Balancing design and circularity

Optimizing the reuse of steel elements in the design of frame structures

Geke Rademaker

TU Delft
ARCADIS

Balancing design and circularity

Optimizing the reuse of steel elements in the design of frame structures

by

Geke Rademaker

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Friday October 7, 2022 at 9:00 AM.

Student number:	4553586	
Project duration:	November 8, 2021 – October 7, 2022	
Thesis committee:	Ass. Prof. dr. M.A. Popescu	TU Delft
	Prof. dr. H.M. Jonkers	TU Delft
	Ir. A.C.B. Schuurman	TU Delft
	Ir. T.H. Moll	Arcadis

TU Delft

Preface

This thesis represents the final chapter of the Master of Civil Engineering at the Technical University of Delft. Within the Master's program, I enjoyed following the track Building Engineering, where I specialized in Structural Design. Due to the different related courses, I discovered parametric design. This promising, relatively new method of designing became something I find really interesting. Together with the current need for sustainability, this resulted in the topic of this thesis.

I would like to thank my research committee. Every meeting I had the opportunity to get proper feedback, improving the completeness of my research. Mariana, I would like to thank you for the time you took to guide me towards a good research topic. After we formulated a topic, you helped me a lot with your knowledge about parametric design. Henk, thank you for your critical view, which made me think deeply about the different steps I was taking in my research. Marco, thank you for providing the engineering-view on this research topic. Your advice helped me to look at this research not only from an academical point of view, but also from a practical one.

This thesis has been created in collaboration with Arcadis. Within Arcadis, I was supervised by Thomas Moll. I would like to thank you for all the useful talks we had, not only about thesis but also about how to start a career. Besides, I would like to thank all the people working at the department SD&E in Rotterdam. By just being in the office and listening to different talks, I had the opportunity to get an idea about how the knowledge I gained during my studies can be applied in practice.

Furthermore, I would like to thank my parents, sister and boyfriend for always being there for me. I would also like to thank my friends, and especially Rik and Amey, who were always available to help me figure out answers to difficult questions I had during the process of writing this thesis. Last but not least, I would like to thank the people related to the Study Association U-BASE, and especially Board 7. During our year as the board we had so much fun, which really helped me to stay motivated.

Geke Rademaker
Delft, September 2022

Abstract

The steel sector is responsible for 4-5% of the total greenhouse gas emissions in the world. Reusing structural steel elements can potentially decrease the need for the production of new steel. However, designing a load-bearing structure with reusable elements poses challenges to the design process. The starting point of the process is different due to a limited availability of structural elements. The design of the load-bearing structure should be based on the measurements of the available reusable elements, while traditionally the amount of elements and their measurements were based on the design. However, the freedom in a design is often limited by certain architectural and structural constraints. Therefore, the focus of this thesis is on how to organize an optimization process in which the aim is to design a load bearing structure containing the least amount of new steel by means of implementing reusable elements, while taking into account the architectural and structural constraints.

In the optimization method developed in this study, the first step is to define the initial geometry given by the designer and to implement the characteristics of the stock of available reusable elements. The next step is to define the constraints. The first constraint is the minimum UC-value which an element can have. The second constraint is the maximum deviation in length which a reusable element can have compared to the member of the initial geometry.

After the constraints have been defined, the first structural calculation will take place. First, the load-distribution per beam will be determined. Subsequently, the shear- and moment-distribution for every beam and the normal force in every column is calculated. The first step in the element assignment-procedure is to assign reusable elements to column positions. During this procedure, available reusable elements which respect the constraints are selected, resulting in different possible column-configurations. A selection of column-configurations might result in the emergence of split levels in the structure.

After the different possible column-configurations are formulated, the same process takes place for the beams. For every different column-configuration, the most efficient combination of the remaining suitable elements is chosen as the final beam-configuration. The most efficient combination is defined by the highest total UC-value of the reused elements.

The assigned elements might differ in length compared to the original elements. Therefore, the nodal coordinates of the initial design need to change. This goal can be achieved in various ways. The number of possibilities is depending on the lay-out of the beam-configuration. After all the results have been formulated, the element-configuration resulting in the least amount of new steel is selected. The possible structures with this element-configuration can be distinguished from each other by the mean UC-value of the columns, the mean UC-value of the beams, the total number of changing angles in the beam-configuration, the number of angles in the beam-configuration changing more than 10% and the minimum angle, which is used to identify the biggest change in the beam-configuration.

After the model has been formulated, a case study is performed. In this case study, the design for a small house functions as the input for the model. Multiple analyses are conducted. Three different stocks are implemented and different values for the constraints are used. Stock 1 and 2 are diverse stocks, in which a maximum of 4 elements have an equal length. Stock 3 is less diverse, in which up to 12 elements have an equal length.

The characteristics of the resulting designs are influenced by the relation between the stock and the original design. In stock 1 and 2, the reused elements are oversized related to the design and therefore have low UC-values when the minimum allowed UC-value is 0.01. When the reused elements are mainly implemented as columns (what happens when the maximum deviation in length is 10%) the UC-values of the columns are 0.33 for stock 1 and 0.37 for stock 2. When the maximum deviation in length is set to 30%, the reused elements are mostly implemented as beams. In this case, the mean UC-value of the beams lies between 0.17 and 0.18 for stock 1 and is 0.20 for stock 2.

When the minimum allowed UC-value is 0.01 and the maximum deviation in length is 10%, stock 3 is able to provide a reusable element for every position. The mean UC-value for the columns is 0.56 and for the beams 0.75.

A diverse stock, together with the combination of a maximum deviation in length of 30% and a minimum UC-value of 0.01, results in drastic changes in the lay-out (up to 19 angles changing more than 10% for stock

1 and 20 for stock 2). A less diverse stock, together with the combination of a maximum deviation in length of 30% and a minimum UC-value of 0.01, does not result in changing angles.

The amount of new steel required to realize the final designs generally lowers when the minimum allowed UC-value is low (0.01 in the analysis). For stock 1 and 2, analyses in which the maximum deviation in length is 30%, give results which include 0.18 and $0.23m^3$ steel respectively. In the result obtained due to the implementation of stock 3, no new steel elements are needed to realize the design.

Therefore, applying the optimization method developed in this study to a design for a load-bearing structure results in a modified design in which the amount of new steel required to realize the design is minimized. However, the actual UC-values corresponding to the different elements and the changes in the design are based on the available stock and the constraints.

Contents

1 Introduction

1.1. Circular Economy in the construction industry

The recent IPCC report states that the human emission of greenhouse gases is responsible for the rise in the global temperature (+1 °C compared to pre-industrial levels) [23]. As of now, the effects of global warming are already observed, resulting in the change of land and ocean ecosystems [23]. In order to limit these global warming effects, the human emission of greenhouse gases is to be reduced. To reach the climate goals which were set in National Climate Agreement (the Dutch implementation of the Paris Climate Agreement from 2015 [34]), a reduction in the emission of greenhouse gases is necessary. In 2030, the volume of the released emissions should be 49 percent less compared to 1990. Up until 2019, the observed reduction was only 18 percent [38].

