MINIMIZING CARBON FOOTPRINT OF A HIGHRISE STRUCTURE LAYOUT WITH PARAMETRIC DESIGN

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ABSTRACT

This paper concerns finding out to what extent it is possible to reduce carbon footprint of a highrise structure with parametric design methods. First, there will be investigated which highrise structure strategy has the best potential to effectively reduce its carbon footprint. Then, strategies to reduce carbon footprint of a structure will be made explicit. Thereafter, an extensive description on how to generate a structural layout with the least carbon footprint possible with parametric design will be made explicit. Because this paper is focused on creating a strategy in order to reduce the carbon footprint of a highrise structure, the research will be characterized as a quantitative approach. Next to literature research being done primarily within the first two sub-questions, data analysis and experimentation will be one of the leading methods used to find the answer for the research question. Choosing a highrise structure with lots of elements that does not require to be lateral load or moment resisting has the best potential to effectively reduce carbon footprint of a structure, which is in this case a shear wall (core) + hinged frame structure. After collecting the data for the structural and carbon footprint properties of construction materials and setting op the conditions for the experiment, a parametric optimization has proved that a structural layout containing timber CLT floors and timber Glulam columns scattered over a grid with divided spans has potential to be approximately 46% more sustainable than a similar traditional concrete layout. Reducing carbon footprint of a highrise structure with parametric design can therefore be done to a great extent.

KEYWORDS: *Sustainability, Highrise, Structure, Computational Design, Parametric Design, Carbon Footprint, Embodied Carbon*

I. INTRODUCTION

1.1. Background: Population Growth, Urbanization and Climate Change

The world is changing and so are our cities. One of the major changes we are facing is population growth. A growing population means we need more spaces in cities to accommodate residences, workspaces, and other facilities. When looking at the Netherlands especially it is quite an interesting phenomenon. According to the central office for statistics of the Netherlands (CBS) the population is estimated to grow due to immigration and increasing lifespan at a higher rate rather than birthrate alone. (CBS, 2020a). This is also the main reason why the Netherlands is on the verge of a huge challenge. According to the report from ABF research to the Ministry of Internal Affairs of the Netherlands, it is estimated that the Netherlands needs at least 1.044.500 residences by 2030 alone due to population growth (Groenemeijer, 2021). In conclusion, due to population growth we need more buildings.

Existing cities as we know have been developing up to the point that it becomes highly concentrated with buildings. This is the effect of rapid urbanization. Urbanization is according to the website of the Environmental Protection Agency of the US the concentration of human population into discrete areas. This leads to land being transformed for residential, commercial, industrial and transportation purposes (US EPA, 2022). This occurrence has and is happening to cities all over the world, so also within cities in the Netherlands. Due to urbanization cities all over the world have been concentrated to a point where there are hardly any opportunities to densify in the city. This has inevitably consequences for the Netherlands since cities in the Netherlands are in high demand of housing due to the housing crisis, and in order to reach one million residences by 2030 we need to rethink ways to densify within existing cities to provide for this demand.

There is also another factor that is changing our world as we know, and it has everything to do with climate change. We are inevitably going to dystopian realities if we as a society do not change the way we treat our planet. According to the report of the International Energy Agency (2019), the buildings and construction sector accounts for 36% of final energy use and 39% of energy and process-related CO_2 emissions in 2018. This makes this sector one of the major contributors to climate change. We need to make sure existing and new-build buildings do not harm the planet and therefore we need to rethink the way how we design our buildings to achieve a sustainable built environment.

1.2. The potential of Highrise

You can think of strategies such as renovation, transformation, repurpose or new-build projects. Within the densest part of the city, new build-projects are difficult to realize and therefore in this context probably the hardest challenge. The concept of developing new-build highrise buildings might be a proper solution for accommodating the demand for densification within urbanized cities in the Netherlands and possibly all around the world. With this building approach, densification within a relatively small footprint becomes possible. Also, according to various sources, implementing the concept of highrise is a great choice from a viewpoint of land prices, demographic change, urban regeneration, infrastructure, transportation, attracting investors, multifunctional use, and land preservation (Short, 2013; Binder, 2015; Kim and Lee, 2018; Abbood et al., 2021). Highrise is especially the best fit within city centers since that is mostly the densest part of the city. As Al-Kodmany has argued in his article:

"To accommodate the influx of urban population while reducing urban sprawl, we must engage the vertical dimension of cities" (Al-Kodmany, 2022, p. 1).

1.3. Problem Statement

The problem with highrise buildings in particular is that it is not a sustainable approach. Highrise buildings emit significantly more carbon than medium or low-sized buildings according to Logan (2021). This accounts for the construction and use of a highrise building. A major contributor to this fact is that highrise buildings require a lot more extensive materials than mid or low-sized buildings. The fact that highrise buildings are typically not sustainable is a problem because making our built environment sustainable is one of the challenges we need to realize in order to save our planet. One of the major contributors of its high carbon footprint is the highrise structure. As stated earlier, highrise structures require more extensive materials than mid or low-sized buildings. With this fact in mind, we need to develop strategies in order to reduce the carbon footprint of a highrise structure.

1.4. Research Questions and structure

This paper is focused on creating a strategy in order to reduce the carbon footprint of a highrise structure. The goal of this research is to test if a simplified highrise structure layout can be significantly more sustainable compared to a traditional highrise structure layout. Another goal of this research is to see which materials result to an optimized carbon footprint layout. In order to achieve this goal, we need a tool that is able to integrate structure, materials and carbon footprint in such a way that they interact with each other. A proper tool for this approach is parametric design. Parametric design gives the user the ability to achieve control and integrity on all domains. When this control and interactability has been achieved, it is only a matter of changing the parameters until you get an optimized result. Therefore, the research question is: *To what extent is it possible to reduce carbon footprint of a highrise structure with parametric design methods?*

This is developed further within these subquestions: *Which highrise structure strategy has the best potential to effectively reduce its carbon footprint? How to reduce carbon footprint of a* *structure? How do you generate a structural layout with the least carbon footprint possible with parametric design?*

Within the first sub-question, I will be making explicit how a highrise structure works, what structural components, materials and layouts are mostly present withing highrise structures and what specific structural layout will be used for the parametric model through.

Within the second sub-question, I will be making explicit how carbon footprint is measured, how you can reduce it and comparing the benefits and drawbacks of structural materials in terms of structural and carbon footprint properties.

Within the last sub-question, I will explain how the parametric grasshopper script works. I will show that every structural component, such as columns, floor slabs, and beams can be interchangeable in different types of materials while making sure that the profile of that material can support the theoretical load. This will automatically change the weight of the structural component.

Once connecting this information to calculate the carbon footprint I will run an optimization to find out which structural configuration has the least amount of carbon footprint. See Figure 1 for reference.

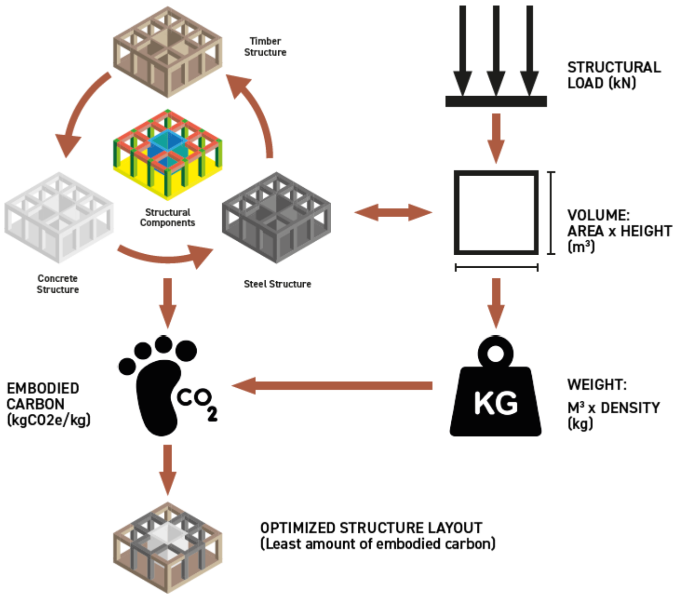


Figure 1. Parametric Strategy Diagram (By author, 2022)

1.5. Methodology and Hypothesis

Within this paper, 3 sub-questions will be explored to answer the research question. Because this paper is focused on creating a strategy in order to reduce the carbon footprint of a highrise structure, the research should be focused on a quantitative approach. Next to literature research being done primarily within the first two sub-questions, data analysis and experimentation will be one of the leading methods used to find the answer for the research question. Data analysis is primarily done by collecting data, setting them as parameters within the parametric design model, and interpreting the results after running the optimization. Experimenting is characterized by developing the conditions to test your hypothesis in order to find the answer for the research question, which is in this case developing the parametric design model.

Within this paper, it is expected that the ideal structural layout of a highrise building with the least amount of carbon footprint will be a mix of materials where harmony exists between carbon footprint and structural performance properties. It is expected that a configuration with timber, which is commonly known as a low carbon footprint material, primarily affects the total carbon footprint. Still, certain construction elements are expected to require high structural performance which makes timber not a viable option but rather a material with a high carbon footprint and structural performance such as steel or concrete.

II. HIGHRISE STRUCTURE STRATEGIES

2.1. The principles of a highrise structure

A Highrise building must meet the same criteria as any other building. The structure needs to be strong, stiff, and stable. In other words, the building needs to be strong enough to prevent tearing or buckling, it needs to be stiff enough to prevent deformation and stable enough to remain standing (Nijsse, 2019). But why does a highrise structure need extensive structural strategies? In simple terms, a highrise building is just a large cantilever rotated 90 degrees. When a cantilever gets taller, it is more sensitive to lateral forces such as wind, which increases the risk of structural failures within each criterion, see Figure 2 for reference. As Ali and Moon asserted in their paper, when a structural system is scaled up, the load effect will eventually be greater than the strength of the structure, thus making it necessary to apply a different strategy for increasing heights (2018). In conclusion, The taller the building, the higher the effect of and demand for lateral loads and vertical loads such as wind and gravity.

