Dominik Auclair

Sustainable Modular Timber Construction

A Holistic Perspective Towards Enhancing the Competitiveness of Timber Construction

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Foreword

The "Sustainable Building Technologies- Community of Practice" (SBTCP) project by Karelia UAS in collaboration with Salzburg UAS and Jade UAS aims to enhance the sustainable development of timber construction through using advanced expertise and technologies. The project is funded by the Ministry of Education and Culture of Finland and Karelia UAS is the coordinating organisation of this project. The project started at the end of 2021 and has played an eminent role in bringing international students from cross-border countries together via workshops and research activities. As a significant part of these international student activities, the SBTCP project hosted the internship activities of Dominik Auclair from Jade UAS, Oldenburg, Germany. During his internship, he had the opportunity to work and share ideas with multidisciplinary experts from Karelia UAS. He was in involved in activities such as background research work for the SBTCP project, as well as construction company and site visits; which eventually supported him to develop his bachelor thesis topic and research further.

The SBTCP project has three fundamental pillars of research activities: 1) sustainable buildings, 2) material sciences, and 3) building information modelling. The sustainability perspective from Karelia UAS resulted in eight possible research topics extensively focusing on the competitiveness of timber construction and sustainable environmental aspects of timber as a building material in cities. After conducting several literature reviews on sustainability, circularity, and competitiveness of timber construction, Dominik's bachelor thesis titled 'Modular Timber Construction' was shaped, which focused on the flexibility and sustainability aspect of modular timber construction techniques.

Dominik's internship activities have been supervised by Prof. Sebastian Hollermann from Jade UAS, and Timo Pakarinen and Shammi Keya from Karelia UAS. In this report we share the background research work conducted by Dominik Auclair. This has been a successful collaboration activity within the SBTCP project and we look forward to continuing this successful cooperation between Karelia UAS and Jade UAS.

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1 The industry perspective on wood construction

Because of climate change and the interest of the population in finding sound environmental solutions there is a good prognosis for timber construction. Most people want environmentally friendly, climate-neutral and renewable materials in their life. Wood can be considered the ultimate sustainable building material. Not only is the material more environmentally friendly than concrete, bricks or steel, but also the processing and transport require less energy, which reduces the carbon footprint (Horx-Strathern, Varga and Guntschnig, n.d.).

There are many advantages that make building with timber more popular. The possibility of prefabrication and the ability to work on different components and on the construction site at the same time shortens the construction time for building and is therefore cost-effective. The sustainability which includes the reusability, and recyclability is a benefit of timber constructions. The quality and lifetime are similar to traditional constructions but especially the reusability of timber reduces the lifecycle cost (Horx-Strathern, Varga and Guntschnig, n.d.). The invention of the cross-laminated-timber (CLT) is a key element making timber construction more competitive compared to concrete. CLT can be used for walls, as well as ceiling and roof elements and can be combined with other building materials. It is a big innovation and is a big step in different types of buildings like detached houses, multistorey building, public buildings, industrial buildings, bridges, etc. (Horx-Strathern, Varga and Guntschnig, n.d.).

The invention of CLT is bringing timber constructions forwards but the companies, architects, engineers, universities and industries must work closely together to optimize different materials, different methods of building timber modules and test new technical possibilities. A faster pace is needed here to improve the competitiveness of timber constructions (Horx-Strathern, Varga and Guntschnig, n.d.).
In recent years, the renovation of existing buildings and the rehabilitation of apartments have increased. One reason for this increase are higher building costs. This part of the development is a positive aspect for timber construction. Wood is a good building material for renovations because wood is easy to process, and is a light material and particularly suitable for renovations, as a higher pace of construction is very important (Horx-Strathern, Varga and Guntschnig, n.d.).

The lack of sound insulation of wood is the biggest disadvantage and needs to be optimised. In most cases, the floors/ceilings of high-rise buildings are made of a hybrid material of wood and concrete. The reason for this is the poor sound insulation of wood. One important task for the industry could be to develop a product like CLT and with additional characteristics for better sound insulation. The problem is that this product would be too expensive. On the other hand, a product with these properties would find much use in the construction industry (Horx-Strathern, Varga and Guntschnig, n.d.).

Timber is a competitive building material with many positive aspects in relation to sustainability, carbon footprint, static properties, creativity and design. However, to be competitive in the future, we need sustainable forest management using modern IT tool und solutions. Forest management implies that forestry can benefit from structural clearing to reduce the loss of healthy trees to fire or disease (Stambler, n.d.).

The Stora Enso Institute carried out an online survey with experts. The survey included questions on timber constructions for today and a prognose for the future. Views of experts on various questions about the timber construction industry today (agreement in %)

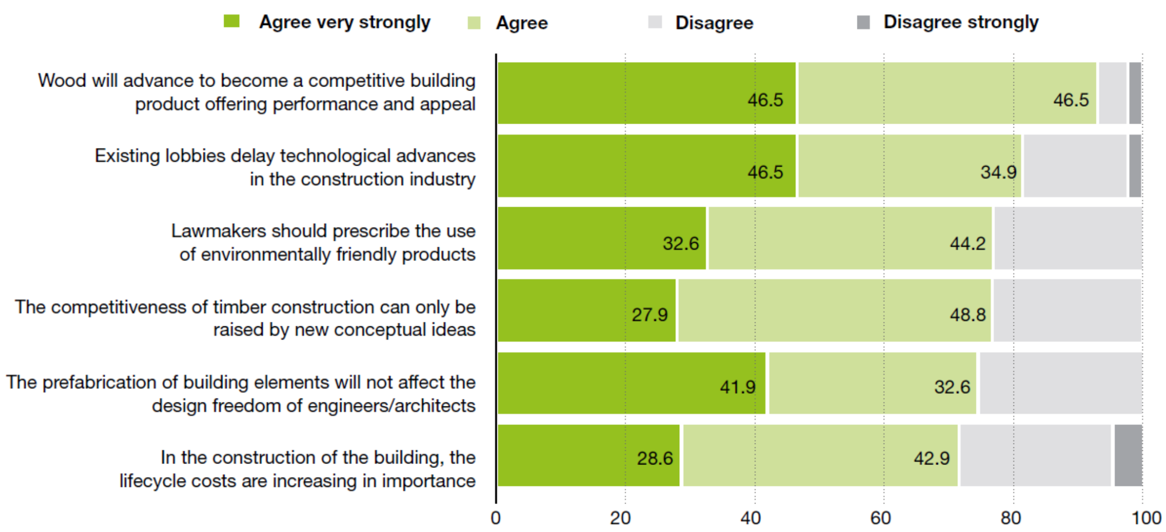

Figure 1: Views of experts on various questions about the timber construction industry today (Source: Horx-Strathern, Varga and Guntschnig, n.d.)

Views of experts on various questions about the timber construction industry for the future (agreement in %). (Horx-Strathern, Varga and Guntschnig, n.d.)

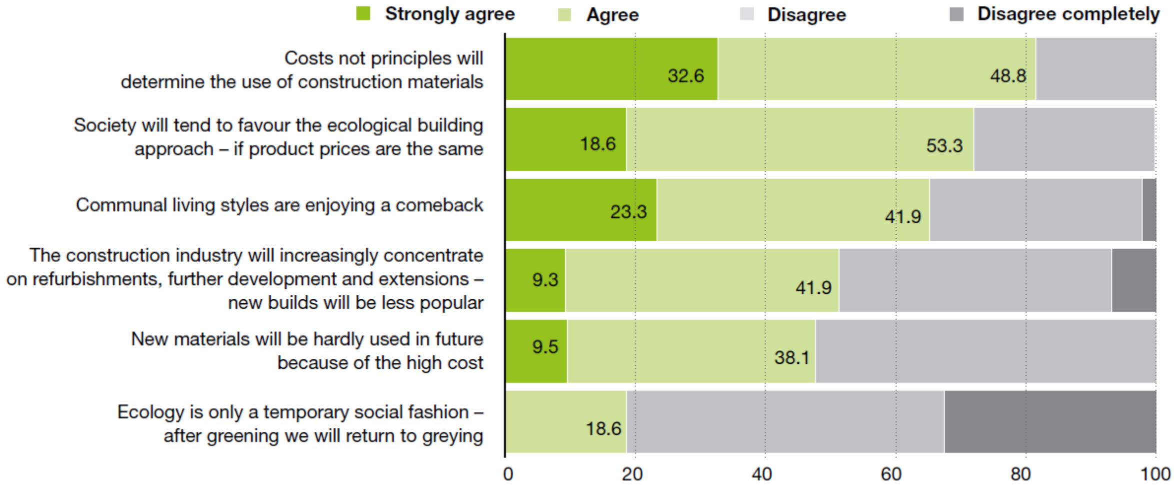

Figure 2: Views of experts on various questions about the timber construction industry for the future (Source: Horx-Strathern, Varga and Guntschnig, n.d.)

2 Key elements of competitiveness of wood construction

The research will be focused on analysing the key elements which create the most important parameters of competitiveness. Wood construction is compared to traditional solutions.