The construction industry is responsible for 39 percent of the total greenhouse gas emissions in the world, of which 11 percent are embodied carbon emissions [11]. Applying the principles of circular economy is one method to reduce the number of these embodied impacts [7]. The ambition of the Dutch government and the Dutch construction industry is to make the complete building process circular before 2050 [36]. There are multiple options to implement the principles of circular economy in the design process. One of these options is to reuse structural elements.

1.2. Reuse of structural elements

One option to implement the principles of circular economy in the design process is to reuse structural elements. Multiple methods on reusing structural elements can be distinguished, namely [6]:

1. **Reuse on the original location of the structure, by renovation or adaptive reuse** If a structure can be renovated on the same location, very few modifications to the structure are necessary. Applying this type of reuse to a structure prevents demolition of the structure. However, in most cases buildings have not been designed to change function.

2. **Reuse of the complete system** In systems where it is possible to disassemble and reassemble the complete structure, the system can be reused completely. The purpose of the structure can possibly change. Examples of such structures are tent structures and modular systems.

3. **Reuse of separate components** The reuse of the separate members within a structural system prevents the production of new elements for the design of a load-bearing structure and therefore mitigates the emissions of greenhouse gasses released during the production process of these elements. An example where separate structural components are reused, is a building called Biopartner 5, located in Leiden, The Netherlands [4].

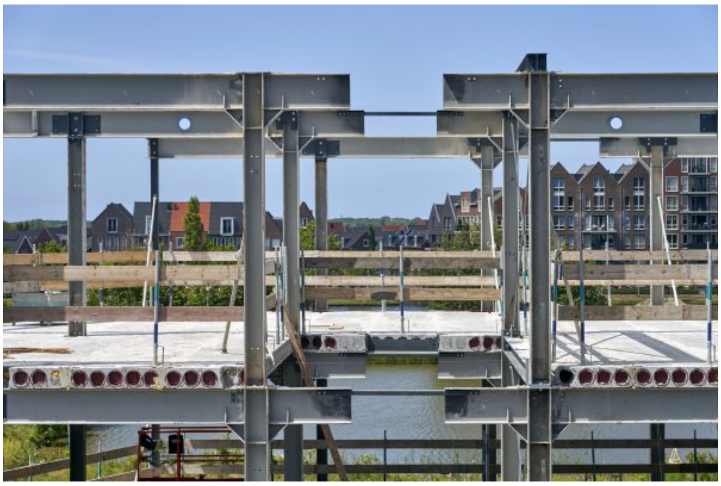


Figure 1.1: BioPartner5. Source: Redactie Bouwwereld [4]

1.3. Designing with reusable elements

Designing a new load-bearing structure with reusable components poses challenges to the design process [15], but can decrease the environmental impact of a structure significantly. In the study of Brutting et al. [9], the analyzed structures made from reusable elements have an environmental impact which is up to 56% lower than structures made from new (recycled) steel.

As of now, the steel sector is responsible for 4-5% of the total greenhouse gas emissions in the world [32]. Reusing structural steel elements instead of producing new structural steel elements can therefore be considered as a relevant step towards mitigating the release of greenhouse gas emissions and therefore to reaching the climate goals.

When designing with reusable elements, the starting point of the process is different due to a limited availability of structural elements. The design of the building should be based on the availability of members, while traditionally application of certain elements was based on the design. Ideally, the members which will be used in the design are therefore to be identified in the beginning of the design process [15].

Implementing reusable elements in the design of a load-bearing structure might decrease the amount of new steel required to realize the design. Yet, the freedom in a design is often limited by certain architectural and structural constraints. This thesis will focus on how to organize an optimization process in which the aim is to design a load-bearing structure containing the least amount of new steel by means of implementing reusable elements, while taking into account the architectural and structural constraints. Furthermore, research will be performed on how the different constraints affect the amount of new steel in the end result.

2
Research Content

2.1. Problem statement and research goal

The approach to designing a load-bearing structure with reusable elements differs from the traditional process. Where initially the design for the structure was created followed by the application of suitable new structural elements, the availability of the elements is now limited and therefore guides the design. However, the freedom in the design is often restricted by certain architectural and structural constraints given by the designer. The question arises how to implement reusable elements in the design for a load-bearing structure in such a way that the amount of new steel required to realize the design lowers, but which respects the architectural and structural constraints given by the designer. The goal of this thesis is therefore to create an optimization process in which the stock and the constraints given by the designer serve as an input and where the output is the design for a load-bearing structure containing the least amount of new steel by means of implementing reusable elements, while following the given constraints. This is also displayed in Figure 2.1.

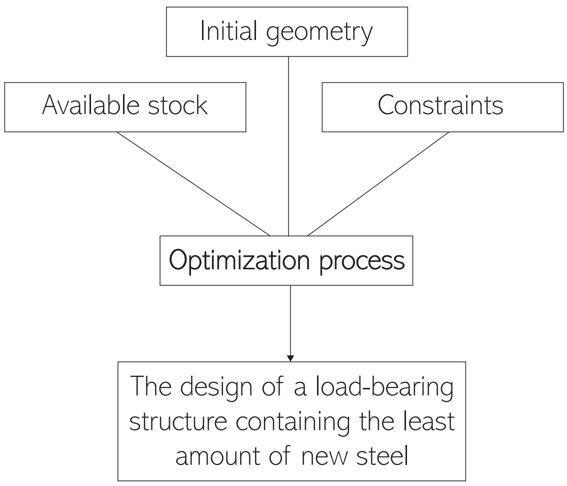


Figure 2.1: Research goal: creating an optimization process

2.2. Research questions

The main research question of this thesis is:

How to implement reusable elements in the design of a load-bearing structure in a way that minimizes the amount of steel required to realize the design and which respects the architectural and structural constraints?

The sub-questions following from the main research question:

1. *How does implementing reusable elements affect the design process of a load-bearing structure?*
2. *How can the optimization problem be defined and modelled?*
3. *How is the amount of new steel in a load-bearing structure affected by the architectural and structural constraints?*

2.3. Structure of the report

This report consists of eight Chapters. In Table 2.1, the constituents of each Chapter are displayed.

Chapter 1&2	Research specifics	- Problem statement - Research goal - Research questions
Chapter 3&4	Theory	- Consequences of reusing structural steel elements - Optimization in combination with reusable elements
Chapter 5	The optimization process	- Geometry definition & stock implementation - Structural calculations - Element assignment - Formation of the results - Structural check and selection of results
Chapter 6	Case study	Case study - Different stocks - Different values for the constraints
Chapter 7	Discussion	- Limitations of the method - Usability of the model - Sustainability
Chapter 8	Conclusion & Recommendations	Answers to the research questions and recommendations for further research

Table 2.1: Structure of the report

3
Reuse

3.1. Circular Economy

The concept of Circular Economy (CE) is an approach to reduce the environmental impacts of different products and to therefore promote sustainable development. Where the concept of Circular Economy is increasingly discussed in literature (30 articles in 2014 and more than 100 in 2016 [14]), the exact definition is debatable. Pietro-Sandoval et al. [29] researched multiple studies and proposed four main components that the definition of the concept of Circular Economy should include: 1) re-circulation of resources and energy, 2) implementation on multiple levels, 3) its importance to achieve sustainable development and 4) its relation to innovation. In the end, Circular Economy is defined as an economic system which changes the relation between human and nature, where the focus lies on preventing the depletion of resources and closing material and energy loops. Furthermore, the concept of Circular Economy can be implemented on three different levels: micro (enterprises and consumers), meso (eco-industrial parks) and macro level (cities, areas, countries). The possibility to facilitate sustainable development in these three levels is also addressed in the study of Kirchherr et al. [21]. Kircherr et al. performed an analysis of 114 definitions of Circular Economy. In this study, the concept of Circular Economy was defined as *"an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in the production/distribution and consumption processes"*. To close the loop (as also mentioned in [29]), this study refers to the 4R framework: *Reduce, Reuse, Recycle, Recover*. However, various options can be found in literature, ascending to a 9R framework in the study of Van Buren et al. [33].