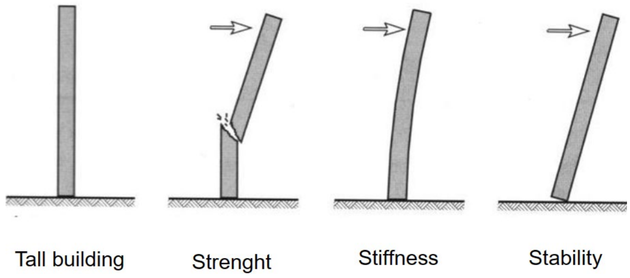


Figure 2. Structural Criteria for a Tall Building (Crielaard, 2022)

When looking at strategies for highrise structures you can identify two types. Interior structures and exterior structures. These systems are classified by the location of the lateral load resisting components (Ali & Moon, 2018). If these elements are present within the building it is considered to be an interior structure and if these elements are present on the facade or even outside of the building it is considered to be an exterior structure. The type of interior or exterior structure and their feasible height-limit is chronologically demonstrated within Figures 3 and 4.

2.2. Choosing a Highrise Strategy

Interior and Exterior structures are all characterized by concrete systems, steel systems or a combination of both. These materials are commonly known as high carbon footprint materials. When it comes to withstanding lateral loads at a scale of highrise structures, only materials with the best structural properties must be used. Therefore, it is difficult to use low carbon footprint materials such as timber as a lateral load resisting element with our current knowledge of building highrise structures. Every other structural element that does not require to be lateral load resisting can be made out of timber. Therefore, a highrise structure with lots of elements that does not require to be lateral load or moment resisting has the best potential to effectively reduce its carbon footprint. Those structural typologies need to contain hinged elements. The only structural typologies that contain these elements are braced hinged frame and concrete shear wall + hinged frame. Both these typologies identify as an interior structure. The braced hinged frame is not the best option since it is limited to only 20 storeys. That is why a concrete shear wall + hinged frame structure with a limit of 40 storeys (+/-150m) is the best option to investigate within this experiment, see Figure 3 for reference.

Within this structural typology, the stability of the building is effectively handled by a concrete shear wall tube, the core, which contains shafts, elevators, and other installations. Since its stability is handled by the core, there is no need for making rigid connections at the locations where columns, floors, and beams meet. The fact that all these connections can be hinged is what makes this approach relatively simple and cheaper than other approaches. That is why this strategy is one of the most commonly used strategies around the world for buildings taller than 30m and smaller than 200m (Nijsse, 2012) (Ham et al., 2022). Finding a layout with the least amount of carbon footprint with this strategy is possibly the most effective and relevant option.

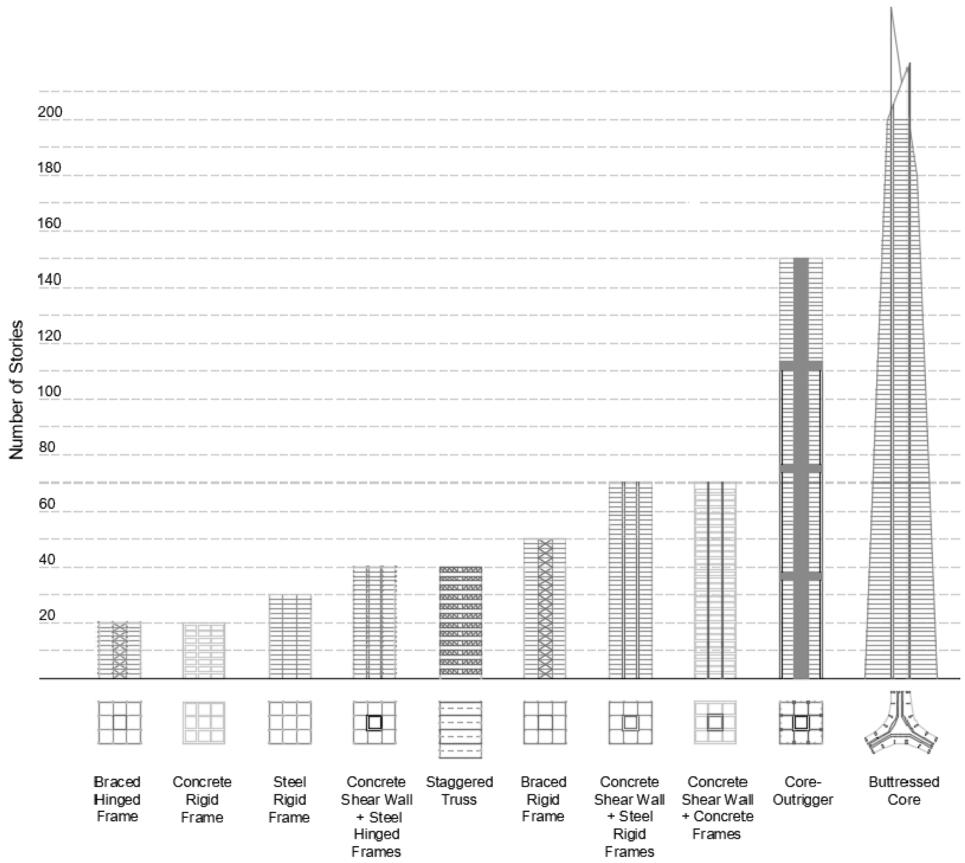


Figure 3. Interior Structures (Ali & Moon, 2018)

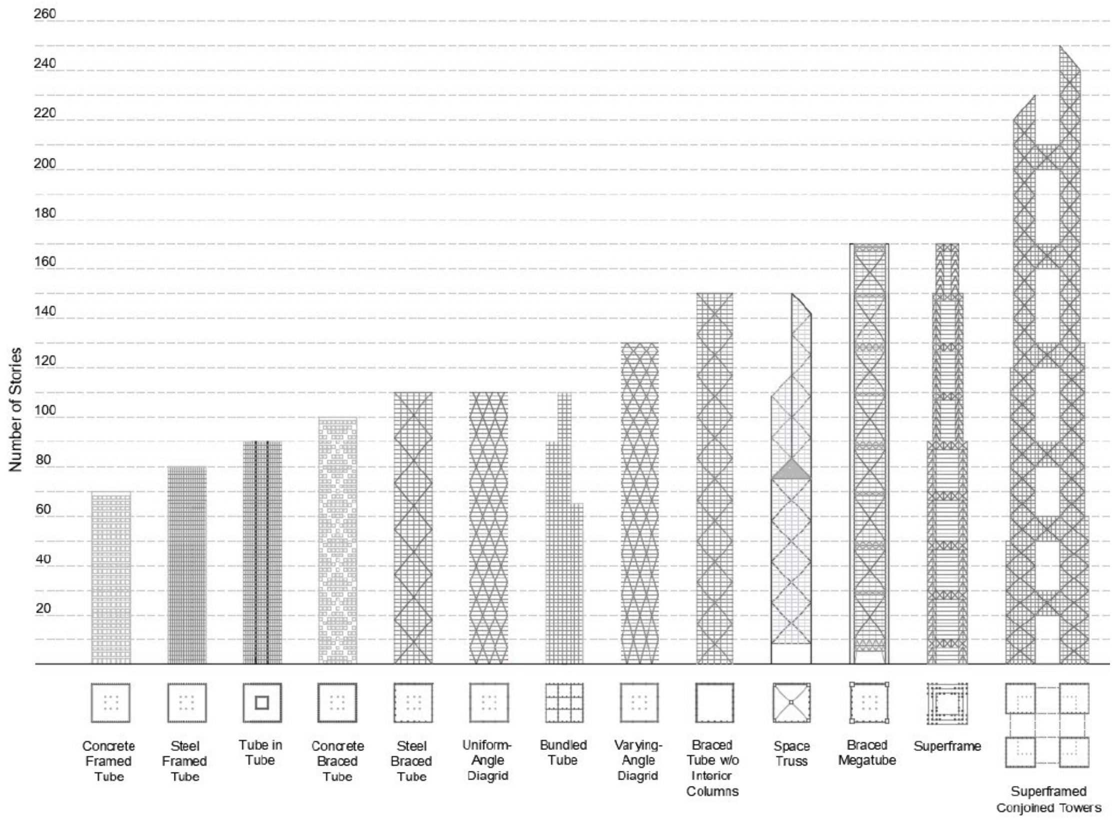


Figure 4. Exterior Structures (Ali & Moon, 2018)

III. CARBON FOOTPRINT STRATEGIES

2.1. Quantifying carbon footprint

The carbon footprint of a certain material can be quantified in two ways: embodied carbon, or embodied energy. Embodied carbon is according to the website of SE2050 the sum of greenhouse gasses emitted during its lifecycle. This includes raw-material extraction, transport, manufacturing, construction, maintenance renovation and sometimes even end of life cycle. Embodied energy is quantified by the sum of energy used during its lifecycle (SE2050, 2022). Embodied carbon is measured in the amount of kilograms CO2 and other greenhouse gasses the material emits during its lifecycle per kilograms of that specific material. (KgCO2e/kg). Embodied energy is measured in the amount of energy used during the lifecycle of a material per kilograms of that specific material (MJ/kg). In relative terms these quantifications of carbon footprint are the same, except for the fact that embodied energy is quantified in energy regardless of its source. This means that if a material is partially produced with green energy, it is still included in the total embodied energy of that specific material as stated on the website of SE2050 (2020). That is why embodied carbon is probably the most relevant option to quantify carbon footprint because the amount of CO2 emitted from a material that has been created renewably is reflected within its value.

2.2. Strategies in order to reduce embodied carbon of a structure

The total embodied carbon of a structure can be reduced in many ways. Think about reducing material quantities, using alternate structural systems and utilizing materials with a smaller carbon footprint. This will also be the main approach within this experiment. You can also try to reduce the embodied carbon of a material itself by finding solutions within the life-cycle of that specific material, but this has been deliberately left out since that is not relevant for the approach of this experiment.