2.1 Characteristics of wood

Wood is a highly versatile material. From softwood to hardwood, it has many characteristics for use as a construction material. The characteristics are different for every type of wood. From the wood grain to colour, the weight, static characteristics to the resistance against weather effects. Every type of wood has pros and cons for different construction types.

2.1.1 General properties

Wood is a material consisting of fibres arranged in the longitudinal direction of the tree. Pinewood is one of the most used woods in the building industry. It is lightweight, which makes it easy to process, and it has a high durability, in addition to a high pressure and tensile strength in the longitudinal direction. However, the pressure and tensile strength crosswise to the fibre direction are lower. Good quality wood has a good resistance against pressure and does not break or deteriorate. It is also possible to use timber as a beam because the bending profits from the wooden structures (Gupta, 2020).

Another pro of using a timber construction is the thermal insulation. The lower density compared with steel or concrete is the reason for this characteristic.

Two negative properties of wood are that it shrinks and swells as a function of the changing moisture content in the wood, and the possibility of insects or fungal infestation when the moisture content is higher than 20 per cent. However, this property is losing importance, since most wooden structures are protected from water and have a constant level of moisture. This only has to be taken into account in timber construction along with the weather influences. The type of wood is important to the level of shrinkage and swelling and even the resistance against insects and fungal is dependent on the type of wood. In addition to structural wood protection against moisture, it is possible to treat wood with chemical preservatives, but here you must be careful to choose a preservative that is not dangerous to health and the environment (baunetzwissen.de, n.d.; Gupta, 2020; Tsoumis, n.d.).

Alongside the many pros and cons of wood as a construction material, a water-proof timber construction has a long lifetime. For a timber construction which needs to endure weather effects oakwood is a better choice, because it is more resistant to moisture than pinewood.

2.1.2 Fire resistance

Wood has good fire resistance. The natural charcoal surface, which arises in the fire, is a protection for the core of the wood. The time it takes for the construction to collapse is therefore long. In one minute about 1mm of wood is burned. This ensures an accurate forecast and a fire resistance period of up to 120 minutes can be achieved comparatively easily (puuinfo.fi, 2020). Next to the natural surface protection, an environmentally friendly and certified low-emission fire protection agent can be used. Another method to protect the construction is to add a protective cladding. For this cladding gypsum is very good because it is a great way for combine the sound insulation and fire protection. In addition, the installation of an automatic sprinkler system is mandatory for a building with more than two floors (nordtreat.com, 2019).

Concrete is a great choice as a fire-resistant building material because it is non-combustible. Wood burns quickly, but the properties described above, with some other fire protection measures, provide adequate fire resistance. Steel also needs some additional fire protection measures. One property of steel is that steel quickly loses strength as it gets warm. The following Figure 3 shows the strength of steel dependent on the temperature (Agarwal, n.d.)

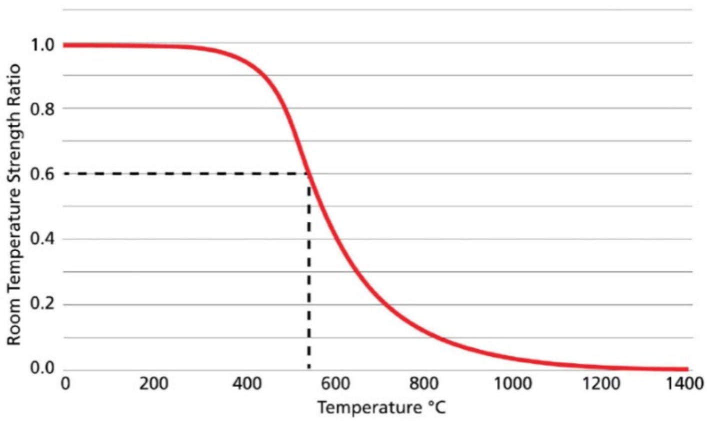

Figure 3: Effect of temperature on steel(source: building.co.uk, 2018)

All in all, it is important to build constructions with a high level of fire resistance. In cooperation with other materials such as gypsum and an automatic sprinkler system, these conditions can be met (nordtreat.com, 2019). Nevertheless, further development for fire resistance is necessary for the future. The claim that timber structures are less fire-resistant than concrete and steel is a disadvantage for competitiveness and needs to be dispelled (Horx-Strathern, Varga and Guntschnig, n.d.).

2.1.3 Sound insulation

A sound is spread in waves and the number of waves per second is the frequency in Hertz. The sound perception of humans has a frequency range of 16Hz to 20.000Hz, but the perception can be extremely different from human to human. Noise with a deep frequency is an especially disturbing sound. One example of a disturbing sound with a low frequency is the noise of walking. Sound insultation in the building industry is concentrated in the frequency range from 100Hz to 3150Hz.

The first stage of the design phase can be effective to reduce disturbing sounds. Here it is important to notice where the rooms are located. In this way is important to look at the area around the building. For example, a sleeping room next to a street with a lot of traffic can be disturbing.

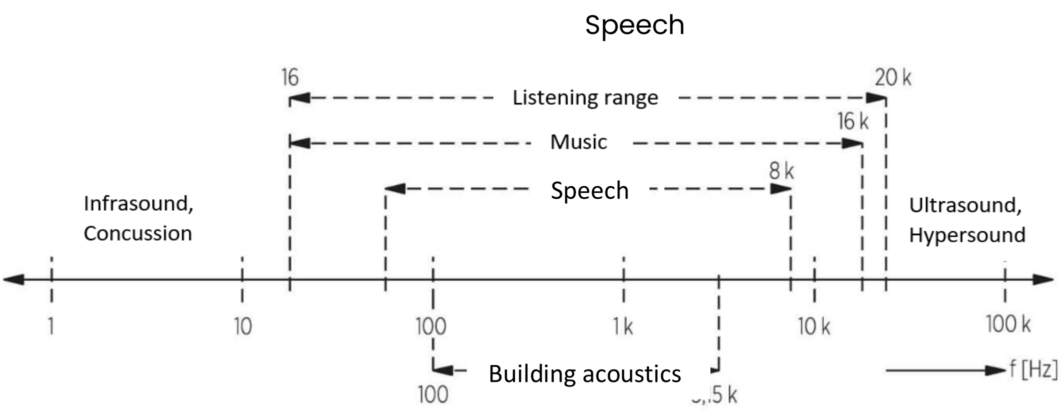

Figure 4: Frequency ranges (source: Broßat, 2022)

Another aspect which should be noted is the layout of the room. A sleeping room is not good when located next to a kitchen or a bathroom because the water pipes can make disturbing sounds. When these aspects are noticed at the beginning of planning, it can be effective for sound insulation (Broßat, 2022).

The poor sound insulation of timber constructions is one of the biggest disadvantages. A sound is spread in sound waves. This sound waves can travel through a material in the form of vibrations. To create a modern house construction with sound insulation some details are important. The density of building materials has an impact on the sound insulation. A material with a high density is able to insulate the vibrations that travel through the material. Timber is a lightweight material and does not have good sound insulation like bricks or concrete. For example, a wall of timber needs to be 600mm to achieve the same result as a 180mm concrete wall. Because of this characteristic we need another solution for the sound insulation. There are aspects which improve the sound insulation in different ways. An elastomer is able to reduce the vibrations of structure-borne noise. In addition, a construction with an air gap is an efficient way to improve the sound insulation, because it interrupts the vibration. This type of construction is a dual layer system. The insulation in the air gap is able to absorb sound waves from the airborne sound and improves the level of sound insulation. These dual-layer systems are effective in walls and in ceilings as well (Broßat, 2022; Lahtela, 2021)