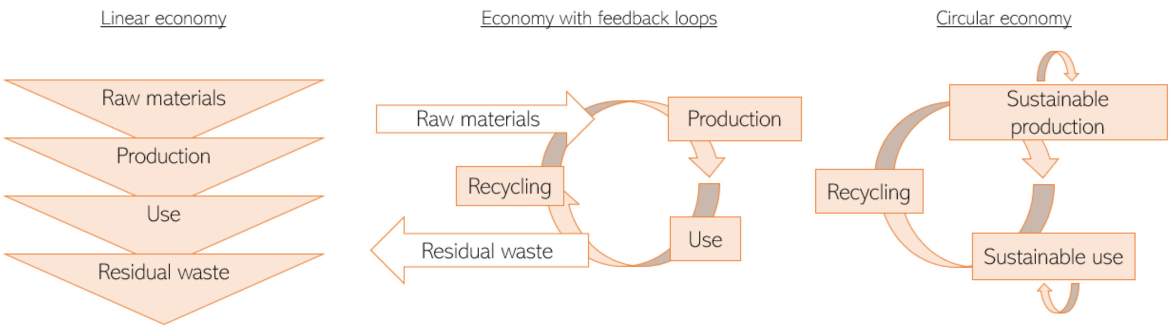


Figure 3.1: Left: Linear Economy; Middle: Economy with feedback loops; Right: A complete Circular Economy (based on [33])

Within the different R frameworks, *Reuse* is a frequently found method to close the loops. Within the 9R framework, *Reuse* is seen as the fourth best strategy to reach an ultimate Circular Framework after *Refuse, Rethink* and *Reduce* [28]. In contrary to *Refuse, Rethink* and *Reduce*, where the perception towards a product potentially changes, *Reuse* only results in an extension of the lifespan of (a part of) the product.

Since the Dutch Government has the aspiration to achieve a circular construction industry by 2050, the possible implementation of the different R frameworks into this sector needs to be discussed. Whereas *Refuse,* *Rethink* and *Reduce* strive towards a more circular economy than *Reuse*, the application might be more time consuming since, compared to *Reuse*, more innovation in the product design is necessary [28]. When reusing structural elements, the structural function of these elements remains the same.

3.2. Designing with reusable elements

As mentioned in Chapter 1, the reusing of structural elements can be carried out in a number of different ways: 1) in-situ adaptive reuse and renovation of building structures, 2) system reuse and 3) component reuse [6]. Option 3 is the most flexible as it allows for a change of function of the structure in which the component is situated. In recent years several projects have been undertaken in which reused elements have been implemented in the load-bearing structure. A selection of projects is displayed in Figure 3.3.

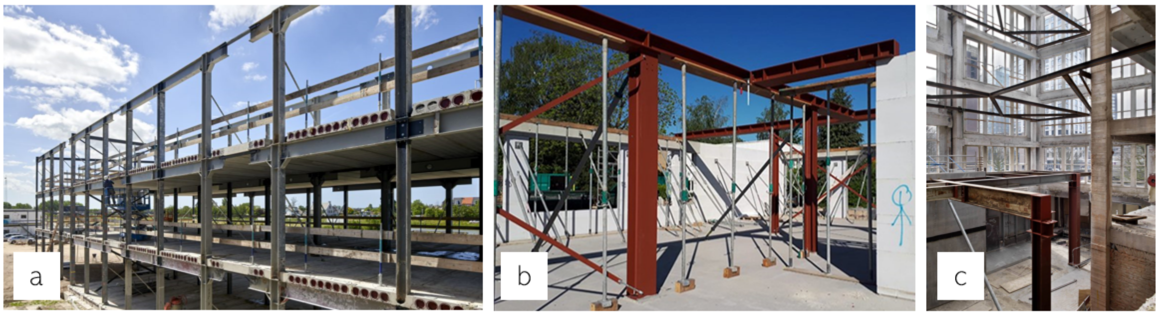


Figure 3.2: Multiple projects in which reused elements are implemented in the load-bearing structure. (a) Biopartner5, Leiden. Source: Redactie Bouwwereld [4]; (b) Avignonlaan, Eindhoven. Source: Sharon Hercules [19]; (c) Hoogstraat 168-172, Rotterdam. Source: Rijnboutt [31]

While steel is a commonly used building material within the construction industry, a significant amount of greenhouse gas is released by the steel industry, accounting for approximately 4-5 percent of the total greenhouse emissions of the world [32]. Reusing steel structural elements can avoid the release of emissions during the production process and can therefore contribute to lowering the total amount of greenhouse gases released during the construction process of a structure.

Different projects where reusable elements are used for the load-bearing structure have been realized in the recent years. In Figure 3.3 three examples are displayed:

1. **Biopartner 5, Leiden** The reused elements included in the load-bearing structure of this building became involved in the project when the initial design was almost completed. In order to be able to implement these elements, the initial design had to be altered. The structural elements used in the supporting structure of this project originated from a building located 750 meters away from the project. Therefore, the reusable elements had to be transported of over a relatively short distance. In the project, a combination of the reused elements and new elements is used. 60 percent of the total members of the building is reused and 40 percent is new. In some parts of the design it was not possible to implement reusable elements. For example, new elements have been implemented in the corners of the building. During the construction of the building, some reusable elements which were placed in the design had to be changed to new elements because they turned out to be shorter than documented. Also, the columns were a bit damaged because of the disassembling process [Contractor, Personal Communication, 2022].

2. **Avignonlaan, Eindhoven** In this design, reusable elements are mostly implemented as columns, since the reusable elements were too big to be implemented as beams. The reusable steel elements were checked. When it was necessary, refurbishment of the elements took place. The material was checked for tension strength, hardness and carbon value. The next step was to clean and sort out the different elements. Later, the elements were cut to size and sandblasted to remove old paint. End plates were welded to the column before transportation.[19]

3. **Hoogstraat 168-172, Rotterdam** The first challenge in this project was to find a suitable stock. This took one to two years. After the stock was found, all the elements had to be measured. After this step was completed, samples of the elements were checked to find out the characteristics. The elements had

to be cleaned because the steel was galvanized and otherwise welding was not possible. In the design, creative solutions were used to implement the reusable elements. For one beam in the building there was not one suitable reusable element, so the engineers decided to make one beam out of three different elements. In some places, where the beams were not long enough, shorter beams were connected resulting in a beam with the desired length [Contractor, Personal Communication, 2022].