2.3. Embodied carbon of material parameters

In order to measure the total amount of embodied carbon of a structural layout, it is important to make a list of materials that will be used in the parametric model, see Table 1 for reference. The values of Embodied carbon are connected to the material toggle parameters within the experiment.

Also included are multiple concrete types differentiated by its strength class and general use. A higher strength class means higher structural performance. The higher the strength class, the higher its embodied carbon value. There are more strength classes available, but the highest strength class present within the ICE database is limited to C50/60 (Jones & Hammond, 2019). That is why the strength class within the calculations of the parametric model is also limited to C50/60 in order to retrieve a reliable embodied carbon value. Surprisingly, Concrete has the lowest embodied carbon value. But even numbers can be deceiving because concrete has a high density, which dramatically affects its carbon footprint up to a point that it potentially becomes high when calculating the total carbon emission when using it in high volumes as a structural material.

Steel has one of the highest embodied carbon values because the raw metals are processed in extremely high temperatures in order to get the product you want. It is also high in density, but since the surface area of steel construction elements are very small it might potentially have a lower embodied carbon value than concrete.

Timber is overall average in embodied carbon, but with its low density has the highest potential to effectively reduce the carbon footprint of a highrise structure. On top of that, Timber also has the potential to store carbon. This is expressed as a negative value in the database. Carbon storage is in this calculation not intended to measure how sustainable a structure layout is compared to others because it is assumed that when the timber structural element is at the end of its lifecycle, it releases its stored carbon value back to the atmosphere. In that way, all the materials present in table 1 will be treated fairly without the bias from the carbon storage. However, it is still calculated for the purpose of comparing timber elements with each other.

In the experiment 3 types of floors will be investigated. A concrete hollow-core slab and two types of timber floorsystems. One timber floortype is supposed to be a lightweight system which is independent from the main structure, and the other timber floortype is a heavier system and supposed to interact with the main structure. The heavy timber floortype is embedded in the main structure, thus making it a suitable candidate for transferring lateral loads to the columns as a replacement for structural beams. For the lightweight timber floortype, a LVL Kerto Ripa floorsystem will be used, and for the heavy timber floor type a CLT floor system will be used.

Every floor system used in this experiment should also comply with performance requirements in order to compare them equally. This not only includes structural performance, but also fire safety and acoustic performance. These requirements are protected by law in the Netherlands by a legally binding document called Bouwbesluit which is based on the construction industry regulations of the European Union (Bouwbesluit, 2012b). Within the Bouwbesluit, the regulations for acoustics state that the Sound reduction index must be higher than 52dB and the Weighted Normalized Impact Sound Pressure level should not be higher than 54dB (Bouwbesluit, 2012a). According to the concrete hollow-core slab supplier dycore, all the variants are within limits of acoustic performance (Dycore, 2021). This makes sense because concrete slabs already contain a lot of mass which enhances sound insulation performances. For timber floor systems it is a different story. Because they are lightweight, they do need more added mass and impact sound insulation to meet the requirements. That is why both Timber floor systems contain impact sound insulation with wood fibre insulation and extra added mass with Gravel. These elements are also more sustainable than other materials with the same purpose due to their low embodied carbon values. For fire safety requirements, there should be atleast 60 minutes of Fire safety (Van Herpen, 2015). Concrete hollow-core slabs start at 90min Fireproof and has potential to be 120min fireproof (Dycore, 2021). Kerto Ripa floors are just within the boundary of 60 minutes and CLT floors are 60min fireproof until it reaches a thickness of 120 mm, and above which makes it 90min fireproof (Metsä Wood, 2017) (Stora Enso, 2017). All the elements required for fire safety and sound insulation are included within the floor detailing for each system in the experiment. Embodied carbon values and mass of these elements are also considered during the calculation process.

In conclusion, with all the different materials and their properties considered, it is too early to state which material(s) has the best potential to reduce the embodied carbon of the highrise structure layout. That is why it is necessary to draw conclusions when running the experiment.

Table 1. Embodied carbon of materials used in the parametric model (Jones & Hammond, 2019) (Arends, 2014) (Stora Enso, 2017) (By Author, 2022)

Element type	**Material type**	**Embodied Carbon (kgCO2e/kg)**	**Density (kg/m^3)/ (kg/m^2)**	**Parameter identification**
Timber	GLT	0,512	410 kg/m^3	Timber Columns, Timber Beams
Steel	Section	1,55	7800 kg/m^3	Steel Columns, Steel Beams
	Rebar	1,99	100 kg/m^3 Part of reinforced Concrete (2500 kg/m^3)	Concrete Columns
Concrete	C 30/37	0,138	2400 kg/m^3 Part of reinforced Concrete (2500 kg/m^3)	Concrete Columns
	C40/50	0,149	2400 kg/m^3 Part of reinforced Concrete (2500 kg/m^3)	Concrete Columns
	C50/60	0,159	2400 kg/m^3 Part of reinforced Concrete (2500 kg/m^3)	Concrete Columns
	Precast reinforced concrete	0,249	2500 kg/m^3	Concrete Beams
Kerto-Ripa Floorsystem	Plywood	0,681	500 kg/m^2	Independent Timber Floor
	Timber Fibre Board	0,715	270kg/m^3	Independent Timber Floor
	Mineral Wool	1,28	4,5 kg/m^2	Independent Timber Floor
	Plasterboard	0,39	57,5 kg/m^2	Independent Timber Floor
	Gravel/ Grit	0,007	48 kg/m^2	Independent Timber Floor
CLT Floorsystem	CLT	0,437	500 kg/m^2	Embedded Timber Floor
	Timber Fibre Board	0,715	270kg/m^3	Embedded Timber Floor
	Plasterboard	0,39	57,5 kg/m^2	Embedded Timber Floor
	Gravel/ Grit	0,007	48 kg/m^2	Embedded Timber Floor
Concrete Hollow-core slab	200mm	0,186	430 kg/m^2	Cocrete Floor

IV. Parametric Design Model Description

4.1. The parametric grasshopper script

In order to conduct the experiment, a parametric model has been made in Rhino Grasshopper which reflects the logic of trying to find out a structural layout with the least amount of carbon footprint. The grasshopper script itself is too complex and too large to display in this paper. Therefore, the script can be simplified as displayed in Figure 5 and 6. The script consists of 3 major components: generating the structure layout, dimensioning structure elements and the embodied carbon calculation. This model also has two locations where parameters can be changed to influence the outcome. The condition parameters define the structural dimensions, boundaries and configuration of the structure layout itself and the material toggle defines the material used for a specific structural component. For this experiment, data has been collected containing material specific properties needed for calculating the structural dimensions and carbon emissions.

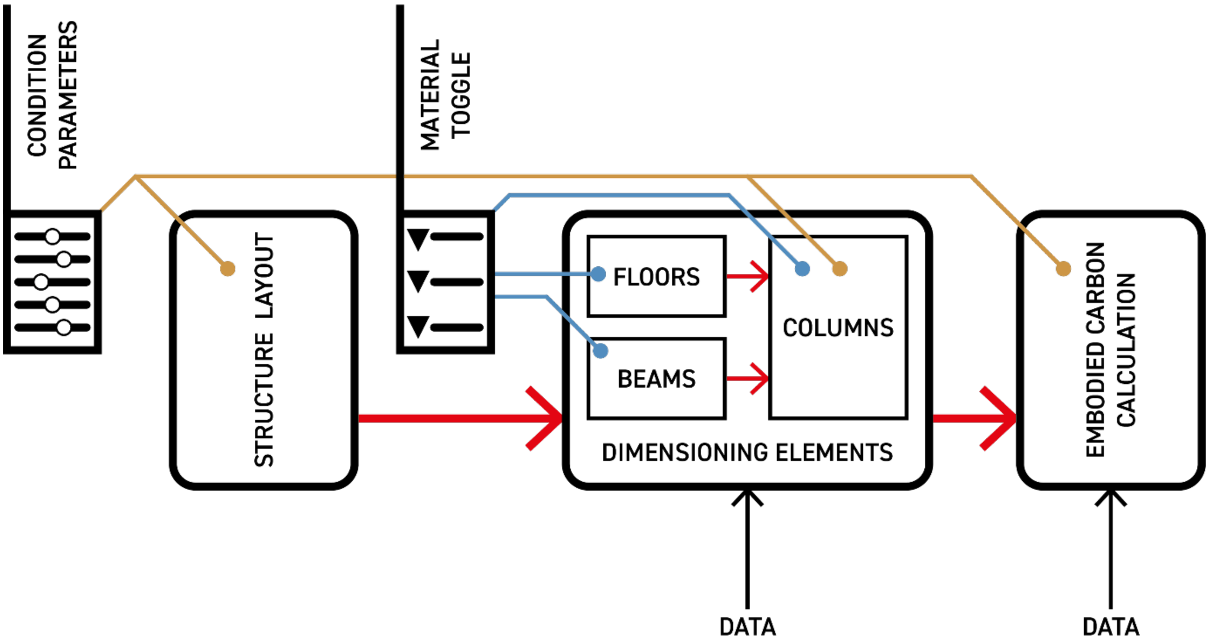


Figure 5. Basic principle of the grasshopper script (By author, 2023)

4.2. Generating the structure layout

The construction strategy used in this model is the core + hinged frame layout which has been explicitly substantiated in the second chapter of this paper. This layout, which represents the ground floor of a 40-storey building, consists of beams, columns, a floor slab, and the core itself. In order to find the answer to the research question, it is necessary to develop the right conditions where you can base your experiment on. The condition parameters control the amount of stories, the story height, the core dimensions, the building dimensions, and the amount of partitions and divisions of beams and columns, as seen in figure 6. These parameters are predefined for the entire experiment and based on the following logic. The building and core footprint has a square layout to encourage simplicity. The core itself is 16 x 16m. This has been chosen from a rule of thumb for the width of the core. Rob Nijsse has stated that the core must be at least $1/10^{th}$ of the height of the structure (Nijsse, 2012). Since this model needs to test the limits of the number of stories possible for this structure strategy, it is limited at 40 stories. That makes the total height of the building 40 x 3,6m = 144m. The core needs to be a minimum of 14,4m. The core in the model is 16m in order to follow a harmonious grid spacing. The ratio for core and utilized floor will be 1:2:1. This means that the total footprint of the building will be 4 times bigger than the core footprint, which makes it 32x32m. The length of the beams that span the core and columns are therefore 8m. The number of partitions is set to two in order to have a layout where all the beams are the same size for simplicity. The amount of divisions between the beams is for this phase of the experiment not activated. After conducting this experiment, a second experiment will be done to compare the optimized layout with an 8m grid to the same structural layout with a 4m grid by setting the amount of divisions parameter to 2 and the amount of partitions parameter to 4. This is expected to give more insight to the effect on the carbon footprint and mass of the structural layout when the span is halved while also the amount of beams and columns increases.