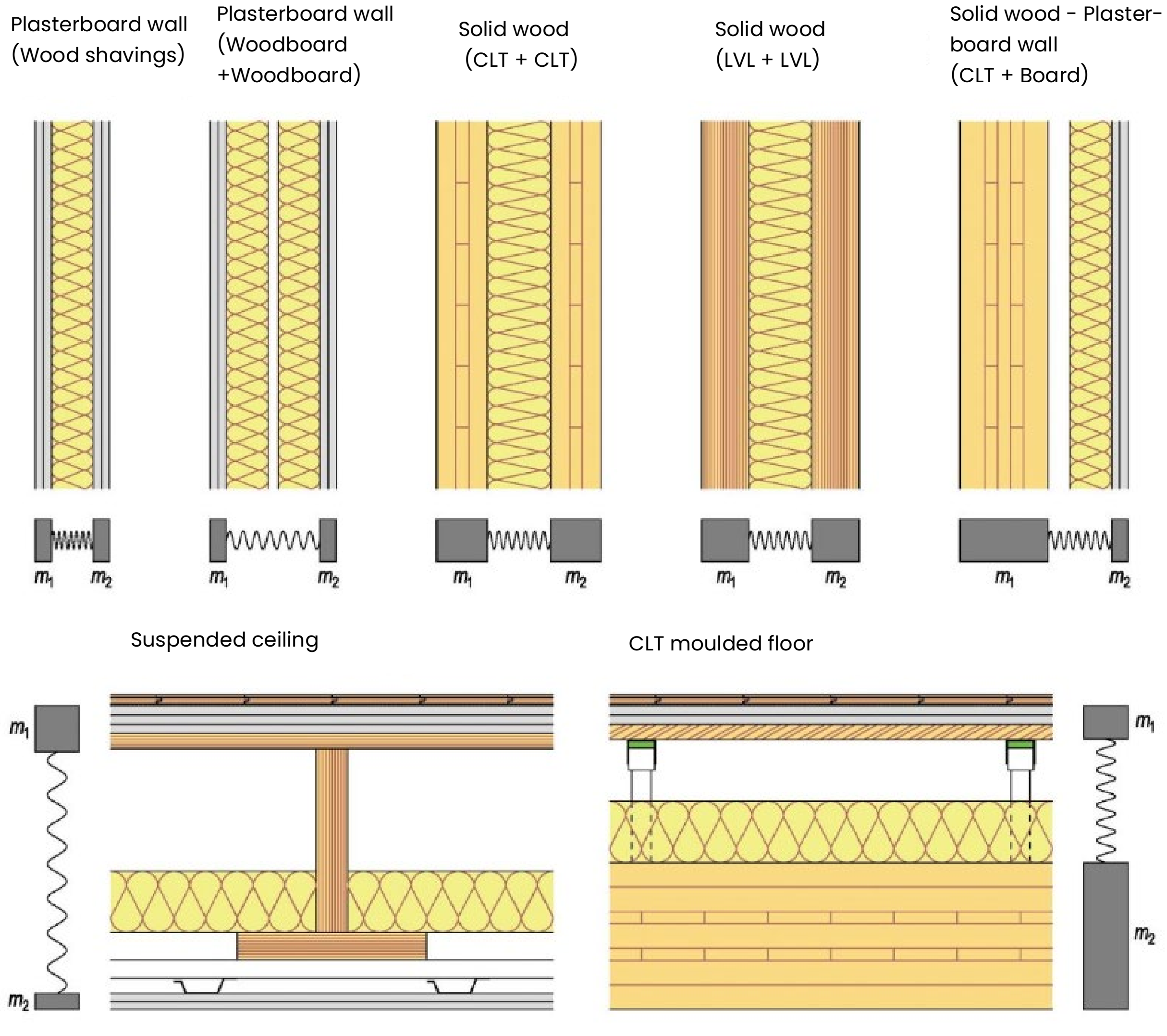

Figure 5: Sound insulation examples of dual-layer acoustic structures (source: Lahtela, 2021)

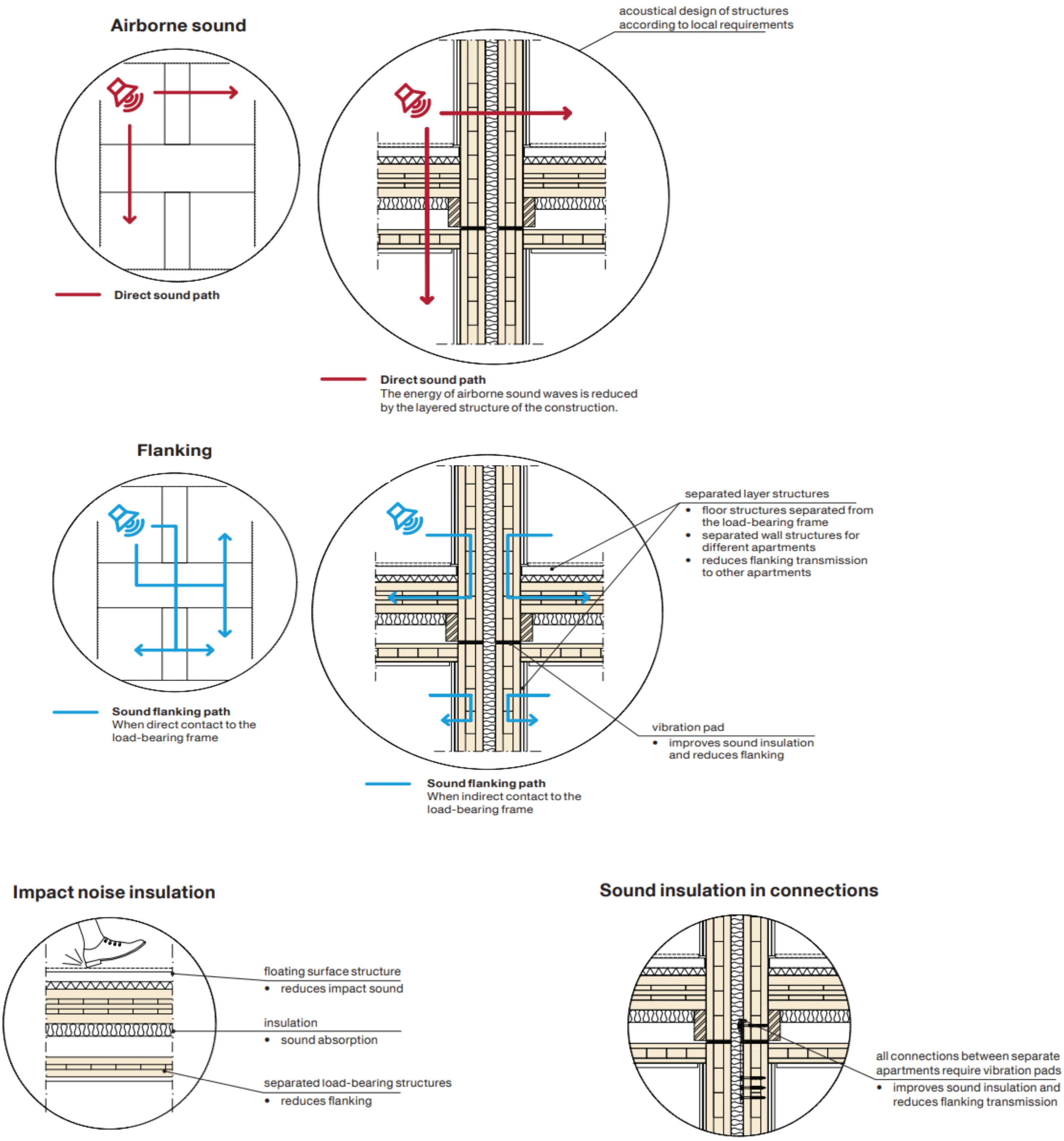

Figure 6: Sound insulation example for a modular timber construction (source: storaenso.com, 2016)

Figure 6 from Stora Enso for modular element buildings shows some details of the connections between the modules. All connections from different apartments are sound insulated with vibration pads to interrupt the structure-borne noise.

Using gypsum cladding can improve the sound insulation and at the same time it is a good solution to improve the fire resistance. The fire resistance of wood is treated in the next section. As sound insulation is one of the greatest weak points, it needs to be constantly developed. New products and new technologies can improve sound insulation and make timber construction more competitive and interesting for the construction industry.

2.1.4 Air quality

Wood is a non-toxic material. Studies show that wood improves indoor air quality and reduces toxicity in buildings (Ossenbach, 2020). Wood can also absorb and release moisture from the air, which balances the air humidity (Laapotti, 2020).

Some timber constructions are treated with chemicals. Most of these are dangerous for humans. You should definitely pay attention to using a non-toxic treatment.

Using natural materials indoors has a positive impact on human health and well-being. Furthermore, wood engages many of our senses because it is warm textured and comforting. Some studies have shown that indoor environments with a timber construction can reduce stress levels (Ossenbach, 2020).

Next to the positive effects on well-being and lower stress levels are volatile organic compounds (VOC). This topic is treated separately in section in 2.4.

2.2 Sustainability

Wood is one of the most sustainable materials for building construction (Horx-Strathern, Varga and Guntschnig, n.d.). In the lifetime of a tree, it binds carbon dioxide and produces oxygen (nordtreat.com, 2019). One cubic meter wood stores 250 kg of carbon and produces 750 kg of oxygen as a waste product of photosynthesis. The total storage amount of one cubic meter wood is 1000 kg of carbon. This means we can store 250 kg of carbon per cubic meter of timber for the lifetime of the timber construction and hopefully after this lifetime in another construction or recycled product. Overall, a timber construction can be carbon neutral (Laapotti, 2020).

The production of timber products is efficient and has a low embodied energy. Wood is a renewable and local resource. In addition, wood is a soft and light building material due to its density, which facilitates processing and logistics compared to heavier materials. This also leads to lower energy consumption.

In addition to the low energy consumption for processing and logistics, the low density has a positive effect on thermal insulation. The thermal insulation is better than from concrete, bricks or steel. This minimizes the needed energy for heating and cooling the building. On the other hand, the low density is a disadvantage for the heat storage. Because wood has a lower density than stone, it cannot store and release as much heat. This means that temperature differences are felt more quickly. This has an influence on the feeling of comfort (Delton, 2017).