3.3. Difficulties when designing with reusable elements

Whether a structural element has a high reuse potential is determined by several factors. In their study, Rakhshan et al. distinguish three main factors which affect the reuse potential of a structural element [30]:

1. the reusable element should match the design of the new load-bearing structure;
2. the potential presence of contaminating, hazardous or banned coatings on the reusable element;
3. potential problems with collateral warranties.

Especially point (1) is a factor that was also encountered in the design processes related to the projects mentioned in Section 3.2. Multiple design-related difficulties connected to these projects can be distinguished:

- Characteristics of the stock do not agree with the initial design necessitating a change in the design (Biopartner5, Leiden) or new elements must be incorporated into the load-bearing structure since no reusable elements are available that fulfill the specified requirements (the beams in Avignonlaan, Eindhoven).
- In characteristic places of the design, as for example corners with specific measurements, it is difficult to implement reusable elements with a set length and strength. Therefore in Biopartner5, Leiden, new elements were used to construct these corners.
- Creative solutions in the design might be necessary as seen in Hoogstraat 168-172 Rotterdam. Here a 'fork'-beam was invented, where three beams were used to function as one, since a suitable beam was absent.

When elements have a high reuse potential, they can be added to a stock. Designing from a stock has its effect on the design process, since the availability of components is limited [15]. Evidently, the design team needs to be more flexible and the building needs to be designed around the available reused components. In their study, Gorgolewski et al. address that the decision to design with reusable elements should be made in the beginning of the project and the reusable elements which will be used for construction need to be identified in the early design phase [15].

3.4. Environmental consequences of designing with reusable elements

The environmental impact of the complete life-cycle of a product can be assessed by a technique called a 'Life Cycle Assessment' analysis [26]. This analysis has a fixed structure and is captured in the international standards (ISO) 14040 [26]. Within a Life Cycle Assessment analysis there are four phases: *the goal and scope definition phase, the inventory analysis phase, the impact assessment phase* and *the interpretation phase* [26] (displayed in Figure 3.3).

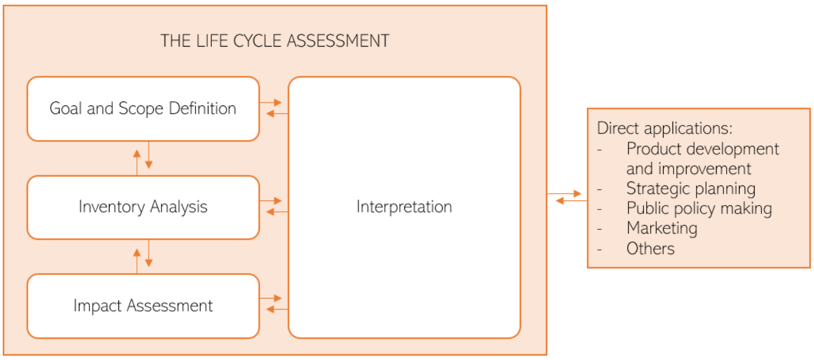


Figure 3.3: The different stages in a Life Cycle Assessment according to EN ISO 14040 (based on [26])

A complete Life Cycle Assessment covers the full life cycle of a product and is called cradle-to-grave or cradle-to-cradle [26]. The latter is a specific kind of assessment, where the end-of-life disposal step is a recycling process. In general, the assessment starts with the manufacturing (cradle) and ends with the disposal phase (grave or cradle). When only a part of the life-cycle is analysed, this is called cradle-to-gate. In this case manufacturing is again the starting point (cradle), but the analysis ends when the product leaves the factory (gate) [26].

In literature, one can find multiple Life Cycle Assessment methodologies to allocate the environmental effects of a building component over a building use cycle [12]. Yet, up to date, there are no methodologies which include qualitative judgement of the effects due to reuse of an element [12].

De Wolf et al. [12] propose to separate the Life Cycle Assessment in three segments: the first life cycle, the intermediate life cycle and the last life cycle. Within these three assessments, the impacts cannot be isolated or summed up. Storage and transformation impacts can be included in the intermediate life cycles. Furthermore, only the environmental impacts due to the use of the element within a certain time limit will be considered.

One example of a study where only (a part of) the intermediate life cycle is considered, is the study of Brutting et al. [9]. In this research, the environmental impact of reused elements is judged by including the emissions released during the deconstruction phase, the transport between factories and the building site, the reconditioning and fabrication of the product and the assembly of the total structure. In contrary to the suggestion of De Wolf et al. [12], the use and end-of-life phase are not considered. In this research the ReCiPe Endpoint (H) V1.12 impact method is used to determine the environmental impact of specific products. This method consists of impact scores of 18 mid-point indicators (e.g. global warming, land use, fossil resources). The mid-point indicators are combined into three end-point indicators: damage to resource availability, to ecosystems and to human health [9]. In this study, three different steel truss structures are subjected to 100 randomly generated stocks. The trusses made from reused elements turn out to have an environmental impact which is up to 56% lower than the minimum-weight structures made from new (recycled) elements.

In the research of Pongiglione et al. [27] the environmental impact of treatment and construction of new and reused elements is considered equal. Yet, due to contrasting processes when producing and transporting the elements, the need for raw material and the energy consumption differs. While new elements need to be produced in a factory, reused elements need to come from a disassembled building, after which they will be transported, cleaned and tested. The environmental impact of this process is hard to evaluate since little data is available. Besides, the environmental burden of the disassembling process is depending on the equipment of the company involved. Furthermore, in the study of Pongiglione et al. [27], this impact is considered small. The environmental impacts due to transportation of products is ignored, since it poses difficulties to the process. Yet, it is considered as the criteria which determines whether reusing elements instead of using new elements is feasible. In the end, the amount of new steel required to make a structure which is partly made from reused elements is compared to the amount of steel required to make the structure completely of new elements. The amount of energy required and the amount of CO_2 emitted when producing these amounts of new steel represents the environmental impacts of both structures. In this study, the designs which feature reused steel allow for 30% reduction in the required energy and emitted CO_2 compared to the traditional, initial design.

3.5. Economical consequences of designing with reusable elements

Using reused structural elements in the design for a load-bearing structure has an effect on the costs. Over the total life cycle, the use of reusable elements is found to be more expensive than the use of new elements made from recycled steel [39]. According to Yeung et al. [39], the aspects which have the most impact on the costs are the deconstruction costs and the value of reused components. Condotta et al. [10] define four negative effects related to the regulatory inconsistencies resulting from building with reusable elements.

1. A prolonged construction process time frame.
2. Increased process costs.
3. Performance assessment issues.
4. The negative perception of the end-user.

As visible, the increase in process costs is named as one of the four effects. This results from the need for certain certifications and the assessment of the elements [10].

Possible methods to reduce the costs are to incorporate 'Design for Disassembly' practices in the initial design of structures [39]. As a result, the deconstruction process will be more efficient. Another outcome will be an increase in the value of the reusable components, since the components will be less damaged during the demolition process. Besides, reusing elements can be supported by establishing element stocks, databases and a market for reused elements [7].