The parametric tools and components controlled by these parameters create the wireframe layout of the beams, columns, floor slab and the core, which forms the base of the structural layout. These elements are in this stage just a representation of that structural element and its dimensions. The beams and columns are just lines/ curves, and the core and slab are represented with surfaces. These elements are interconnected with parametric tools in such a way that they efficiently interact with one another.

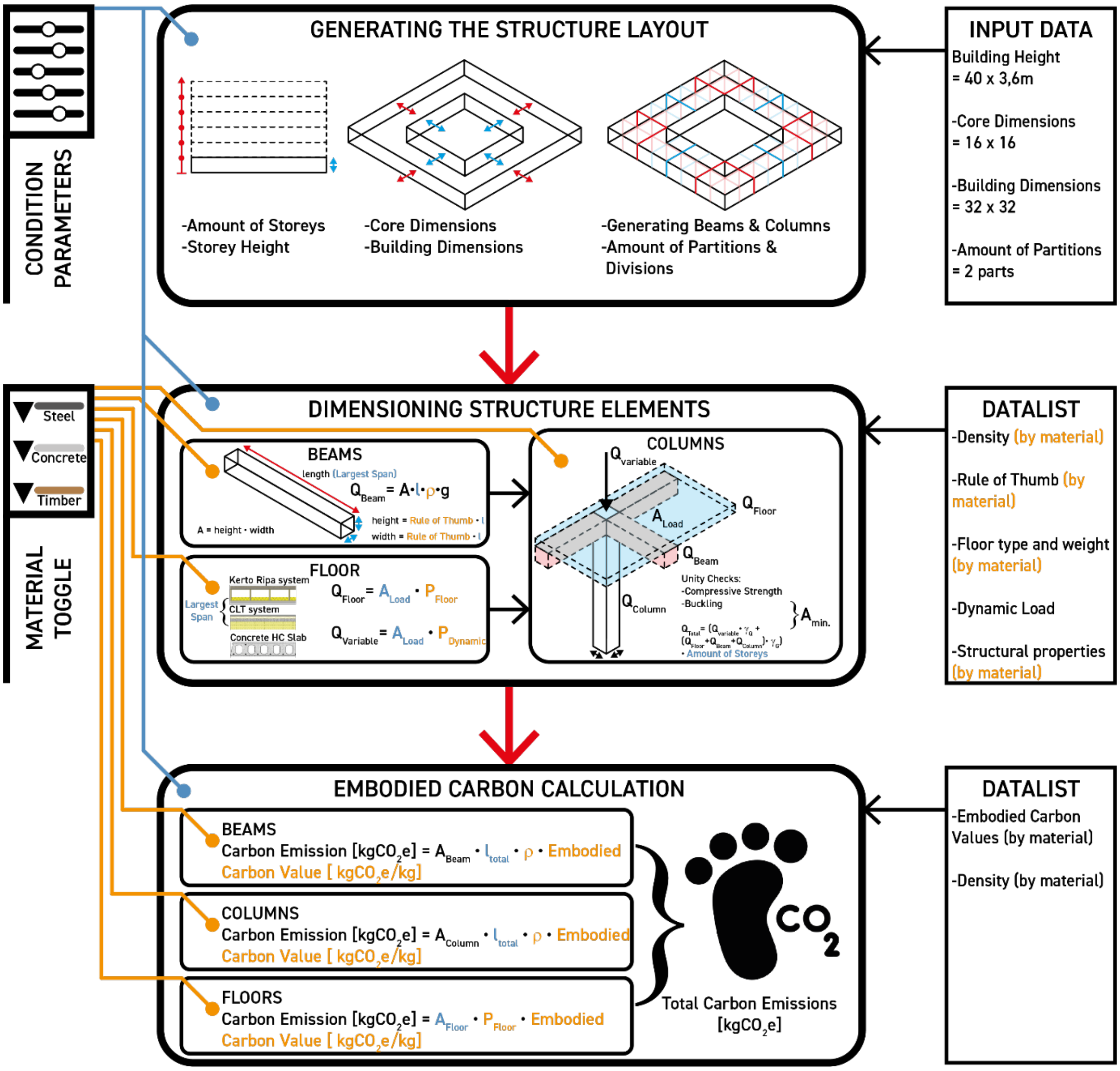


Figure 6. Simplified flowchart of the grasshopper script (By author, 2023)

4.3. Dimensioning structure elements

From the wireframe layout, the length and boundaries of the structural elements are determined. The dimensions of a structural element are influenced by the chosen material, controlled by the material toggle parameters. The material toggle contains concrete and timber as an option for the floor and for the beams and columns steel, concrete, and timber as an option. The chosen material influences the material properties retrieved from (data) sources that is needed to calculate the dimensions of a structural element. For an overview of the methodology to calculate the dimension of structural elements overall, see figure 6 for reference.

Since the size of the core is characterized mainly by the ability to transfer lateral loads to the foundation rather than withstanding its vertical load, it can be reasonably assumed that the core size remains rather the same within every possible configuration. That is why the core is left out of the calculation. Instead, a visual representation of the core has been displayed where the thickness of the core is $1/20^{th}$ of the length of the core. (16/20=0,8m).

4.4. Generating the Floors by material

The first step is to dimension the floor. For this experiment three types of floors will be used. A concrete hollow-core slab, a lightweight timber floor system using the Kerto Ripa system and a heavy timber floor using a CLT floor system. As explained in the last chapter, the lightweight timber floor system is independent from the main structure and the heavy timber floor system participates with the main loadbearing structure. Therefore, for the heavy timber floor type, the beams are automatically excluded from the calculation. The mass per m^2 is characterized the height of the floor element and if necessary, the mass of the fire safety and acoustic finish layers included. The floor height needed for this layout is defined by the largest floor span which is in this case 8m. When looking at the diagrams given by the construction manual (Arends, 2014) and the CLT guide from Martinsons (2016), the floor type with its structural properties is automatically picked for the calculation from the largest span of the structure layout. For this experiment a 200mm concrete hollow-core slab, KRB-2400x25-5x45x240-2400x25 Kerto Ripa floor, and L320-7s CLT floor were automatically picked for this layout, see appendix for reference. The values of the floor mass and its finish layers are used as a parameter to calculate the column profile and later on for the embodied carbon calculation.

4.5. Generating the Beams by material

The next step is to dimension the beams. In order to keep the model simple, the dimensions of the beams are defined by the rule of thumb for the height of the beams. It has been tested that a load specific beam does not necessarily affect the profile of the columns that much since the rule of thumbs are quite accurate for a span of 8m. For concrete and steel the height of the beams are $1/20^{th}$ of the span length and for timber it is $1/12^{th}$ of the span length. Since all beams are 8m long, every beam will be the same length. The mass of the beam profile per m is characterized by multiplying the profile height with the profile width and density. For steel in particular, it is not quite so simple as for concrete or timber. There are lots of steel profiles available on the market. Think about I beams, rectangular beams and circular beams. The weight, dimensions and other properties of a certain profile is specified from a list provided by the distributor of steel profiles, see the appendix for reference. To keep simplicity, only the HEA profile family will be used for the beams. The steel beams are modelled in such a way that the height from the rule of thumb calculation defines the specific HEA profile, which automatically retrieves the mass of the profile. The values of the mass beams, if not excluded, are used as a parameter to calculate the column profile and later on for the embodied carbon calculation.

4.6. Generating the Columns by Material

Columns do also have a rule of thumb for the thickness of the profile. But, since the total amount of load will be in relative terms way higher than low-sized buildings, the rule of thumb does not apply any more and should be calculated in a more accurate way.

The first step is to automatically collect all the parameters needed for the calculation, which is in this case the largest column loadfield, variable load, floor mass, total beam length carried by the column with the largest loadfield, mass of the beam profile, storey height, number of storeys and the density of steel, concrete, and timber.

The next step is to calculate the minimum column thickness/ profile for sufficient compressive strength. The mathematical expression that calculates this value has been generated by using the formulas in the construction manual and applying algebra. From the calculated column thickness or area, the minimum column thickness/ profile in order to prevent buckling is calculated. The value with the highest minimum value will be the thickness/ area of the column of that specific material. For concrete specifically, the strength class is also set as an interchangeable parameter since a different strength class affects the embodied carbon of that material.

Just like the calculation of the steel beams, the calculation of the steel column works a little bit different. The SHS-HF profile family is the most viable option to use as a column because steel is naturally a material that is sensitive to axial forces and this profile family is the best at resisting axial forces due to the fact that it has the highest area values. This profile also does not have a weak direction since it is a square profile. From calculating the min. area for sufficient compressive strength, the min. second moment of area (Iz in N/mm^4) needed in order to prevent buckling is calculated. The profile type that withstands both unity checks will be used as a column. This is of course modelled in such a way that the profile type is automatically chosen depending on the calculated values.

4.7. Embodied carbon calculation

In order to calculate the total amount of carbon emitted by the structural layout, it is required to collect the data values needed for the calculation by material. These parameters are mainly the mass and/ or density of that specific object.