The following Figure 7 shows a comparison of different materials with their Eco Index 3 (OI3) for typical thickness of some construction materials in the manufacturing phase and CO_2 emissions in tonnes used for a single storey house in Sydney, Australia (oopeaa.com, 2022).

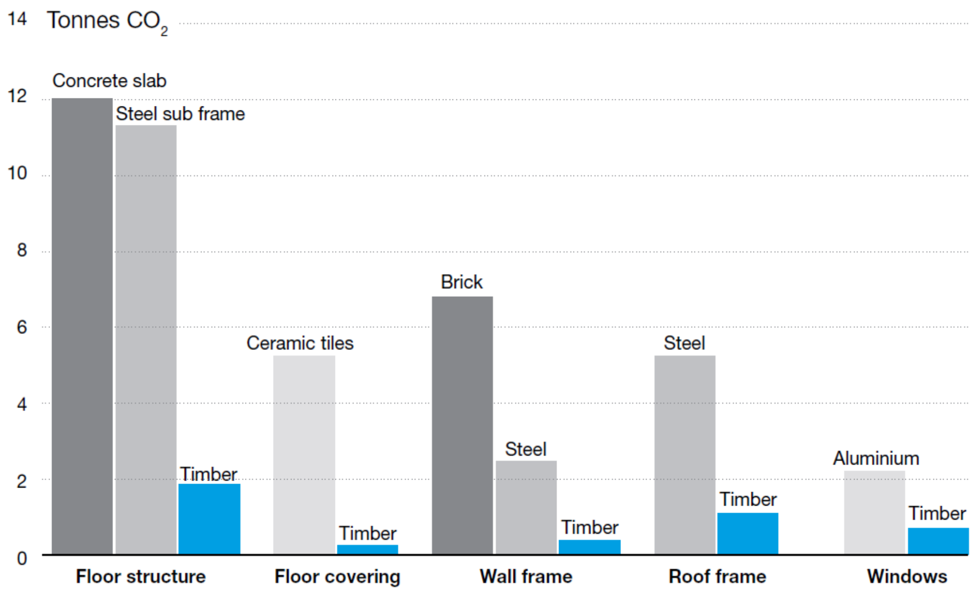

Figure 7: CO2 emissions for different materials (source: Horx-Strathern, Varga and Guntschnig, n.d.; forestrycorporation.com.au, 2008)

The difference in Figure 8 between reinforced concrete and concrete and from brick masonry to bricks shows the big influence of steel and cement according to the Eco Index.

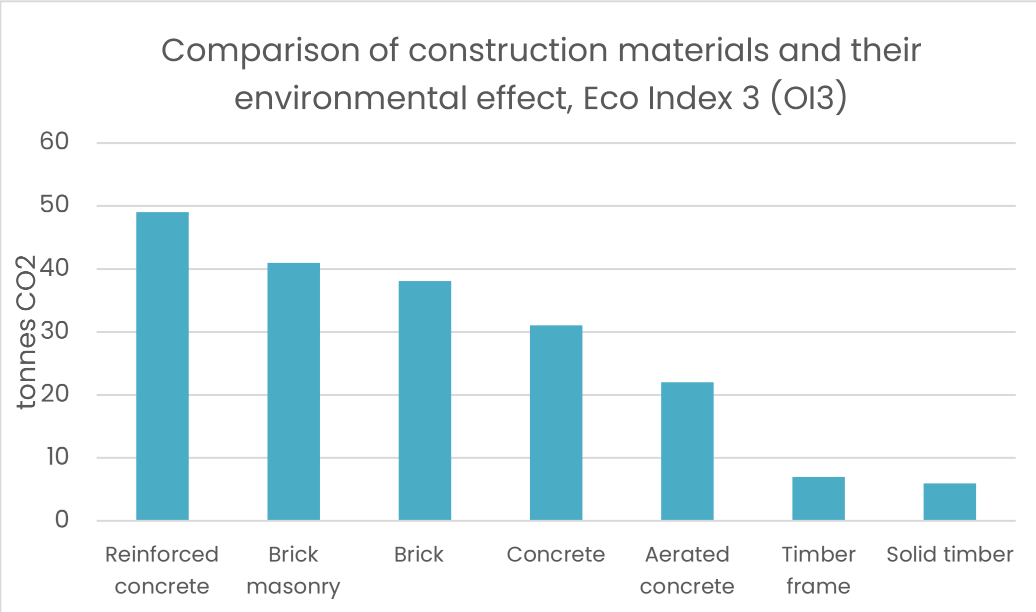

Figure 8: Eco Index 3 (OI3) for typical thickness of some construction materials in the manufacturing phase (source: Horx-Strathern, Varga and Guntschnig, n.d.)

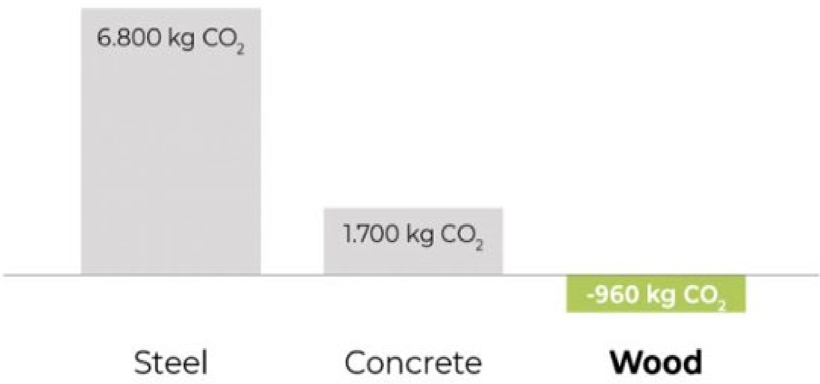

Figure 9: CO2 per 1m³ of construction materials

Wood can be recycled easily for different products. Depending on the condition, is it possible to use old timber constructions entirely or only some parts from timber constructions again. The rest of waste products can be used for different kinds of recycling. The quality of the wood determines which kind of recycled product it can be useful for. The following points indicate different grades of recycling for wood-based materials.

- Clean recycled wood: animal bedding and mulches
- Industrial feedstock grade: wood-based materials like chipboards or paper
- Fuel grade: biomass fuel (slrecyclingltd.co.uk, n.d.)

Compared to all other building materials, steel is the best recyclable material. It can be melted and processed into new products without loss of quality (Donovan, 2020). On the other hand, recycling concrete is more difficult than timber. For the recycling of concrete, it is usually broken up into small pieces. The crushed concrete has to be separated from iron and other materials and can then be used as gravel, for example. It takes a lot of energy to break concrete and sort the broken concrete (Rodriguez, 2019).

Timber constructions are the best choice compared to traditional constructions. The processing and logistics are more efficient, and carbon can be stored for the lifetime of the timber construction. For example, alone concrete produces 7% and steel produces 7% of the global carbon emissions (carbonclean.com, 2021; Laapotti, 2020).

2.3 Economic solutions for construction

Timber construction is an economic alternative building technology to traditional constructions. The sustainable usage of local forests is a good foundation for using more wood in construction instead of other materials. A positive characteristic of wood is the easy process of drilling, screwing, gluing and planing the surface. With these processes is it possible to produce components with a higher durability, tensile and pressure strength. This option, combined with the light weight of wood, enables the production of building elements in a factory under good working conditions and the delivery of building elements to the construction site. This way of building can be faster than traditional construction. In a production hall is it possible to use tools which are too big for the construction site and these better tools can increase the pace of production and also the quality. Next to the prefabrication it is possible to prepare everything on the construction site at the same time (timberframetech.co.uk, n.d.). Another point to save time is that a timber construction is independent of the weather. Apart from the working conditions for the workers, it is possible to work in sub-zero temperatures or in the rain when the timber is protected. However, it should be as dry as possible while it is being used in construction (timberframetech.co.uk, n.d.).

In the previous section on the industry perspective concerning wood constructions, it was mentioned that timber constructions are great building materials for renovations and housing densification. This is an important topic for the future. For such projects a timber construction is a good choice. The prefabrication and easy processing have advantages compared to other building materials. The construction site can be quiet, clean, needs less space and is faster. These facts contribute positively to the use of timber (Horx-Strathern, Varga and Guntschnig, n.d.).

The renewability of timber has a huge impact on the economy. After water, sand is the second most used resource in the world. However, the word wide shortage of sand has been known for a long time and is a problem. This increases the competitiveness of timber. Wood is renewable, but it can also become scarce. This occurrence was seen in the last years of the corona pandemic (Newcomb, 2022).

As the degree of reusability increases, this also has an impact on economic efficiency. The material can be reused instead of being demolished. However, in order to build reusable structures, attention must be paid to this already in the planning phase. This topic is dealt with in another section. However, in this way, the value of the materials could be preserved.

One big problem with timber construction is that we need to close the skills gaps and we need to refine the processes. Lack of experience with large wood structures and skilled workers and process managers makes this construction type more expensive (nordtreat.com, 2019).

In the same online survey from the Stora Enso Institute, experts spoke about challenges, deficits and potential. The following figures show the results of their statements.