3.6. Conclusion

From Chapter 3, different conclusions can be drawn:

- Reuse is one method to implement circular economy in to the building industry. Reuse results in an extension of the lifetime of a product [28].
- Designing with reusable elements might decrease the environmental impact of a structure [9]. Since the steel industry is responsible for approximately 4-5% of the total greenhouse gas emissions in the world [32], building with reusable elements can be seen as a necessity for the future when the aim is to reach the Dutch climate goals for 2050.
- Building with reusable elements has its effect on the design process. If the goal is to build with reusable elements, it is recommended to determine this early in the design process [15]. In that case the design can be adjusted to the stock and the stock can therefore be used in the most efficient way.
- There is no standard method by which the environmental impact of a structure including reusable elements needs to be calculated. In different studies, different methods have been used. One difference between using reusable elements and new elements is the possible need for extra transportation. Reusable elements may have to come from a location far from the building site, resulting in extra emissions. In Appendix C, the relation between the CO_2 emissions due to transportation and production of steel is investigated. Transportation causes extra emissions, however, a relatively big distance can be covered before the emissions due to production are met.
- The economical consequences due to designing with reusable elements are related to:

  1. Deconstruction costs [39].
  2. The value of the reusable elements [39].
  3. The need for certain certifications [10].
  4. The need for assessments of the elements [10].

  A possible method to reduce the costs of implementing reusable elements in the future might be the implementation of 'Design for Disassembly' practices in the design for new buildings. When the building is deconstructed in a later stage, the deconstruction process goes faster and is more evident. Another solution to sooth the economical consequences is to start developing element stocks, databases and a general marked for reused elements [7].

4

Optimization

4.1. Optimization techniques in Civil Engineering

Optimization techniques can be implemented to a research when one strives to obtain the best result under specific conditions. In the recent years, applying optimization techniques in the field of Civil Engineering gained interest [24]. In the construction sector, optimization can be applied in different stages of a project life cycle, namely: design, construction, operation and maintenance. One can distinguish different categories of optimization in the field of Civil Engineering, which is called *structural optimization* [24]:

- **Size optimization** The design variables are the cross-sectional areas of structural members.
- **Shape optimization** The design variables are the nodal coordinates of the structures.
- **Topology optimization** The optimal design is achieved by aiming to delete unnecessary structural members. Besides, the focus lies on how nodes or joints are connected and supported.
- **Multi-objective optimization** Two or more of the size, shape or topology optimization are performed simultaneously.

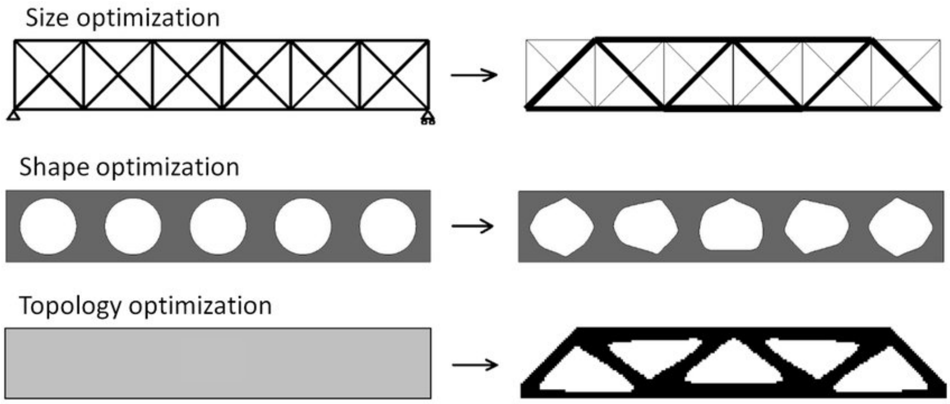


Figure 4.1: Different categories of structural optimization [16]

When optimizing, one needs to determine the problem. In general, the objectives in structural optimization can be divided in four categories [24]:

1. **Structural performance improvement** The goal is to improve specific properties of the original structure. Examples are: aerodynamic performance and dynamic seismic performance.
2. **Cost minimization** The goal is to minimize total costs. This can be achieved by lowering the total volume or weight of the structure.

3. **Environmental impact minimization.** The goal is to reduce the energy consumption or greenhouse gas emissions during the life cycle of the product.

4. **Multi-objective** 1, 2 and/or 3 combined.

The three fundamental points of an optimization problem are: design variables, objective functions and constraints [24]. Constraints refer to certain limits or requirements. The design variable can either be *discrete* or *continuous*. For *discrete* variables it is only possible to have a isolated values. On the contrary, *continuous* variables can take on every value within a certain range. The range in which the design variables are located is called the design or search space. A distinction can be made between the feasible and the infeasible domain. When all the design variables respect the constraints, the domain is feasible. If not, the space is considered infeasible.

4.2. Optimization with reusable elements

As stated in 3.3, designing from a stock of reusable elements requires a different approach to the design process compared to designing with new elements, by reason of the starting point being different [15]. The availability of structural members guides the design, whereas in day-to-day situations the structural members are defined after the lay-out of the structure has been established. Another complication might be the potential increase in costs [39] (as stated in 3.5) which occurs when constructing with reused instead of new elements. However, designing with reusable steel elements potentially causes a decrease in the environmental impact [7]. Reducing the release of greenhouse gases is desirable to reach the ambition of keeping the temperature-rise below 1.5 ºC.

Within literature, multiple studies focus on optimizing the process of designing with reusable elements. In Table 4.1, different characteristics of these researches are displayed.

Author	Brutting et al. [7]	Van Gelderen [35]	Brutting et al. [9]	Brutting et al. [8]	Kim et al. [20]
Topic	Truss Structures	Truss Structures	Reticular Structures	Frame Structures	Noise Barrier Tunnel
Retrieve from	Electric Pylon	Building	Building	Building	Noise Barrier Tunnel
Apply to	Roof	Truss	Truss	Building	Noise Barrier Tunnel
Objective	Reduce structural mass and maximize element capacity utilization	Minimize volume and maximize average unity check and reuse percentage	Minimize environmental impact	Minimize environmental impact	Minimize CO_2 emissions, minimize total costs

Table 4.1: Different research regarding optimization with reusable elements

As shown in Table 4.1, the research of Brutting et al. ([7], [9], [8]) focuses on the minimization of the environmental impact of different structures. In [7] the shape of the structure transforms due to topology and geometry optimization, with the reduction of structural mass and a maximization of element capacity utilization as the goal. Also the research of Van Gelderen [35] focuses on truss structures, where in this research the goal is to minimize volume and maximize average unity check and reuse percentage.

In more recent research of Brutting et al. ([9], [8]) the structure's geometry remains unchanged, however the cross-sections of the different members change to cross-sections available from stock whenever this is possible within the limits given. Within the research of Kim et al. [20], the focus lies on minimizing both the environmental impacts and the costs. In Section 4.3, the different optimization processes used within the named researches are described to provide a clear overview of the different steps.

4.3. Optimization processes

4.3.1. Truss structures (1)

In the research 'Design of Truss Structures Through Reuse' Brutting et al. [7] perform an optimization on both topology and geometry, as visible in Figure 4.2. In this research, a two-step algorithm is used. First, the element assignment and the topology optimization are performed after which the geometry optimization takes place. This is repeated until a certain convergence is reached. This is the case when successive iterations do not result in further waste or mass reductions.