First it is important to quantify the total weight of a specific material. This is done with a different approach for some materials. Materials with the profile area as a parameter need to be multiplied by the total length and the density of that specific material. Materials with the mass/m^2 as a parameter need to be multiplied with the total area. The material used are controlled by the material toggle parameters of course.

The second step is to multiply the total weight of that specific material with the embodied carbon value of that specific material, see table 1 for reference. The calculated value is the carbon footprint of that specific material present in the structural layout expressed in kgCO2e.

The last step is to sum up all the calculated carbon emission values. That value is the total carbon footprint of that structural layout expressed in kgCO2e.

V. RESULTS, CONCLUSION AND DISCUSSION

5.1. Early conclusions during the process

When playing with the parameters and looking at the values, many conclusions can be made before running the optimization. One of the first things noticed is that steel has the worst embodied carbon values for beams and columns, even though steel structures have the slimmest profiles. Furthermore, when following the calculations of the columns, all the structural layouts containing steel columns and a concrete floor fails. This is because the maximum area that the steel profile can be is always lower than the minimum amount of area needed to prevent buckling. This can be solved by making the loadfield of the columns smaller by making more divisions, or by decreasing the number of floors. Also, there is still a possibility to search for a steel profile with stronger structural properties than given in this calculation.

Another thing noticed is that floors are the major contributors of the total carbon emission value. That is because the floors contain the most amount of materials per m^2 than beams and columns. Literature stated that 75% of the total carbon emission is from floors (Eleftheriadis et al., 2018), and this is also confirmed by the model within some types of material layouts. Furthermore, the finish layers for acoustic and fire safety performance significantly contributes to the carbon footprint and weight of the structural layout. Especially with the Kerto Ripa floor system since its floor mass comes primarily from the finish layers due to its properties being a lightweight structural floor.

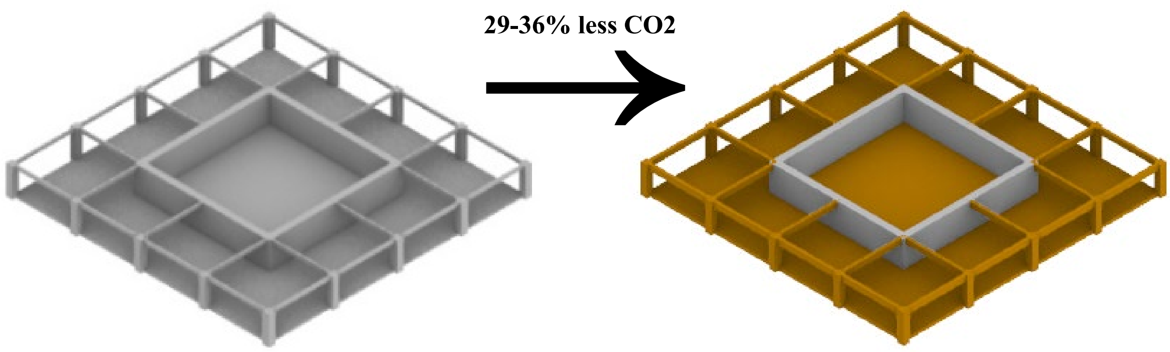
Concrete has the lowest values of embodied carbon than other structural elements. Still, concrete does not perform that well in terms of carbon footprint since it has a high density. Even with this fact considered, when you choose a higher strength class, the total embodied carbon value actually decreases a bit even though the relative embodied carbon value becomes higher when choosing a higher strength class. This is because the structural performance of a higher strength class changes the dimensions of the structural columns in such a way that the profile size decreases which automatically decreases its weight and total embodied carbon value. This means that a high strength class is actually more sustainable which is quite an interesting and unexpected phenomenon.

As expected, Timber performs best in terms of embodied carbon. Even though it contains the biggest structural dimensions in all domains, it still outperforms the commonly used structural elements. This is due to the fact that timber has a low density and low embodied caron value. The total embodied carbon value of concrete hollow-core slabs are significantly higher than all other counterparts. This proves that something that has been prefabricated is not always the most sustainable option.

5.2. Finding the structural layout with the least amount of embodied carbon

When looking at table 2, you can see every possible structural layout that can be made from the material parameters (strength class differences not included). After running a quick optimization with the Galapagos component, the structural layout with the least amount of embodied carbon has been found.

The structural layout with a timber slab, timber beams and timber columns are the best option and thus with a value of 78.250 kgCO2e the most sustainable option for this ground-floor structure layout, see Figure 7 for a visual representation. The highrise structure strategy chosen for this experiment is traditionally and commonly materialized with every structural component being concrete. That contains a value of 110.500 to 123.100 kgCO2e within this experiment depending on its strength class. That means that the optimized layout in this experiment has approximately 29 to 36% less carbon emission than its concrete counterpart and that makes it 29 to 36% more sustainable. This layout also has the ability to store more than 100.000 kg of CO2 which means that it contributes to cleaner air. The weight of this layout is also significantly less than the traditional layout, more than 3 times to be specific. This can be problematic in terms of maintaining stability for highrise structures, so this has to be considered to the credibility of the experiment as well.



CO2 Footprint: 110.500 - 123.100 kgCO2e

CO2 Storage: 0 kgCO2e

Weight: 559.800 - 626.300 kg

CO2 Footprint: 78.250 kgCO2e

CO2 Storage: -123.200 kgCO2e

Weight: 193.700kg

Figure 7. Visual representation of the traditional and optimized structure layout (By author, 2022)

5.3. Testing different configurations of timber structure layouts

From the first experiment we know that a full timber frame has the least amount of carbon emissions. But there is also another full timber frame. In this case the CLT floor system with timber columns. These are two major approaches to mass timber construction. For this experiment, these mass timber structure typologies will be compared to each other in terms of carbon footprint, carbon storage and weight. In order to further analyze the effect on the carbon footprint, carbon storage and weight, there is also an alternative version computed of these timber layouts where the grid is divided in half by increasing the amount of partitions and divisions from the parameters as stated in the previous chapter. This means that the dimensions of the structure layout remain the same whereas the amount of columns and optionally beams increases in a way that all the spans change from 8m to 4m.

From figure 8 you can see that the lightweight timber structure with a span of 8m is significantly performing better in terms of carbon footprint (potential of 36% less CO2 than the traditional layout) compared to the heavy structure (13%). Obviously from the last experiment it was expected that the lightweight timber structure would be the winner, but it was not expected that the other timber typology has significantly more CO2 emissions. This can be explained due to the fact that the heavy timber structure contains more embedded wood due to a solid wood CLT layer of 320mm thick. That also explains why the weight of that layout is approximately 100.000 kg higher than its lightweight counterpart. But, as the way you can change perspective in terms of sustainability, the heavy timber structure has significantly more potential to store carbon than its lightweight counterpart.

Seen from Figure 8, a rather strange phenomenon occurs when you divide the 8m grid to a grid of 4m. Even though the amount of columns and optionally beams increases, the weight of the structure actually decreases and at the same time its carbon emissions as visible for both timber layouts. Especially the heavy timber structure has a considerable difference between the 8m grid and 4m grid. When you compare the values of the 4m grid with the 8m grid, you can see that the heavy timber structure layout with a 4m grid has potential of 46% less CO2 than the traditional 8m grid layout. This has even better performance than the winner of the last experiment. On top of that, it has more potential to store carbon than the winner of the last experiment and it contains more weight which makes it a more favorable option for structural purposes. This can be explained due to the fact that smaller spans significantly decrease the amount of material needed for floors, and floors affect 75% of the total carbon emissions as explained earlier. Since the weight of the CLT floor system relies on the span, decreasing the span actually decreases the weight significantly, whereas for the lightweight Kerto Ripa floor system, the weight comes mainly from the finish layers which do not increase or decrease with the span. on the structural pr timber Also with smaller spans, the dimensions of columns and beams effectively decreases as well and compensates for the increased number of columns and beams.

In conclusion, decreasing the span is a more sustainable option than maintaining large spans due to the fact that the total carbon emissions decreases.