Figure 10 shows the experts' opinions on why wood is not used so often as a structural element in buildings. (Horx-Strathern, Varga and Guntschnig, n.d.)

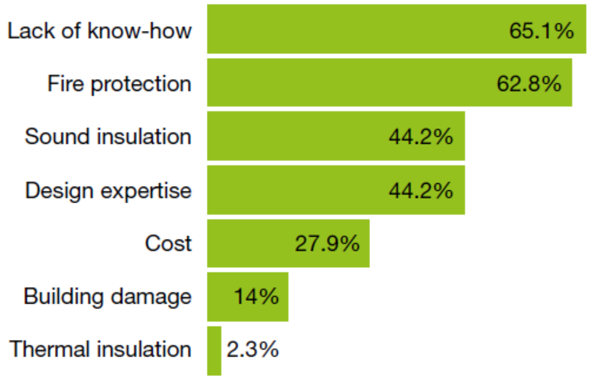

Figure 10: Our deficits in timber constructions

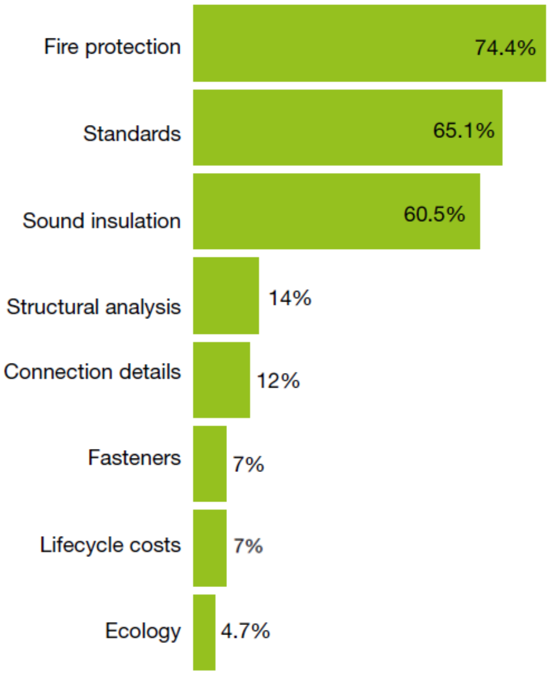

Figure 11: Challenges in the development for the future of multi-storey timber constructions

Figure 11 is the result of a discussion on the challenge in constructing multi-storey residential buildings with timber. (Horx-Strathern, Varga and Guntschnig, n.d.)

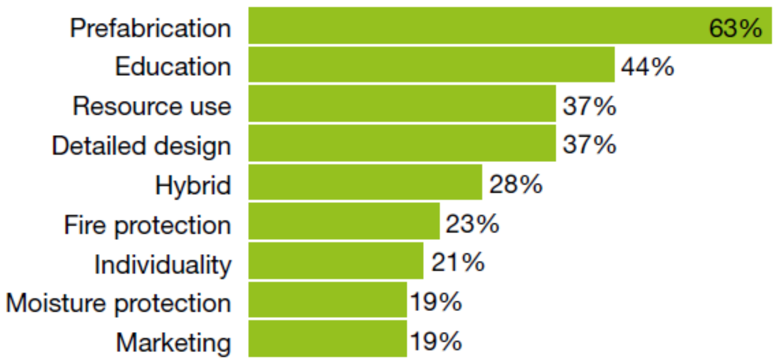

Figure 12: The greatest technological development potential of timber constructions and CLT in the

Figure 12 shows the results of the expert survey on the greatest technological development potential for timber constructions and CLT in the future. (Horx-Strathern, Varga and Guntschnig, n.d.)

The experts from the online survey agreed on three negative and three positive trends in the timber industry. The three negative and positive points are:

- Lobbying by the massive construction industry
- Prejudices against timber constructions
- High standards and regulations
- Ecology
- Short construction time and prefabrication
- Flexibility

(Horx-Strathern, Varga and Guntschnig, n.d.)

Compared to traditional construction, the experience and skill level concerning timber constructions is lower because traditional construction with concrete, steel and bricks has dominated the market. However, in recent years, wooden structures have gained in importance, and we can improve the skills and close the deficit gaps to make timber constructions more competitive.

2.3.1 Need for a cost efficiency assessment

Comparing the costs of different types of construction is difficult. There are many factors that can influence the costs. Often timber construction is cost efficient and in some situations a traditional construction is the better choice. The first factor is the actual situation with the material costs and delivery time. The material prices are dependent on the supply and demand. Wood is a regrowing material, but the demand can be higher than the supply. Two reasons for the low supply are the huge forest fires all over the world and the great damage to our forest by pests.

The second factor is the complexity and type of building, which makes it difficult to compare the different construction methods and the building costs dependent from the complexity of the construction. The following Figure 13 shows two layouts with the same number of squares. The difference is the number of corners and the length of the walls. These corners and walls increase the cost of construction. (hus.lt, n.d.)

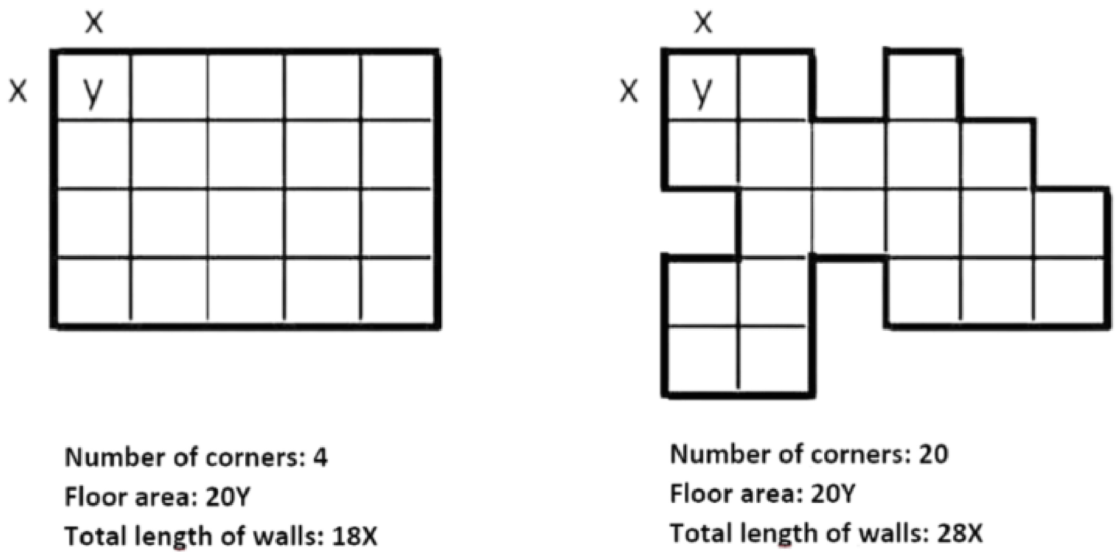

Figure 13: Comparison of two different layouts with the same size

The biggest advantage of timber constructions is the prefabrication of elements. This opportunity increases the pace and productivity because of consistent conditions in the manufacturing company. Next to this positive aspect it reduces the building time a lot which increases the cost efficiency.

The conclusion from the cost factors is that timber construction is highly competitive in comparison to traditional building materials and the use of timber constructions will be more important in the future, but as described in the section on economics we need to close the skill gaps and we need to refine the processes. The lack of experience with large wood structure and the missing skilled workers and process managers make this construction type more expensive (nordtreat.com, 2019). The challenge is for the industry to reduce the cost of timber construction. There is a need to find ways to make the materials cheaper, to optimize processes and increase the pace and to reduce the labour costs.

2.4. Architectural design solutions

The different types of wood with their different surfaces, colours, textures, grains and characteristics give the architect limitless possibilities for designing houses. Developments in the important topic of climate change are important for the population. There is a great deal of interest nowadays in more sustainable design. This point is positive for timber construction. The processing of timber is an advantage which improves building components and allows the design of building elements in different forms. The only limit for some design parts is the size for transportation (Bahadursingh, n.d.; Gupta, 2020).

One disadvantage of the use of wood in architectural designs is the cost. Another disadvantage of timber construction is the care of the wood against the effects of the weather. Some wood facades need more attention and need to be treated with colour or glaze after some years. This can be an additional maintenance cost. However, this depends on the type of wood and whether it is work intense or not because some wood facades such as Siberian Larch have a good weather resistance.

The variety of the different wood characteristics is a great foundation for different kinds of architectural design and there are limitless and timeless combinations that can be used with steal, glass, bricks concrete etc. (Bahadursingh, n.d.; Gupta, 2020).

Figure 15: EY Centre by fjmt, Sydney, Australia

Figure 14: Longfu Life Experience Center by LUO studio, Puyang, China

2.5 Volatile organic compounds (VOCs)

Some products in timber constructions such as paints or the building material itself for example emit volatile organic compounds (VOC) in gas form. The concentration of the VOCs indoors are much higher than outdoors. VOCs includes a variety of chemicals which have short- and long-term adverse health effects.