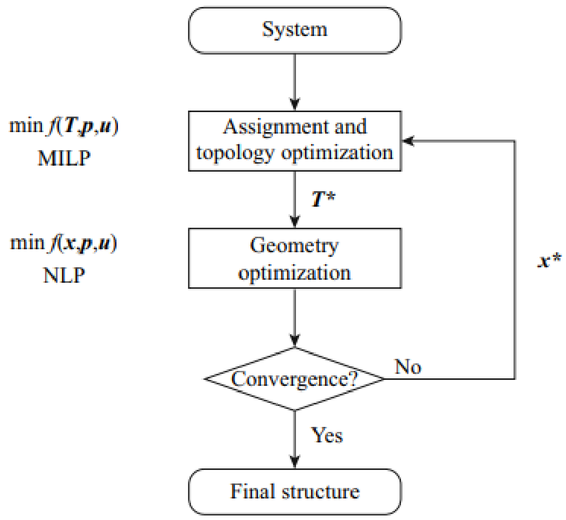


Figure 4.2: Methodology in the research of Brutting et al. [7]

As visible in Figure 4.2, the first step is to assign elements to the geometry. This is done using matrix $T \in \{0,1\}^{mxs}$, where m is the amount of possible beam positions. If there is an element from stock group j at position i in the structure $t_{i,j} = 1$. The stock includes different elements divided in s element groups based on different properties. The system topology is changed when at a certain position no element is located. Equation 4.1 and 4.2 [7] assure that there is a maximum of one assignment per position i which originates from one of the available element groups j.

$$\sum_{j=1}^{s} t_{i,j} \leq 1 \forall i = 1...m \tag{4.1}$$

$$\sum_{i=1}^{m} t_{i,j} \leq 1 \forall j = 1...s \tag{4.2}$$

$$t_{i,j} \in \{0,1\} \forall i,j$$

As stated in Table 4.1, the aim of this optimization process is to reduce the structural mass M of the structure and therefore to maximize element capacity utilization [7].

$$\min_{T,p,u} M(\boldsymbol{T}) = \bar{l}^T \boldsymbol{T}(a \circ \rho) \tag{4.3}$$

$$\boldsymbol{B}\boldsymbol{p}^{(k)} = \boldsymbol{f}^{(k)} + \boldsymbol{D}\boldsymbol{T}(\boldsymbol{a} \circ \boldsymbol{y}) \forall k \tag{4.4}$$

$$\boldsymbol{b}_i^T \boldsymbol{u}^{(k)} \sum_{j=1}^{s} \frac{e_j a_j}{\bar{l}} t_{i,j} = p_i^{(k)} \forall i,k \tag{4.5}$$

$$-\boldsymbol{T}(\boldsymbol{a} \circ \boldsymbol{\sigma}) \leq \boldsymbol{p}^{(\boldsymbol{k})} \leq +\boldsymbol{T}(\boldsymbol{a} \circ \boldsymbol{\sigma}) \forall k \tag{4.6}$$

$$-\sum_{j=1}^{s} t_{i,j} p_{i,j}^{buck} \leq p_i^{(k)} \forall i,k \tag{4.7}$$

$$\boldsymbol{u}^{(k)}_{min} \leq \boldsymbol{u}^{(k)} \leq \boldsymbol{u}^{(k)}_{max} \forall k \tag{4.8}$$

$$\bar{l}_i \sum_{j=1}^{s} t_{i,j} \leq \sum_{j=1}^{s} t_{i,j} l_j \forall i = 1...m \tag{4.9}$$

In the Equations 4.3, 4.4 and 4.6, the design variables of the assignment matrix $\boldsymbol{T}$ are used. The Equations 4.5 to 4.7, include the state variables $\boldsymbol{p}^{(k)} \in \mathbb{R}^m$. The nodal displacements $\boldsymbol{u}^{(k)} \in \mathbb{R}^d$ are included in Equation 4.8. This vector has size d, referring to the number of free degrees of freedom.

In Equation 4.3, the structural mass of the truss is calculated. This is done by multiplying the length of each element $\bar{\boldsymbol{l}} \in \mathbb{R}^m$, the cross sectional areas $\boldsymbol{a}$ and the material densities ρ, which are assigned through $\boldsymbol{T}$. In Equation 4.4, static equilibrium of forces at the different nodes is guaranteed. $f^{(k)} \in \mathbb{R}^d$ resembles the vector of static external forces and $\boldsymbol{B} \in \mathbb{R}^{dxm}$ the equilibrium matrix. The addition of self-weight is assured by multiplying matrix $\boldsymbol{D} \in \mathbb{R}^{dxm}$, the area of the associated cross sections $\boldsymbol{a}$ and the corresponding weights $\boldsymbol{y}$. Half of the element lengths $\bar{\boldsymbol{l}}$ are included in matrix $\boldsymbol{D}$, located at the corresponding vertical degrees of freedom at member ends. Equation 4.6 ensures that these member forces do not exceed the allowable stress. In Equation 4.7 local member buckling is considered and it is checked whether the forces are below the allowable force. Equation 4.8 assures nodal displacements are within serviceability limits. Lastly, Equation 4.9 gives the certainty that the assigned elements are either equal of longer than the original lengths.

After the element assignment and the topology optimization are finished, the result $T*$ is obtained. In the result $T*$ not all elements are connected to others, since it is possible that the length of the element does not match the distance between the nodes. Therefore, geometry optimization is performed where the distances between the nodes vary by changing the nodal coordinates $\boldsymbol{x}$. In the end result, the distances match with the length of the assigned elements. This procedure is described in the publication Optimization Formulations for Design of Low Embodies Energy Structures Made from Reused Elements [5].

4.3.2. Truss structures (2)

In the research of Van Gelderen [35], Truss Topology Optimization with Reused Steel Elements, the member adding scheme of He et al. [18] has been used as a basis. This method is based on the ground structure method; a method to perform topology optimization. The first step of this method is to define the design space and placing the nodes within these boundaries. The next step is to create all possible connections between the nodes. The solution with the minimal volume is chosen as the optimal result. However, this methodology results in a long computational time. When the number of nodes grows, the number of possible connections between all of these nodes also increases, resulting in many different possibilities for the end result.

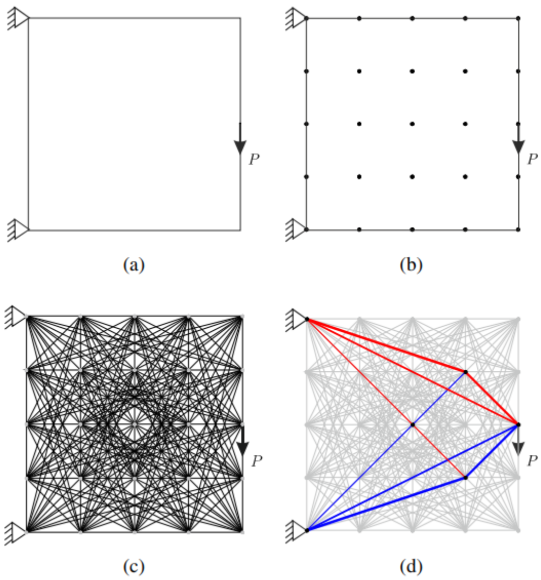


Figure 4.3: The Ground Structure Method [18]

The method of He et al. [18] used in the research of Van Gelderen [35], results in a lower computation time. In this adaptive 'member adding scheme' a reduced ground structure (initial connectivity) and a 'possible member list' are formed. In the first iteration, the topology of the initial connectivity is optimized, after which the volume of the cross sections are minimized and the nodal displacements are calculated. After the displacements are known, the virtual strain for each element in the 'possible member list' can be calculated. The members with the highest virtual strain are added to reduced set of members. At some point, no violation of virtual strain occurs, resulting in the final optimized design with the minimal volume.