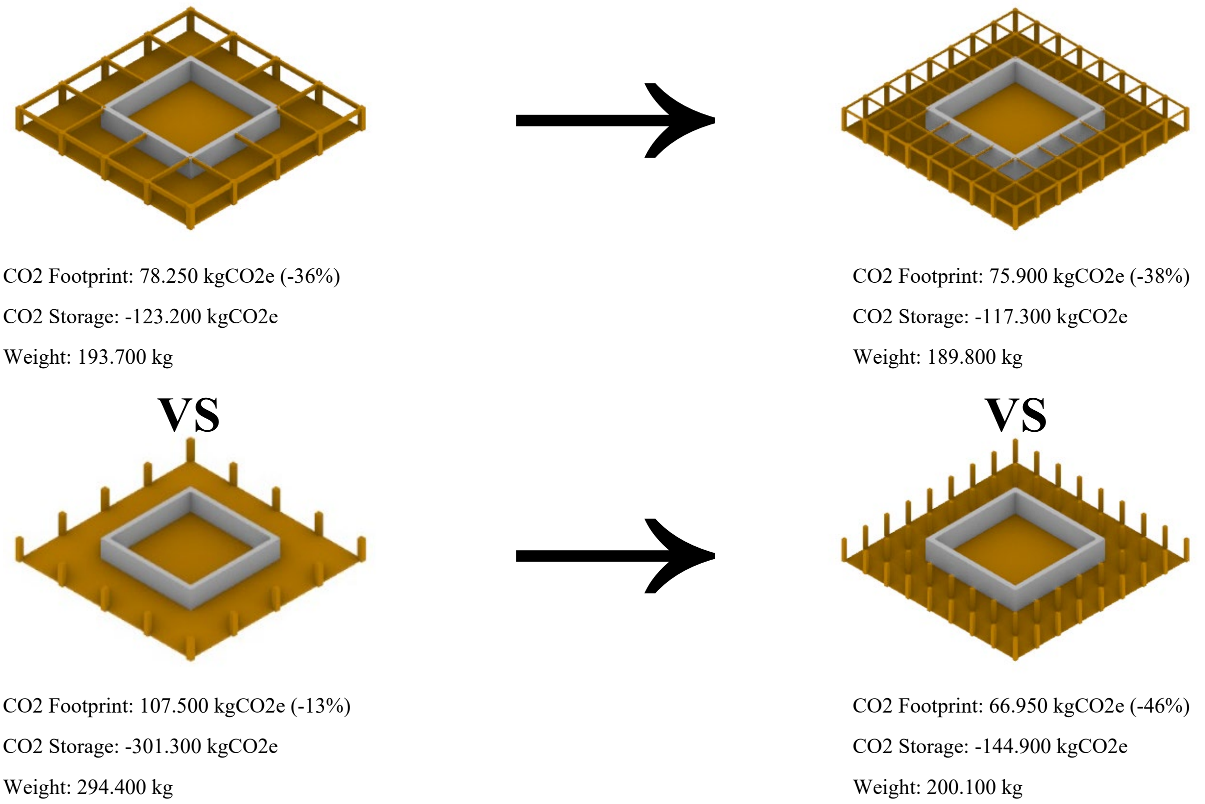
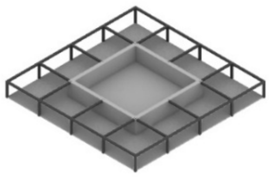
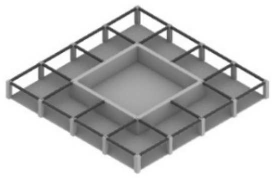
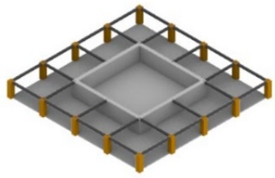
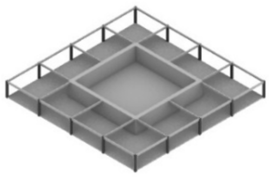
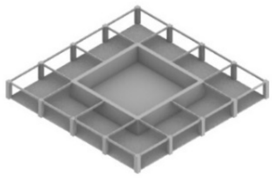
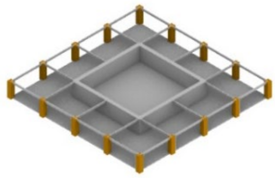
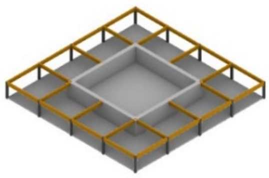
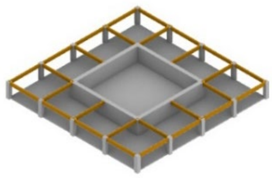
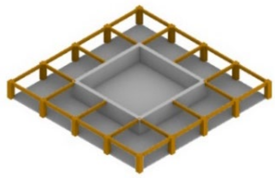
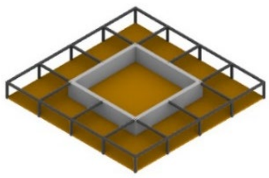
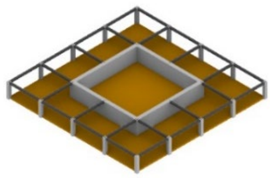
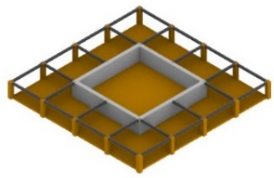
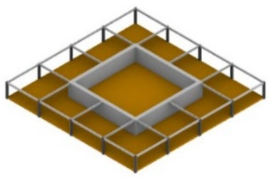
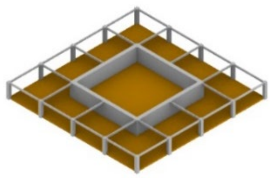
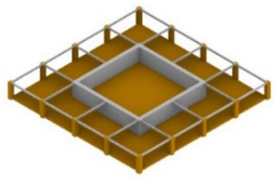
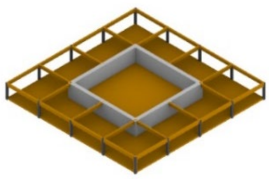
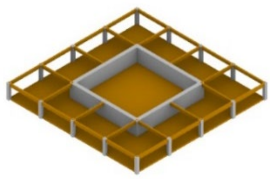
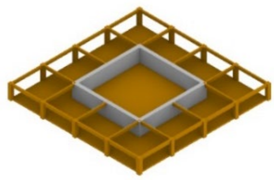
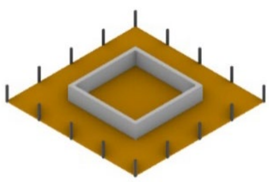
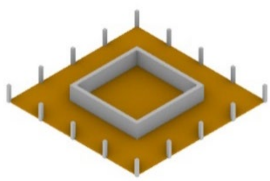
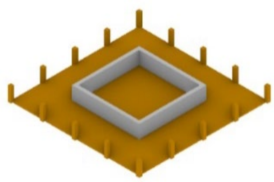


Figure 8. Comparison between Timber Floor systems and division of the existing grid (By author, 2023)

5.4. Conclusion of the research

Following the findings of the sub-questions and the results of the experiment, the answer to the research question, *to what extent is it possible to reduce carbon footprint of a highrise structure with parametric design methods*, can be answered. Choosing a highrise structure with lots of elements that does not require to be lateral load or moment resisting has the best potential to effectively reduce carbon footprint of a structure, which is in this case a shear wall (core) + hinged frame structure. After collecting the data for the structural and carbon footprint properties of construction materials and setting op the conditions for the experiment, a parametric optimization has proved that a structural layout containing timber CLT floors and timber Glulam columns scattered over a grid with divided spans has potential to be approximately 46% more sustainable than a similar traditional concrete layout. Reducing carbon footprint of a highrise structure with parametric design can therefore be done to a great extent. Since this experiment is done in a simplified but yet justified method, the exact amount of carbon footprint from a more complex simulation with an increased amount of considered factors and detailing of this structural layout might differ from the results within this experiment but, in relative terms possibly be comparable. Also, due to the fact that only one structural layout has been investigated, more experiments should be done to compare this strategy to other structure typologies. Thus, more research is needed.

Table 2. Every Structural Layout possible from Material Parameters (By Author, 2023)

	Steel Columns	Concrete Columns	Timber Columns	
Steel Beams				Concrete Floor
Concrete Beams				
Timber Beams				
Steel Beams				Independent Timber Floor
Concrete Beams				
Timber Beams				
No Beams				Embedded Timber Floor

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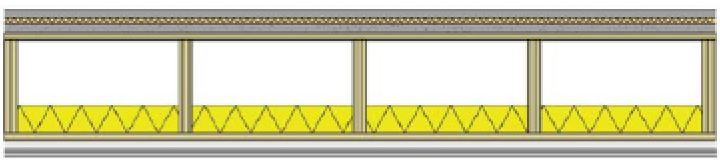
APPENDIX 1 (ARENDS, 2014)

Kerto-Ripa Box gewicht zper vierkante meter en maximaal toelaatbare overspanning

Naam	Hoogte	Gewicht	Dak	Vloer woning	Vloer kantoor	Vloer school	Vloer winkel	Vloer bijeenk.
	mm	kN/m²	m	m	m	m	m	m
KRB-2400x25-5x45x200-2400x25	250	**0,35**	10,25	7,65	**7,15**			
KRB-2400x31-5x45x200-2400x25	256	**0,38**	10,50	7,90	**7,40**	5,65	4,80	4,35
KRB-2400x25-5x45x225-2400x25	275	**0,36**	10,90	8,25	**7,70**			
KRB-2400x31-5x45x225-2400x25	281	**0,39**	11,15	8,50	**7,95**	6,30	5,30	4,85
KRB-2400x25-5x45x240-2400x25	290	**0,37**	11,25	8,60	**8,05**			
KRB-2400x31-5x45x240-2400x25	296	**0,40**	11,50	8,85	**8,30**	6,70	5,60	5,15
KRB-2400x25-5x45x260-2400x25	310	**0,38**	11,65	9,05	**8,45**			
KRB-2400x31-5x45x260-2400x25	316	**0,41**	11,90	9,35	**8,75**	7,25	6,10	5,50
KRB-2400x25-5x45x300-2400x25	350	**0,40**	12,50	9,80	**9,35**			
KRB-2400x31-5x45x300-2400x25	356	**0,43**	12,75	10,05	**9,60**	8,10	7,05	6,40
KRB-2400x25-5x45x360-2400x25	410	**0,43**	13,65	10,75	**10,40**			
KRB-2400x31-5x45x360-2400x25	416	**0,46**	13,90	11,00	**10,60**	9,20	8,50	7,75
KRB-2400x37-5x45x360-2400x25	422	**0,49**	14,10	11,25	**10,80**	9,45	8,15	7,40
KRB-2400x37-5x45x360-2400x37	434	**0,55**	14,60	11,80	**11,00**	10,00	8,65	7,90
KRB-2400x25-5x51x400-2400x25	450	**0,47**	14,40	11,40	**11,05**			
KRB-2400x31-5x51x400-2400x25	456	**0,50**	14,65	11,70	**11,30**	10,05	9,35	9,35
KRB-2400x37-5x51x400-2400x25	462	**0,53**	14,85	11,95	**11,50**	10,30	9,55	9,00
KRB-2400x37-5x51x400-2400x37	474	**0,59**	15,35	12,50	**11,85**	10,80	10,15	9,55
KRB-2400x25-5x57x450-2400x25	500	**0,53**	15,35	12,25	**11,85**			
KRB-2400x31-5x57x450-2400x25	506	**0,56**	15,60	12,50	**12,10**	10,95	10,30	10,30
KRB-2400x37-5x57x450-2400x25	512	**0,59**	15,80	12,75	**12,30**	11,10	10,55	10,55
KRB-2400x37-5x57x450-2400x37	524	**0,65**	16,30	13,35	**12,65**	11,55	10,90	11,05
KRB-2400x25-5x63x500-2400x25	550	**0,59**	16,25	13,05	**12,65**			
KRB-2400x31-5x63x500-2400x25	556	**0,62**	16,45	13,35	**12,85**	11,65	11,20	11,20
KRB-2400x37-5x63x500-2400x25	562	**0,65**	16,70	13,60	**13,05**	11,85	11,35	11,35
KRB-2400x37-5x63x500-2400x37	574	**0,71**	17,15	14,15	**13,45**	12,25	11,75	11,75
KRB-2400x43-5x63x500-2400x43	586	**0,77**	17,55	14,50	**13,90**	12,65	12,10	12,10
KRB-2400x25-5x75x600-2400x25	656	**0,73**	17,90	14,70	**14,15**			
KRB-2400x31-5x75x600-2400x25	656	**0,76**	18,15	15,00	**14,40**	13,10	12,55	12,55
KRB-2400x37-5x75x600-2400x25	662	**0,79**	18,35	15,20	**14,60**	13,25	12,75	12,75
KRB-2400x37-5x75x600-2400x37	674	**0,86**	18,80	15,65	**15,00**	13,70	13,15	13,15
KRB-2400x43-5x75x600-2400x43	686	**0,92**	19,20	16,05	**15,40**	14,05	13,50	13,50