The effects on our health can include:

- Eye, nose and throat irritation
- Headaches, loss of coordination and nausea
- Damage to liver, kidney and central nervous system
- Risk for cancer (epa.gov, 2022)

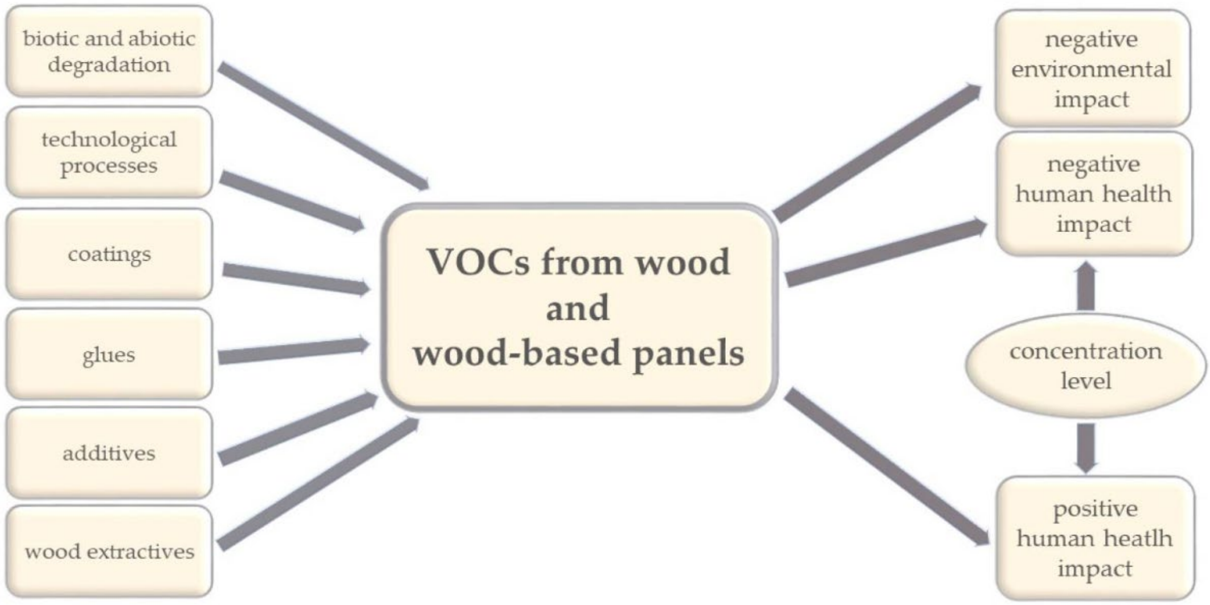

Figure 16: VOCs from wood and wood-based-panels; their sources and impacts

Wood is a natural material with many positive aspects for air quality und the well-being. On the other wood extractives include VOCs formed by terpenes, aldehydes, terpenoids, flavonoids, alcohols and ketones. The amount of VOCs is dependent on the type of wood, the lifecycles of the tree and if its sapwood or heartwood. The process of making timber is an important factor for the amount of VOCs.

For wood-based-materials, the type of wood, the manufacturing with the heating, pressure, and the connection material all have an important impact on the amount of VOCs. The thermal heating process is suitable method to reduce the VOC emission. The most VOC´s are escaped by 140 degrees and the terpenes are almost completely escaped. For wood-based-materials, even the pressure time by the manufacturing plays an important role to reduce the VOC emission. Next to the thermal heating process, an improved air exchange rate is an option for reducing the VOC-concentration (Adamova, Hradecky and Panek, 2020).

The VOC concentration is dependent on the building material. Some studies have shown that emissions decrease with time after finishing the construction site. The following graph present the average value of VOCs (TVOC) in different types of constructions in long-term assessment (Mayr, 2022).

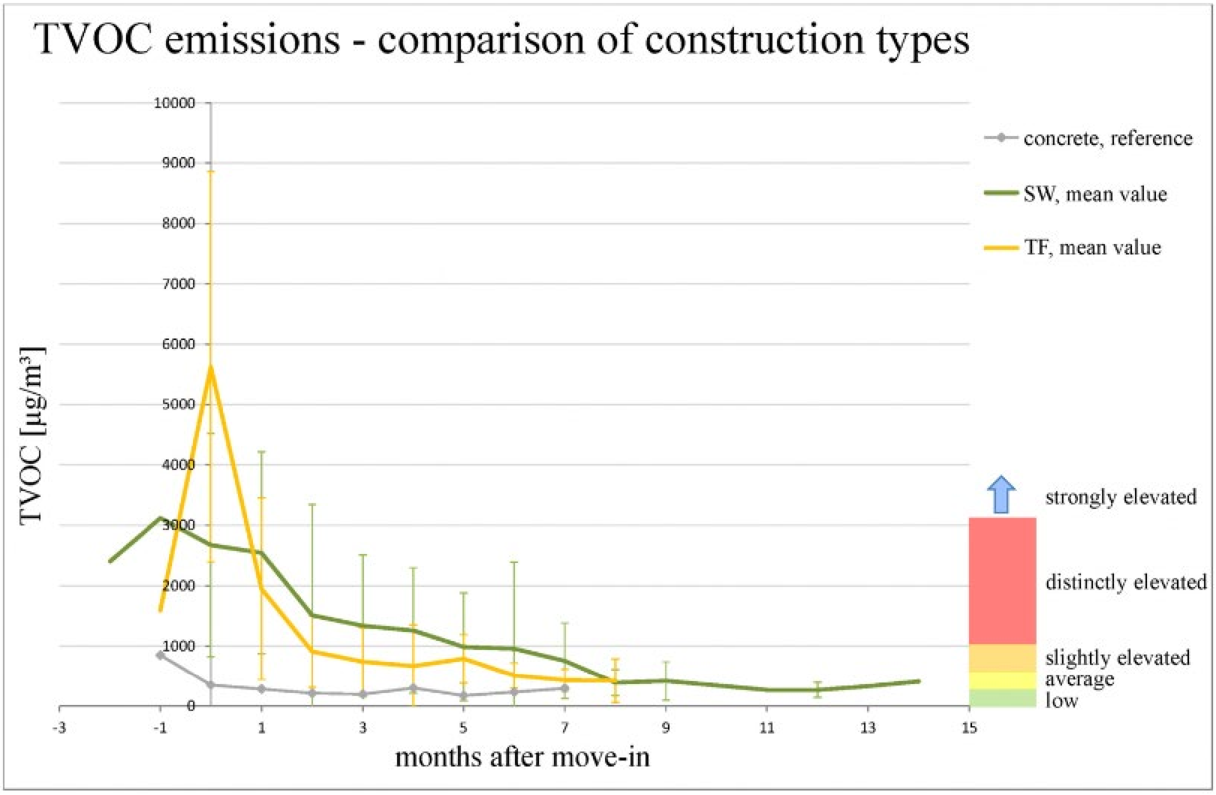

Figure 17: TVOC emission - comparison of construction types

SW – solid wood construction
TF – timber-frame construction (Mayr, 2022)

The overall VOC emissions in different wood structures and the impact on health and well-being need further research.

3 Requirements of circular economy in the design phase

The following study will focus on exploring model-based circularity for timber-based structures at the early stage of design.

3.1 Introduction

The building industry is one of the leading causes of greenhouse gas emissions and is largely responsible globally for the scarcity of natural resources such as white sand. Improving the circularity of building materials has great potential to reduce these two aspects. There are three ways to change the building industry and achieve a higher circularity.

- Ensuring longer lifetime of buildings and building materials to save emissions, materials and costs.
- Protecting the quality of building materials, decreases the emissions, the reparations and new building materials.
- Recycling only the unusable building material (Jockwer, 2020).

The following figure shows the lifecycle of building materials. The goal is to achieve a circular flow of the building materials.