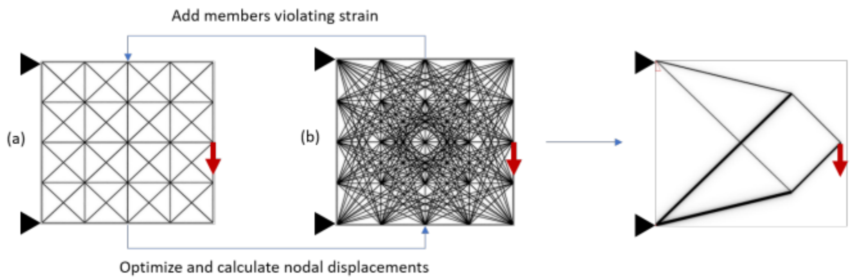


Figure 4.4: The adaptive 'member adding scheme': a) initial connectivity, b) possible member list and c) the final design [35]

This described method works for new elements. However, when working with reusable elements only, this method has to undergo certain changes. Van Gelderen [35] added different steps. First, the structure is calculated as described above, after which the members in the optimized structure are replaced by available elements in stock. Members which cannot be replaced remain new. After this step, the displacements are calculated and the designs are verified for requirements for virtual strain, maximum unity check, minimum efficiency and reuse percentage. After this step has been completed, inefficient design or designs in which new elements are present are penalized which withholds them from returning in the optimization process. The final step is to add members again for which violation of strain occurs. When all the requirements are met, the optimized structure is presented.

4.3.3. Reticular structures

In this work of Brutting et al. [9], the environmental impact of reticular structures is minimized. Compared to the previous mentioned research of Brutting [7], this study allows elements to be cut into multiple useful parts instead of one. The result is an increase in solution space. As also done in previously discussed research, the optimization process starts with the element assignment process. The entries of the assignment matrix $\mathbf{T} \in \{0,1\}^{mxs}$ (where s is the size of the stock together with the available new elements) are formulated according to the following procedure:

$$t_{i,j} = \begin{cases} 1 & \text{if member } i \text{ is part of the structure, either as the result from applying a reusable element} \\ & \text{to this position } j \in \mathbb{R} \text{ or by producing a new element with an adequately dimensioned} \\ & \text{cross-section for its position } j \in \mathbb{N} \\ 0 & \text{if member } i \text{ is not part of the structure} \end{cases}$$

To make sure there is an element on each location, Equation 4.10 [9] is drawn up.

$$\sum_{j=1}^{s} t_{i,j} = 1 \forall i = 1...m \tag{4.10}$$

Another set of design variables is defined $y_{j\in\mathbb{R}} \in \{0,1\}$. This shows if members are cut out of stock elements.

$$y_{i,j} = \begin{cases} 1 & \text{element } j \in \mathbb{R} \text{ is used to produce one or more members for the structure} \\ 0 & \text{element } j \in \mathbb{R} \text{ is not used to produce a member for the structure} \end{cases}$$

Equation 4.11 [9] assures that not more elements can be cut from one element than the available length allows.

$$\sum_{i=1}^{m} t_{i,j} = 1 \forall j \in \mathbb{R} \tag{4.11}$$

Compared to the previously mentioned research by Brutting et al. [7], the objective of the optimization process changes. In this research discussed in this Section [9], the objective is to minimize the 'environmental costs'. The objective is displayed in Equation 4.12.

$$\min_{\boldsymbol{y},\boldsymbol{T}} \sum_{j\in\mathbb{R}} c_j \cdot y_j + \sum_{j=1}^{s} \sum_{i=1}^{m} c_{i,j} \cdot t_{i,j} \tag{4.12}$$

Different structural optimization constraints are added to complete the formulation. These constraints are related to maximum stress, nodal displacements and deformation of the elements, member buckling and the equilibrium of forces.

4.3.4. Frame structures

In the next research which will be discussed, performed by Brutting et al. [8], the end result is a frame structure. Where truss structures are only subjected to normal force, frame structures are subjected to moments, shear force and normal force. This has an effect on the optimization process. In this study Brutting et al. [8] compare two different approaches to optimizing with reusable elements. The first approach is called *1-to-1* assignment of stock elements, the second approach is called the *cutting stock* approach. In the first approach, one reusable element can be used for one member. In the second approach one reusable element can form the basis for multiple new members. In Figure 4.5 the two different approaches are shown. The original stock elements are indicated in grey, the new members in black. The difference between the length of the grey and the length of the black bar is the cut-off length.

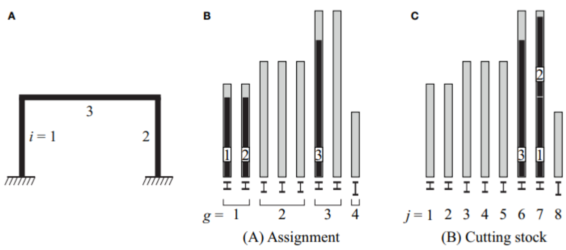


Figure 4.5: Comparison of the *1-to-1* assignment and *cutting stock* approach [8]

In this research, two optimization methods are discussed: *1-to-1* assignment approach and the *cutting stock* approach. The assignment of stock elements for *1-to-1* assignment approach is formulated by the following Equations [8].

$$\min_{\boldsymbol{t}} \sum_{i=1}^{m} \sum_{g \in S} t_{ig} c_{ig}^{A} \tag{4.13}$$

$$\sum_{g \in S} t_{ig} = 1 \forall i = 1...m \tag{4.14}$$

$$\sum_{i=1}^{m} t_{ig} \leq n_g \forall g \in S \tag{4.15}$$

$$\bar{l}_i \leq \sum_{g \in S} t_{ig} l_g \forall i = 1...m \tag{4.16}$$

The member position is indicated with i, the element stock group with g. When there is an element assigned to a specific position of a specific group, $t_{ig} = 1$, otherwise $t_{ig} = 0$. The vector t presents where the members are located. The objective is to minimize the amount of 'costs' c_{ig}^{A} associated to assignment t_{ig}. Equation 4.14 ensures that a stock element is assigned to each member. In Equation 4.15 the number of usable stock elements is constrained to the number of available elements. In the last Equation, 4.16, the length of an assigned stock element to a member can only be equal or larger than the length of the member itself.