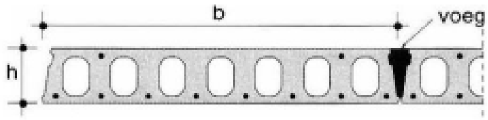
OPBOUW

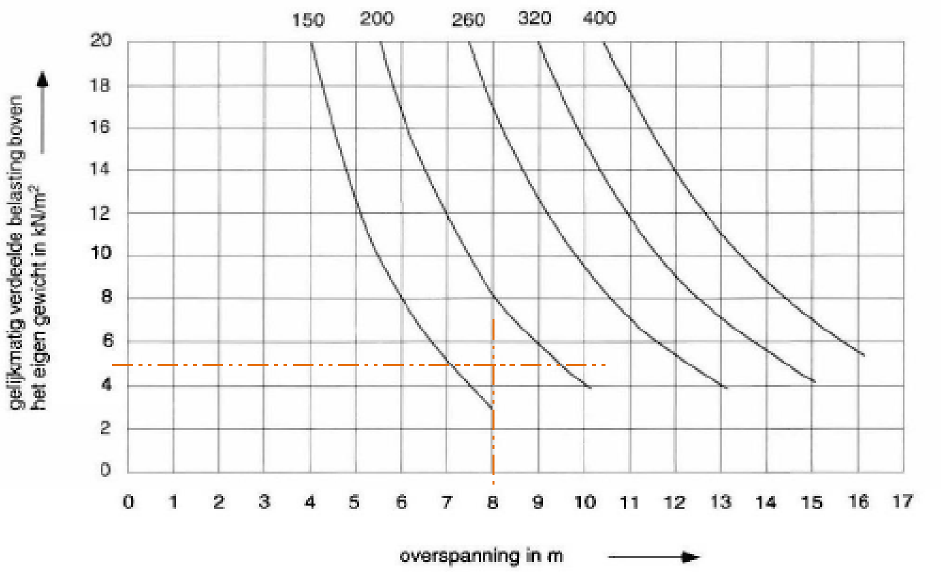
25mm Zwevende gipsvezelplaat
20mm Houtvezelisolatie
30mm Grind in honingraatstructuur
362mm KRB-2400x25-5x45x300-2400x37
90mm Minerale wol
27mm Stalen veerregels
12,5mm Gipsvezelplaat
12,5mm Gipsvezelplaat



Totaalgewicht rustende belasting op/aan Kerto Ripa box) 110 kg/m².

APPENDIX 2 (ARENDS, 2014)





Kanaalplaten worden door verschillende producenten geleverd, die elk hun eigen bijzondere specificatie aan hun plaat meegeven. Deze samenvatting is gemaakt om een beeld te geven van de mogelijkheden van kanaalplaten. Bij een definitief ontwerp kunt u bij de leverancier nauwkeurige gegevens opvragen.

h (hoogte)	mm	**150**	**200**	**260**	**320**	**400**
b (standaard breedte)	mm	1200	1200	1200	1200	1200
aantal kanalen	stuks	8 tot 11	6 tot 11	5 tot 7	4 tot 7	4
gewicht inkl. voeg	kN/m²	2,7	3,1	4	4,7	4,8
voegvulling (kwaliteit B15)	l/m	6	7,3	11	12	15
sterkteklasse[1]		B50–B65	B55–B65	B55–B65	B55–B65	B65
milieuklasse		1 of 2	1 of 2	1 of 2	1 of 2	1 of 2
brandwerendheid	min.	30 tot 120	60 tot 120	90 tot 120	90 tot 120	90 tot120
A (oppervlak)	$\times 10^3$ mm²	130	150	190	230	230
z_s (zwaartepunt)	mm	73,6	99,1	122	152	204
I (traagheidsmoment)	$\times 10^6$ mm⁴	310	685	1470	2640	4640
m.b.t. utiliteitsbouw						
ℓ_{max} verdieping[2]	m	7,2	8,9	12,5	14,6	16,5
ℓ_{max} dak[3]	m	8,0	9,9	12,5	14,6	17,5
max. plaatlengte bij						
breedte 300 mm	m	7,2	8,5	10,4	13,0	
breedte 400-500 mm	m	7,2	7,9	10,4	13,0	
breedte 600-1200 mm	m	8,1	10,0	12,6	14,7	

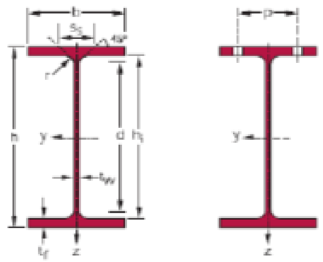
1) voorspanstaal meestal FeP1860
2) ver.bel. 3,0 kN/m² en afwerking 1,0 kN/m²
3) ver.bel. 1,0 kN/m² en afwerking 1,0 kN/m²

min. opleglengte bij metselwerk=100 mm; bij beton=80 mm; bij staal=70 mm

APPENDIX 3 (ARENDS, 2014)

Désignation / Designation / Bezeichnung	Dimensions / Abmessungen							Dimensions de construction / Dimensions for detailing / Konstruktionsmaße				
	G (kg/m)	h (mm)	b (mm)	t_w (mm)	t_f (mm)	r (mm)	A (mm^2 x10^2)	h_i (mm)	d (mm)	Ø	p_{min} (mm)	p_{max} (mm)
HE 100 A	16.7	96	100	5	8	12	21.2	80	56	M 10	54	58
HE 120 A	19.9	114	120	5	8	12	25.3	98	74	M 12	58	68
HE 140 A	24.7	133	140	5.5	8.5	12	31.4	116	92	M 16	64	76
HE 160 A	30.4	152	160	6	9	15	38.8	134	104	M 20	78	84
HE 180 A	35.5	171	180	6	9.5	15	45.3	152	122	M 24	86	92
HE 200 A	42.3	190	200	6.5	10	18	53.8	170	134	M 27	98	100
HE 220 A	50.5	210	220	7	11	18	64.3	188	152	M 27	98	118
HE 240 A	60.3	230	240	7.5	12	21	76.8	206	164	M 27	104	138
HE 260 A	68.2	250	260	7.5	12.5	24	86.8	225	177	M 27	110	158
HE 280 A	76.4	270	280	8	13	24	97.3	244	196	M 27	112	178
HE 300 A	88.3	290	300	8.5	14	27	112.5	262	208	M 27	118	198
HE 320 A	97.6	310	300	9	15.5	27	124.4	279	225	M 27	118	198
HE 340 A	105	330	300	9.5	16.5	27	133.5	297	243	M 27	118	198
HE 360 A	112	350	300	10	17.5	27	142.8	315	261	M 27	120	198
HE 400 A	125	390	300	11	19	27	159.0	352	298	M 27	120	198
HE 450 A	140	440	300	11.5	21	27	178.0	398	344	M 27	122	198
HE 500 A	155	490	300	12	23	27	197.5	444	390	M 27	122	198
HE 550 A	166	540	300	12.5	24	27	211.8	492	438	M 27	122	198
HE 600 A	178	590	300	13	25	27	226.5	540	486	M 27	122	198
HE 650 A	190	640	300	13.5	26	27	241.6	588	534	M 27	124	198
HE 700 A	204	690	300	14.5	27	27	260.5	636	582	M 27	124	198
HE 800 A	224	790	300	15	28	30	285.8	734	674	M 27	130	198
HE 900 A	252	890	300	16	30	30	320.5	830	770	M 27	132	198
HE 1000 A	272	990	300	16.5	31	30	346.8	928	868	M 27	132	198