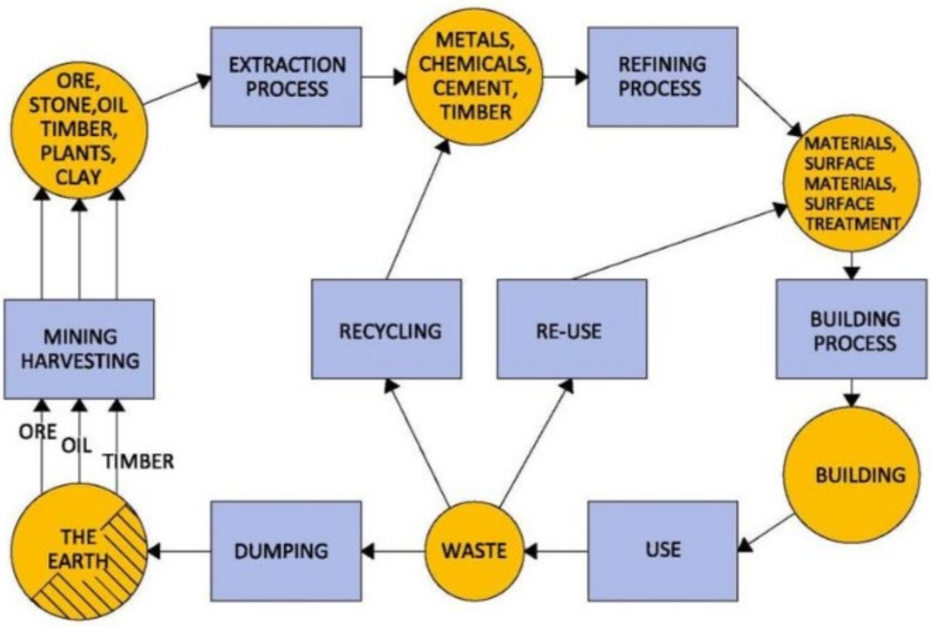

Figure 18: Conventional resource flow and the economy circularity in the inner circle (Hood, Priselac and van Gendt, 2015)

3.2 Design for adaption (DA)

3.2.1 Benefits of DA

Design for adaptation is a concept to improve the circularity of the building industry. The main aspect of this concept is to design construction techniques where it becomes possible to repair, replace or improve important components such as the floor, ceiling, walls and facades. With this concept, the goal of achieving a longer building service life can be achieved. This concept includes a design that can be adapted in the event of changes in use or if a component is damaged. The bullet list below outlines the main features of the concept:

- Changes in use may involve changing the supporting structure or requiring more or less space.
- Easy repair or replacement of the supporting structure after damage such as fire or water increases the service life.
- Energy consumption problems can be solved by simply replacing relevant parts. For example, a facade can be replaced or adapted.
- The building can be adapted to new user requirements.

This kind of building concept involves a higher lifetime because it can be modified for different situations and user requirements. One example is in family life after a certain time children grow up and move to another place. Then the house may be too large compared to requirements and may need modification. The requirements of the user may also change and need more or less space and DA makes it possible to modify the house (Jockwer, 2020). We need to divide DA into several categories as following:

- Versatile: Versatile means being able to change the layout of the rooms. In this way it is possible to make easy and cheap adjustments based on changing requirements of the occupants, new work patterns or the number of the occupants.
- Convertible: Convertible buildings are planned for changing functions due to social conversions regarding the market, social demands, ownership, or occupancy, for instance.
- Scalable: The main objective is the possibility to enlarge or reduce the building in a horizontal or vertical direction when more or less space is needed.
- Refitable: Buildings should be able to convert their performance by changing their service, skin or space. Reasons for necessary changes may arise from new laws, regulations, environmental conditions or technologies.

- Adjustable: This means that furniture and items can be easily adjusted due to changing requirements and technologies to improve the indoor environment and comfort, reducing the need for new equipment.
- Movable: This aspect can be important for structural building typologies under certain conditions, such as changing climatic conditions and population movement (Arvaniti, 2020).

Design for adaption can increase the lifetime of the building, which means saving building materials, increasing the cost efficiency, improved usage of space and can decrease the maintenance costs in the case of damage (Jockwer, 2020). In the case of damage to the building, for example, in the kitchen or in the bathroom, it is a benefit if the floor or the ceiling is built for easier repair or exchange of some parts. In this case it can save money, materials and time. Another case could be a fire incident and the used water for extinguishing the fire. Water has massive consequences for a timber-construction building. This form of damage can be as high as the damage from the fire. Here, easy adaption of the floor, ceiling and walls could be beneficial for repairing such damage as well (Jockwer, 2020).

Additionally, changes in weather conditions can be a further reason for DA. Climate change has a huge impact on the weather. With the concept of DA, it is possible to adapt the building due to climate change effects.

Another opportunity for DA is co-housing. This style of living has a positive impact on community spaces. In addition to the social impact, co-housing can also be more sustainable, as the living space is better used and living together means that there is no need to heat a second flat. It has the same effect on electricity consumption because, for example, the kitchen may also be shared. However, in a co-housing apartment privacy is very important for the inhabitants. All these aspects should be factored in at an early stage of the design phase. The building needs a concept that enables it to build a co-housing apartment without demolishing any part of the existing structure (moda.ca, n.d.).

All of these factors must be considered in the early stages of design. It is a lot of work to develop new construction for adaption and it needs a longer planning time than a traditional construction. However, the possibility of prefabrication and the ever-growing experience in DA are a good basis for using this concept more in the future.

3.2.2 Potential pitfalls

Economic pitfalls: Creating a more flexible building with the potential for different uses over its lifetime can be more expensive. The possibility of changing conditions or changing structure makes it more difficult to calculate the statistics for supporting elements. This leads to stronger supporting elements which need more materials and more money.

Environmental pitfalls: The same reason of the economic pitfalls can increase the usage of building materials in structures leading to environmental pitfalls.

Process pitfalls: The priorities for DA need to be set at an early stage of the planning. The risk for conflicts with other priorities can be high. For example, the budget may be more important for the customer and this may make it difficult to achieve DA. The level of communication needs to be higher in projects with DA because it is more demanding.

3.3 Design for deconstruction and reuse (DDR)

3.3.1 Benefits of DDR

The goal of design for deconstruction and reuse is similar to the DA concept and is to protect the building materials and create a closed-loop principal for better resource efficiency. The disassembled materials could create a market for reusable materials. The longer lifetime of the building materials can reduce the cost and reduce the embodied energy and $CO2$ emissions of the building industry (Arvaniti, 2020). Here the challenge is to develop simple connection solutions between the building components to enable relatively easy deconstruction. The connections must be made in such a way that they can be released without damaging the building material. Damaged material loses its value and is more difficult to reuse. The size of the used materials is also important for the construction. Taller materials can be reused for more construction purposes, but may be hard to deconstruct. A smaller component is lighter and easier to disassemble, but the reusability possibilities are lower.

Time is also an important factor and has an impact on the DDR. It takes much more time to deconstruct every component without causing any damage than to demolish the construction. Here fits the old saying "time is money" (Arvaniti, 2020; Kanters, 2018). Simpler connections between two components have benefits for both the deconstruction and reusability. Additionally, this way is easier for deconstruction as it works in the other way as well and provides for a work facilitation in the building phase. This involves a shorter building phase and a higher cost efficiency (Kanters, 2018). The planning is similar to DA and is more comprehensive than in traditional constructions because of the connections between components, which need to be strong enough but need to be removable as well. There is also a skills gap which needs to be filled and needs to be developed in the building industry to reduce the planning time. Every connection in constructions like DA

and DDR need constant documentation. This part is very important to assess the quality of the materials during the deconstruction because without the information about the connections it is difficult to deconstruct.
Figure 17 shows a method used by Bregroup measuring the deconstruction potential of build residential buildings. This measurement includes considerations of:

- Components and materials
- Connection types
- the accessibility of connections and components
- the deconstruction processes
- the level of information (bregroup.com, n.d.).

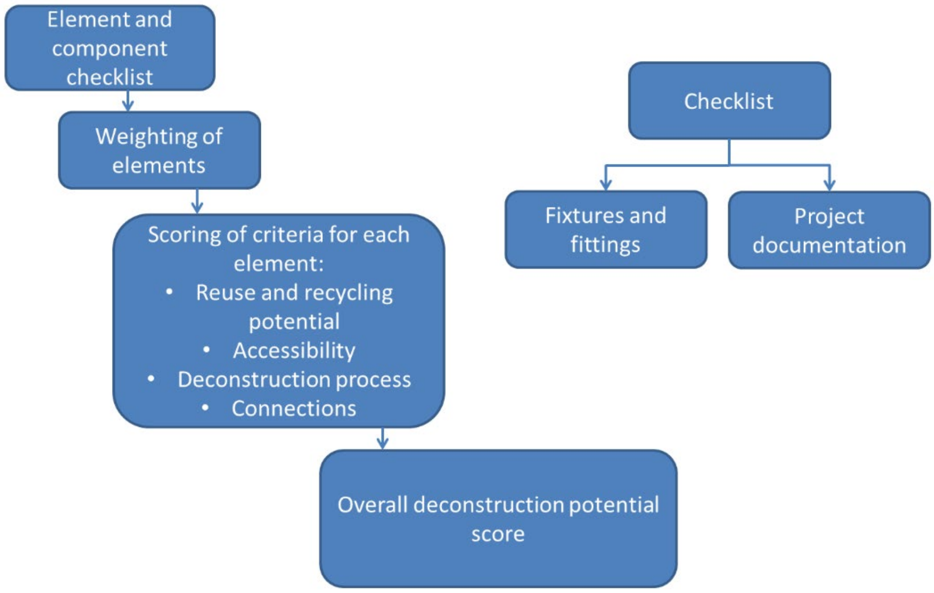

Figure 19: Methodology measuring the deconstruction potential

Figure 17 was developed for the topic of DDR but it can also be applied to DA and modular timber construction.

3.3.2 Potential pitfalls

Economic pitfalls: The planning of DDR is more intensive and increases the costs. Especially when the project team has less experience with this concept. The development of the connection tools needs a close cooperation with the structural engineer this increases the cost of the connection details.

Communication pitfalls: The communication and documentation are the most important things in projects like this from the beginning of planning to the finished construction site to the end of life-time of the building. This expenditure increases the costs.

