiffness							
Tensile strength parallel to the grain	ft.0	n/mm^2	39.2	39	38.8	38.7	38.5
Tensile strength perpendicular to the grain	ft.90	n/mm^2	35.8	36	36.2	36.3	36.5
Compression strength parallel to the grain	fc,0	n/mm^2	27.2	27	26.9	26.8	26.7
Compression strength perpendicular to the grain	fc,90	n/mm^2	24.8	25	25.1	25.2	25.3
Bending strength parallel to the grain	fb,0	n/mm^2	40	40	40	40	40
Bending strength perpendicular to the grain	fb.90	n/mm^2	30	30	30	30	30
Sheer strength panel parallel to the grain	fv,0	n/mm^2	9.5	9.5	9.5	9.5	9.5
Sheer strength panel perpendiclar to the grain	fv,90	n/mm^2	9.5	9.5	9.5	9.5	9.5
Sheer strength plainar parallel to the grain	fr,0	n/mm^2	2.67	2.59	2.62	2.57	2.59
Sheer strength plainar perpendiclar to the grain	fr,90	n/mm^2	2.34	2.41	2.39	2.43	2.41
Mean modulus of elasticity parralel to the grain in bending	Eb,0	n/mm^2	6450	6450	6450	6450	6450
Mean modulus of elasticity perpandicular to the grain in bending	Eb,90	n/mm^2	2540	2540	2540	2540	2540
Mean modulus of elasticity parralel to the grain in tension	Et,0	n/mm^2	9148	9093	9052	9019	8993
Mean modulus of elasticity perpandicular to the grain in tension	Et,90	n/mm^2	8352	8407	8448	8481	8507
Mean modulus of elasticity parralel to the grain in compression	Ec,0	n/mm^2	9148	9093	9052	9019	8993
Mean modulus of elasticity perpandicular to the grain in compressio	Ec,90	n/mm^2	8352	8407	8448	8481	8507
Mean modulus of ridigty in sheer panel parralell to the grain	Gv,0	n/mm^2	620	620	620	620	620
Mean modulus of ridigty in sheer panel perpandicular to the grain	Gv,90	n/mm^2	620	620	620	620	620
Mean modulus of ridigty in sheer planar parralell to the grain	Gr,0	n/mm^2	206	206	206	205	205
Mean modulus of ridigty in sheer planar perpandicular to the grain	Gr,90	n/mm^2	183	186	189	190	192
Materialproperties - Other							
Density	p	kg/m^3	700	700	700	700	700
Specific gravity	gamma	kN/m^3	6860	6860	6860	6860	6860
Water vapor premeability		Wet cup	90	90	90	90	90
		Dry cup	220	220	220	220	220
Thermal cooficient parallel	T1	µstrain/C	8	8	8	8	8
Thermal cooficient perpandicular	T2	µstrain/C	8	8	8	8	8
Thermal conductivity		W/mK	0.17	0.17	0.17	0.17	0.17
Sound insulation (Airborne)		dB	24.4	24.4	24.4	24.4	24.4
Sound absorbtion		500-1250 Hz	0.1	0.1	0.1	0.1	0.1
		1000 - 2000 Hz	0.3	0.3	0.3	0.3	0.3
Biological durability		Class	2	2	2	2	2
Bonding quality		Class	3	3	3	3	3
Durability (moisture)		Class	3	3	3	3	3
Fire reaction		Class	D-s2 d0	D-s2 d0	D-s2 d0	D-s2 d0	D-s2 d0
Formaldehyde emmission		Class	E 0.5	E 0.5	E 0.5	E 0.5	E 0.5
Salespoints							
Locations		City_Name	Adana	Adana	Adana	Adana	Adana
			Duzce	Duzce	Duzce	Duzce	Duzce
			Gaziantep	Gaziantep	Gaziantep	Gaziantep	Gaziantep
			Gebze	Gebze	Gebze	Gebze	Gebze
			Istanbul	Istanbul	Istanbul	Istanbul	Istanbul
			Kirklareli	Kirklareli	Kirklareli	Kirklareli	Kirklareli
			Konya	Konya	Konya	Konya	Konya
			Samsun	Samsun	Samsun	Samsun	Samsun
Webpage			https://www.turkish	https://www.tur	https://www.tur	https://www.tur	https://www.turl
Extra info							
Links to more info			https://drive.google	https://drive.go	https://drive.go	https://drive.go	https://drive.goc
Missig data based on			Metsa/ Granta edup	Metsa/ Granta e	Metsa/ Granta e	Metsa/ Granta e	Metsa/ Granta ec
Notes							