Désignation / Designation / Bezeichnung	Valeurs statiques / Section properties / Statische Kennwerte											
	axe fort y-y / strong axis y-y / starke Achse y-y					axe faible z-z / weak axis z-z / schwache Achse z-z						
	I_y (mm^4 x10^4)	Wel.y (mm^3 x10^3)	Wpl.y* (mm^3 x10^3)	i_y (mm x10)	A_{vz} (mm^2 x10^2)	I_z (mm^4 x10^4)	Wel.z (mm^3 x10^3)	Wpl.z* (mm^3 x10^3)	i_z (mm x10)	s_s (mm)	I_t (mm^4 x10^4)	I_w (mm^6 x10^9)
HE 100 A	349.2	72.76	83.01	4.06	7.56	133.8	26.76	41.14	2.51	35.06	5.24	2.58
HE 120 A	606.2	106.3	119.5	4.89	8.46	230.9	38.48	58.85	3.02	35.06	5.99	6.47
HE 140 A	1033	155.4	173.5	5.73	10.12	389.3	55.62	84.85	3.52	36.56	8.13	15.06
HE 160 A	1673	220.1	245.1	6.57	13.21	615.6	76.95	117.6	3.98	41.57	12.19	31.41
HE 180 A	2510	293.6	324.9	7.45	14.47	924.6	102.7	156.5	4.52	42.57	14.80	60.21
HE 200 A	3692	388.6	429.5	8.28	18.08	1336	133.6	203.8	4.98	47.59	20.98	108.0
HE 220 A	5410	515.2	568.5	9.17	20.67	1955	177.7	270.6	5.51	50.09	28.46	193.3
HE 240 A	7763	675.1	744.6	10.05	25.18	2769	230.7	351.7	6.00	56.10	41.55	328.5
HE 260 A	10450	836.4	919.8	10.97	28.76	3668	282.1	430.2	6.50	60.62	52.37	516.4
HE 280 A	13670	1013	1112	11.86	31.74	4763	340.2	518.1	7.00	62.12	62.10	785.4
HE 300 A	18260	1260	1383	12.74	37.28	6310	420.6	641.2	7.49	68.13	85.17	1200
HE 320 A	22930	1479	1628	13.58	41.13	6985	465.7	709.7	7.49	71.63	108.0	1512
HE 340 A	27690	1678	1850	14.40	44.95	7436	495.7	755.9	7.46	74.13	127.2	1824
HE 360 A	33090	1891	2088	15.22	48.96	7887	525.8	802.3	7.43	76.63	148.8	2177
HE 400 A	45070	2311	2562	16.84	57.33	8564	570.9	872.9	7.34	80.63	189.0	2942
HE 450 A	63720	2896	3216	18.92	65.78	9465	631.0	965.5	7.29	85.13	243.8	4148
HE 500 A	86970	3550	3949	20.98	74.72	10370	691.1	1059	7.24	89.63	309.3	5643
HE 550 A	111900	4146	4622	22.99	83.72	10820	721.3	1107	7.15	92.13	351.5	7189
HE 600 A	141200	4787	5360	24.97	93.21	11270	751.4	1156	7.05	94.63	397.8	8978
HE 650 A	175200	5474	6136	26.93	103.2	11720	781.6	1205	6.97	97.13	448.3	11030
HE 700 A	215300	6241	7032	28.75	117.0	12180	811.9	1257	6.84	100.1	513.9	13350
HE 800 A	303400	7682	8699	32.58	138.8	12640	842.6	1312	6.65	106.1	596.9	18290
HE 900 A	422100	9485	10810	36.29	163.3	13550	903.2	1414	6.50	111.1	736.8	24960
HE 1000 A	553800	11190	12820	39.96	184.6	14000	933.6	1470	6.35	113.6	822.4	32070



HEA

APPENDIX 4 (ARENDS, 2017)

Hout

	gezaagd hout populierenhout en naaldhout			gelamineerd hout met homogene opbouw		
rekenwaarden in N/mm^2	symbool	C18	C24	symbool	GL24h	GL28h
Buigsterkte vezelrichting	$f_{m;0;d}$	10	14	$f_{gl;m;0;d}$	14	16
treksterkte // vezelrichting	$f_{t;0;d}$	6	8	$f_{gl;t;0;d}$	10	11
treksterkte ⊥ vezelrichting	$f_{t;90;d}$	0.3	0.3	$f_{gl;t;90;d}$	0.2	0.3
druksterkte // vezelrichting	$f_{c;0;d}$	10	12	$f_{gl;c;0;d}$	14	15
druksterkte ⊥ vezelrichting	$f_{c;90;d}$	1.3	1.5	$f_{gl;c;90;d}$	1.6	1.7
schuifsterkte	$f_{v;0;d}$	1.2	1.5	$f_{gl;v;0;d}$	1.6	1.9
elasticiteitsmodus in de bruikbaarheidsgrenstoestand	$E_{0;ser;rep}$	9000	11000	$E_{gl;0;ser;rep}$	11600	12600
elasticiteitsmodus in de uiterste grenstoestand	$E_{0;u;rep}$	6000	7400	$E_{gl;0;u;rep}$	9400	10200
elasticiteitsmodus ⊥ vezelrichting	$E_{90;ser;rep}$	300	370	$E_{gl;90;ser;rep}$	390	420
afschuivingsmodulus	$G_{ser;rep}$	560	690	$G_{gl;ser;rep}$	720	780
volumieke massa [kg/m^3]	ρ_{rep}	320	350	ρ_{rep}	380	410

Staal

constructiestaal - rekenwaarden in N/mm^2				Volumieke massa = 7800 kg/m^3
kwaliteit	E_{rep}	$f_{m;d} = f_{t;d} = f_{c;d}$	t_d	
S235	210×10^3	235	134	Let er op dat voor constructiestaal de elasticiteitsmodules *E* onafhankelijk is van de sterkteklasse!
S275		275	157	
S355		355	202	

Beton

Sterkte- en vervormingseigenschappen voor beton (naar Tabel 3.1 in NEN-EN 1992-1-1+C2:2011)														
sterkteklasse	C12/15	C16/20	C20/17	C25/30	C30/37	C35/45	C40/50	C45/55	C50/60	C55/67	C60/75	C70/85	C80/95	C90/105
f_{cd} [N/mm^2]	8,0	10,7	13,3	16,7	20,0	23,3	26,7	30,0	33,3	36,7	40,0	46,7	53,3	60,0
$f_{ctd;0,95}$ [N/mm^2]	1,3	1,7	1,9	2,2	2,5	2,8	3,1	3,3	3,5	3,7	3,8	4,0	4,2	4,4
$E_{cm} \times 10^3$ [N/mm^2]	27	29	30	31	33	34	35	36	37	38	39	41	42	44
$E_{cd} \times 10^3$ [N/mm^2]	22,5	24,2	25,0	25,8	27,5	28,3	29,2	30,0	30,8	31,7	32,5	34,2	35,0	36,7
Volumieke massa:	ongewapend beton: 2400 kg/m^3							gewapend beton: 2500 kg/m^3						

APPENDIX 5 (MARTINSONS, 2016)

Table of span widths [1)]

Martinsons CLT panels Format: 3000 x length x thickness (mm)

Load type[2)]		Category A (Housing) 2.0 kN/m²				Category B (Offices)	2.5 kN/m²	Category C:3 3.0 kN/m²		Category C:4 4.0 kN/m²		Category C:5 5.0 kN/m²	
Panel[3)]	Panel dead load [kg/m²]	Max. span width[4)]	Deformation[6)]	Max. span width[5)]	Deformation[6)]	Max. span width[4)]	Deformation[6)]	Max. span width[4)]	Deformation[6)]	Max. span width[4)]	Deformation[6)]	Max. span width[4)]	Deformation[6)]
L60-3L	24	2.3	L/315	2.0	L/465	2.2	L/310	2.4	L/211	2.2	L/218	2.1	L/206
L70-3L	28	2.6	L/321	2.6	L/321	2.5	L/309	2.7	L/218	2.5	L/217	2.4	L/203
L80-3L	32	3.1	L/304	3.0	L/333	2.9	L/315	3.2	L/211	3.0	L/203	2.8	L/207
L90-3L	36	3.4	L/312	3.4	L/312	3.2	L/320	3.5	L/217	3.3	L/208	3.1	L/207
L100-3L	40	3.7	L/316	3.7	L/316	3.5	L/318	3.9	L/206	3.6	L/211	3.4	L/207
L120-3L	48	4.5	L/302	4.3	L/341	4.2	L/318	4.6	L/218	4.3	L/214	4.1	L/206
L140-3L	56	5.1	L/313	4.7	L/395	4.9	L/306	5.3	L/217	5.0	L/209	4.6	L/204
L100-5s	40	3.5	L/318	3.5	L/318	3.4	L/301	3.7	L/208	3.4	L/214	3.2	L/213
L120-5s	48	4.0	L/317	3.9	L/315	3.8	L/319	4.2	L/212	3.9	L/212	3.7	L/208
L130-5s	52	4.6	L/319	4.4	L/336	4.4	L/317	4.9	L/205	4.6	L/201	4.3	L/205
L140-5s	56	4.5	L/308	4.3	L/350	4.3	L/305	4.7	L/211	4.4	L/208	4.1	L/214
L150-5s	60	5.2	L/302	4.6	L/397	4.9	L/312	5.3	L/222	5.1	L/202	4.8	L/203
L160-5s	64	5.7	L/311	5.0	L/420	5.5	L/302	5.7	L/244	5.6	L/210	5.3	L/208
L180-5s	72	5.7	L/335	5.0	L/446	5.6	L/309	5.7	L/263	5.6	L/227	5.5	L/202
L200-5s	80	6.3	L/368	5.6	L/514	6.3	L/325	6.3	L/290	6.3	L/240	6.3	L/205
L230-5s	92	6.8	L/422	6.0	L/594	6.8	L/374	6.8	L/335	6.8	L/279	6.8	L/239
L210-7s	84	6.3	L/380	5.6	L/528	6.3	L/335	6.3	L/300	6.3	L/248	6.3	L/211
L240-7s	96	7.1	L/455	6.3	L/643	7.1	L/406	7.1	L/364	7.1	L/303	7.1	L/260
L270-7s	108	7.4	L/500	6.5	L/722	7.4	L/446	7.4	L/404	7.4	L/338	7.4	L/290
L280-7s	112	7.4	L/493	6.6	L/673	7.4	L/440	7.4	L/398	7.4	L/332	7.4	L/286
L300-7s	120	7.7	L/538	6.9	L/726	7.7	L/481	7.7	L/438	7.7	L/367	7.7	L/317

1) EKS10, SS-EN1995-1-1, Safety class 3, Climate class 1, Dead load = panel dead load + 50 kg/m²
2) Useful loads excluding movable dividing walls as per 6.3.1.2(8) i SS-EN 1991-1-1
3) 'L' = Lengthways outer layer. '60' = thickness in mm. '3L' = 3 layers.

4) Natural frequency minimum req. ≥ 8 Hz, Flex ≤ 1.3 mm at 3.0 m floor structure width
5) Natural frequency rec. for housing ≥ 10 Hz, Flex ≤ 0.9 mm at 3.0 m floor structure width
6) Semi-permanent combination equiv. 6.16a & 6.16b (SS-EN 1990)


Plywood joint


Laminated loose tongue


Visible joint


Butt joint


Half and half