Market pitfalls: The market for used building materials needs to be better. It is difficult to organize and find the correct used materials for a new project. In addition to this expenditure, come higher costs and time intensive transport needed for the delivery of the materials to the construction site. This increases the overall cost of the construction.

Design pitfalls: Design for deconstruction and reuse limits the diversity of architecture and the diversity of materials (Melton, 2020).

3.4 Modular Timber Constructions

Modular timber constructions are prefabricated modules which you can set up everywhere and combine with other modules. This includes a shorter building time with a higher variety of building designs. We need to differentiate two types of modular constructions. The first type is the relocatable modular construction. For example, these could be modules which are used as an office building from construction site to constructions site. The other type of modular buildings are permanent modular constructions. In the lifetime of the building, it is possible to extend the building with new modules or downsize it. The modules from downsizing the building can be sold or used in another place. Damage can be fixed by changing the modules. This kind of variability can increase the lifetime of the building because it can be easily adapted to current situations.

The modules can be used not only in connection with other modules, but also to connect timber modules with existing buildings regardless of the building type. For example, a traditional brick construction can be extended with a modular timber construction. A light weight timber construction makes it possible to expand existing building with a new floor of a modular timber construction on the rooftop. In this way we can increase the lifetime of the building and the density of population (Horx-Strathern, Varga and Guntschnig, n.d.).

Especially for public buildings such as schools or hospitals it is a good option to use a modular timber construction. The building can adapt to various usage situations and existing buildings can be expanded. It could be 30-50% faster to build a building with timber modules than using traditional methods and it could be a fast solution for different space problems in buildings such as schools, hospitals or for housing immigrants (sh-module.de, n.d.; Wilson, 2019). One company from Germany has specialized in modular timber constructions since 2004 and has a huge demand for school extensions. A prefabrication rate of 70-80% increases the pace, quality of processes, quality of the building materials and the working conditions, which includes a safer working place. All these positive aspects are the result of working under weather protection with the possibility of more working equipment, especially the bridge crane and, for example, a dust extraction system in combination with a saw. (sh-module.de, n.d.; Wilson, 2019). Modern technologies and tools are helpful in reducing waste and safe materials. It is possible to reduce waste by up to 50%. For example, why should we produce a CLT wall and cut the windows out of the wall? We can leave voids in places of windows while producing the wall. Its better in terms of material consumption (nibs.org, 2018). When the time comes to deconstruct the building or decrease the space of the building, it is possible to reuse every volumetric module. Approximately 70% of the value from every module can be reused (sh-module.de, n.d.).

There are some challenges for the modular construction industry which need to be noticed.

- Mass production: Same size of modules is better for the planning, productions of buildings like hotels and to connect different modules. As soon as there are different sizes of modules it is more demanding.
- Planning: Changing decisions during the manufacturing process can have a major impact on the statics, the modules on the lower floors, the connection between the modules and, depending on the size of the modules, a fixed arrangement since the planning phase. As a result, in the early design phase, the building must be almost completely thought through, and a change is usually not possible.
- Logistics: The transportation of modules can be complicated. On a construction site they do not need so much space because the modules are prefabricated. However, to transport the modules requires good road conditions, with a transportation permit and escort vehicle. Additionally, enough space is needed on the construction site for the trucks and a movable crane which can carry more than 20 tonnes (nibs.org, 2018; realprojectives.com, 2019).

3.5 Documentation with building information modelling (BIM)

Every method for a circular economy needs good documentation. Without the needed information it is difficult to adapt or deconstruct components and save the quality of the building material. The information should include the types of connection tools and the location of the connections between the components. For this, documentation of the actual usage and development of Building Information Modelling is required (bregroup.com, n.d.).

BIM has many benefits and is one of the most important tools for the future of the building industry. This article provides only a short introduction to the benefits. The use of BIM increases the productivity, improves the coordination, gives complete snapshots of the project, has better documentation and reduces rework and costs (outsource2india.com, n.d.).

3.6 Conclusion

The aim of these three building concepts Design for Adaption (DA), Design for Deconstruction and Reuse (DDR) and Modular Timber Constructions is to save building materials, energy and carbon. This is to be achieved with a longer lifespan of the construction and with the preservation of the quality of the building material after deconstruction. However, for better competitiveness it constantly needs further development. The connection details and the planning of the construction need more time in the early stage of design phase. However, a well planned construction includes a better prefabrication with a high quality of components, which has benefits for the final construction on the construction site. In the design phase they can develop the building and the connection tools to increase the building lifetime or preserve the quality of the building materials.

4 Low-rise vs. high-rise building

This section of the study includes comparative analysis of GHG mitigation of wooden structures. The study explores the potential of wooden structure based on height, therefore related construction techniques, impact on environment etc.

4.1 Which is the most sustainable design choice?

In this section we discuss which construction type is the most sustainable choice. The height of a building has a huge impact on the environment. Independent of the used material type, the foundations and all supporting elements need to be bigger and need more and stronger material than for low-rise constructions. O**ne of the** main aim**s** of building skyscrapers fro**m the design perspective** is to raise the density of the population **in a given area**. However, higher construction has some cons, too. Around the building we need more space than by a low-rise construction and the floors loose space in connection with the height (Adetunji, 2021; Poon, 2021; Sanders, 2021). These two points reduce the density. In addition to the higher material consumption, there is a higher consumption of energy, too. The upper floors need more energy for cooling and heating the apartments and elevators need more energy. Finally, it is more difficult to care for and clean the building compared to lower buildings and the building costs are approximately20-25 per cent more expensive. Furthermore, after the lifetime of the building it is more difficult to demolish or deconstruct a high-rise building (timesproperty.com, 2022). One computer model-based study compared the carbon emission of 4 different type of cities. In comparison were populations of 20,000 or 50,000 people and if the construction type of the buildings was high-rise or low-rise (see Figure 16). The study shows that low-rise cities are more environmentally friendly than high-rise cities like New York City. The life-cycle carbon emissions from a high density, low-rise city increased by 132 per cent for a high-density, high-rise city. The difference between a high-rise, low-density city and a low-rise, low-density city was a little bit higher. Here the increase of the life-cycle carbon emissions were by 142 per cent (Adetunji, 2021; Poon, 2021; Sanders, 2021).

The result of this study is not that low-rise buildings are bad for the environment. The study means that cities with low-rise buildings and a high-density like Paris are more environmentally friendly (Poon, 2021).

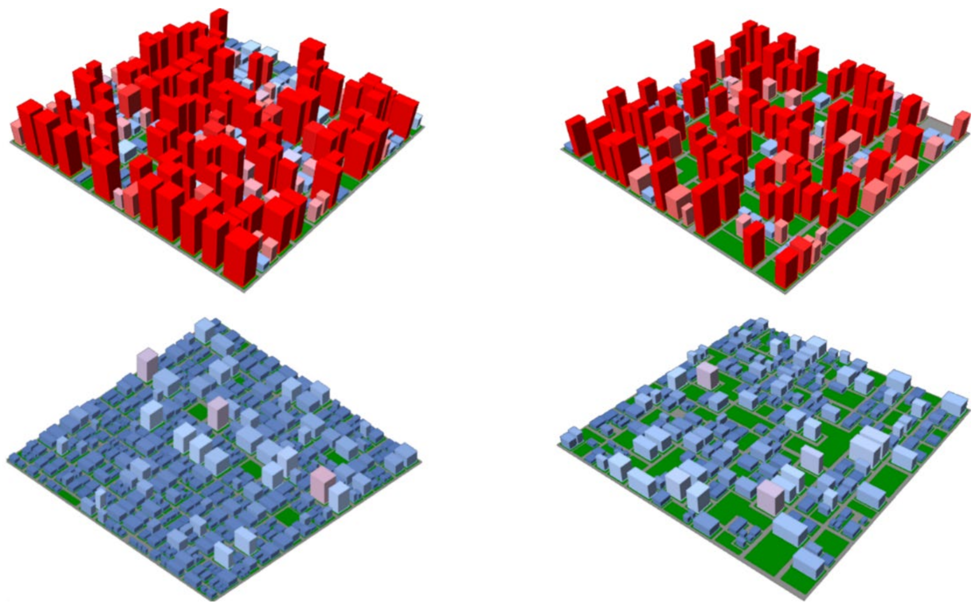

Figure 20: Four scenarios analysed in a study of the most sustainable city design

4.2 Wooden buildings

The study “Which is the most sustainable design choice?” before treated low-rise and high-rise buildings with traditional construction materials. This means concrete, steel and bricks. When we compare this study with the same buildings as wooden construction, at time we get the same result. Dependent on the height, the foundations and the supporting elements are bigger and stronger. However, because of the light weight of the timber, the result is that we can save material in the foundations and the supporting elements.

The result of this comparison is that the total carbon emissions are lower than for traditional constructions, but the difference between low-rise and high-rise building is lower in comparison to concrete, steel and bricks. The reason for these savings of carbon emissions is the lower consumption of concrete in the foundations.

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