For the *cutting stock* approach, the formulation of the Equations 4.13 to 4.16 need to be extended since the goal for this approach is to be able to cut the elements in multiple useful members. Where in the *1-to-1* approach elements can be divided in groups, this approach requires an individual assessment per element. New variables are introduced to the problem (as also seen in the previously discussed research [9]) $y_j \in \{0, 1\}$. When $y_j = 1$ the element is at least partly used and when $y_j = 0$ the element is not used at all. The extended element assignment-procedure is shown in Equations 4.17 to 4.19 [8].

$$\min_{\boldsymbol{t},\boldsymbol{y}} \sum_{j \in S} y_j c_j^{B} + \sum_{i=1}^{m} \sum_{j \in S} t_{ij} c_{ij}^{B} \tag{4.17}$$

$$\sum_{j \in S} t_{ij} = 1 \forall i = 1...m \tag{4.18}$$

$$\sum_{i=1}^{m} t_{ij} \bar{l}_i \leq y_j l_j \forall j \in S \tag{4.19}$$

To complete the discussed formulations, structural constraints need to be applied. Formulations of these equations are based on the formulations of Mellaert et al. [37].

In the research of Mellaert et al. [37], size optimization is performed on frame structures using a mixed-integer linear programming approach. The benefit of this approach compared to e.g. stochastic algorithms is the ability to find the global optimum. As mentioned before, the difference between the optimization of trusses and the optimization of frames is the presence of shear forces and moments. Besides, the stress resultants vary along the member and the stress resultants come from both normal force and moments. Moreover, nodal rotations need to be considered. Therefore, this process is more complex since it includes more complex resistance constraints and an increase in the number of state variables.

The result from the structural analysis is a frame structure with optimized steel members. However, this system is used for 2D structures resulting in the need for the structures to be calculated from two different sides. Therefore, two different analysis have to be performed.

4.3.5. Noise barrier tunnels

The research of Kim et al. [20] has a different set up since this research has multiple objectives: minimizing CO_2 emissions and minimizing costs. The methodology of the research consists of four steps:

- The creation of a design, in this case a design for a noise barrier tunnel (NBT).

- The development of a new design by combining the first design with reusable elements originated from a disassembled NBT. In this research, the design of the structure is divided in four different pieces, as displayed in Figure 4.6. Every component is labeled $I_{m,n}$, where n refers to the kind of beam, and m refers to the source of the beam, where the source can be different kinds of other NBTs.
- A component procurement plan is created for the design.
- The CO_2 emissions and the costs of the structure are analyzed and afterwards minimized to come up with the optimal solutions.

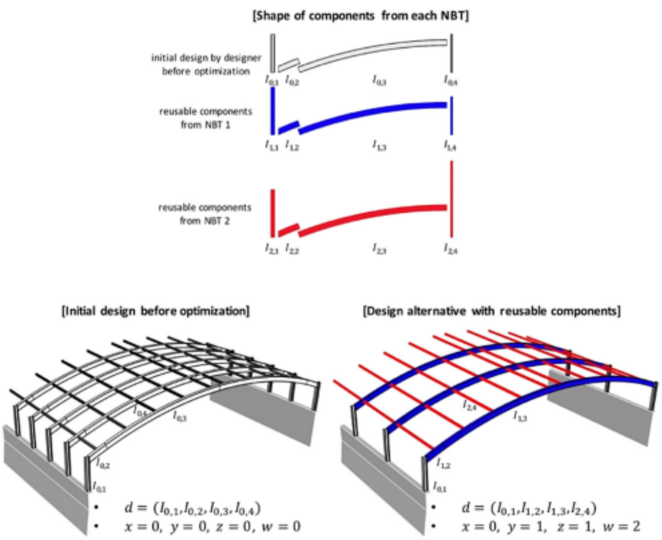


Figure 4.6: Division of the structure into four different parts [20]

The optimization is performed by a NSGA II algorithm. This is a genetic algorithm and it therefore follows the following steps: (1) Generate an initial population, (2) evaluate the objective function, (3) generate child population, (4) Constraint check and penalization and (5) Check stopping criteria.

4.4. Conclusion

The literature study performed Chapter 4 results in certain conclusions which can become useful in the next part of this research.

1. An optimization problem needs have a goal which can be quantified by an objection function. This goal can be reached by changing the value of certain design variables, while respecting constraints. Therefore the objective, the design variables and the constraints in an optimization problem need to be clear.
2. An optimization problem in which reusable elements are involved is different compared to the an optimization problem in which it is possible to use every element available on the market. The types of element which can be used as structural members of the geometry are limited by the available stock.
3. In most of the discussed research, the method used consists of steps:
   (a) Geometry definition
   (b) Element assignment
   (c) Structural calculations
   (d) Optimization

5

Formulation of the Model

The aim of this research is to develop an optimization process that modifies the design of a load-bearing structure to implement reusable elements, in order to minimize the amount of new steel required to realize this structure. However, there are certain architectural and structural constraints the outcome should respect. The analyzed literature in Chapter 4 provided an insight in the desired set up of the model consisting of this optimization process. In most of the research where similar models were developed, different steps could be distinguished. Apart from optimization itself, the steps included:

1. Geometry definition
2. Element assignment
3. Structural calculations

There is no software package known to the author that allows all the steps discussed and it was therefore decided to write a script using the coding language Python. In this case, the transfer of information between different software packages is avoided, which facilitates the optimization process.

In Figure 5.1, an overview of the model is given in which the steps described above can be recognized. Different stages of the model are shortly outlined in the text below.

- **Geometry definition** The geometry is defined by implementing a list of nodes and a list which clarifies the connections between these nodes. These connections represent the beam-configuration. These characteristics serve as an input for the model. Hereafter, the model starts running to determine the amount of triangles, quadrilaterals and pentagons in the beam-configuration. This information is required for a later stage, when the end result will be formulated.
- **Implementation of the stock** The stock consists of different groups of equal elements. The group is defined by the length of the elements, the profile of the elements, the structural material of the elements and the number of elements of which the group consists.
- **Initial load calculation** First, the distributed load acting on each beam has to be quantified. After this is known, the corresponding moments, shear forces and normal forces can be determined per beam or column.
- **Structural requirements** To function as a proper load-bearing structure, the load-bearing structure has to fulfill certain structural requirements provided by the Eurocode. For this reason, multiple checks will be performed:
  - Moment resistance of the beams
  - Shear resistance of the beams
  - Deflection of the beams
  - Normal force resistance of the columns

  - Buckling resistance of the columns

  Another point of attention is the aim is to design an efficient structure. Therefore the goal is to assign reusable, available profiles in a way that the summation of all the corresponding UC-values is the highest possible.

- **Architectural requirements** As a starting point, the designer can implement certain architectural requirements in the model:
  - The minimum UC-value the elements implemented in the design can have.
  - The maximum percentage the length of a potentially applicable reusable element available in stock can deviate from the original element located at this position.
- **Element assignment** The element assignment-procedure consists of two steps: the assignment of beams and the assignment of columns. The difference between the two steps is further explained in Section 5.4 and Section 5.5.
- **Formulation of the end result** As a result of the model, multiple options are presented. Designs with the same element-configuration require the same amount of new steel to realize the design. However, these designs can be distinguished by the mean UC-value of the beams, the mean UC-value of the columns, the minimum angle between two beams, the number of changing angles and the number of angles changing more than 10%.

In next paragraphs, these different stages of the model are described more elaborately.

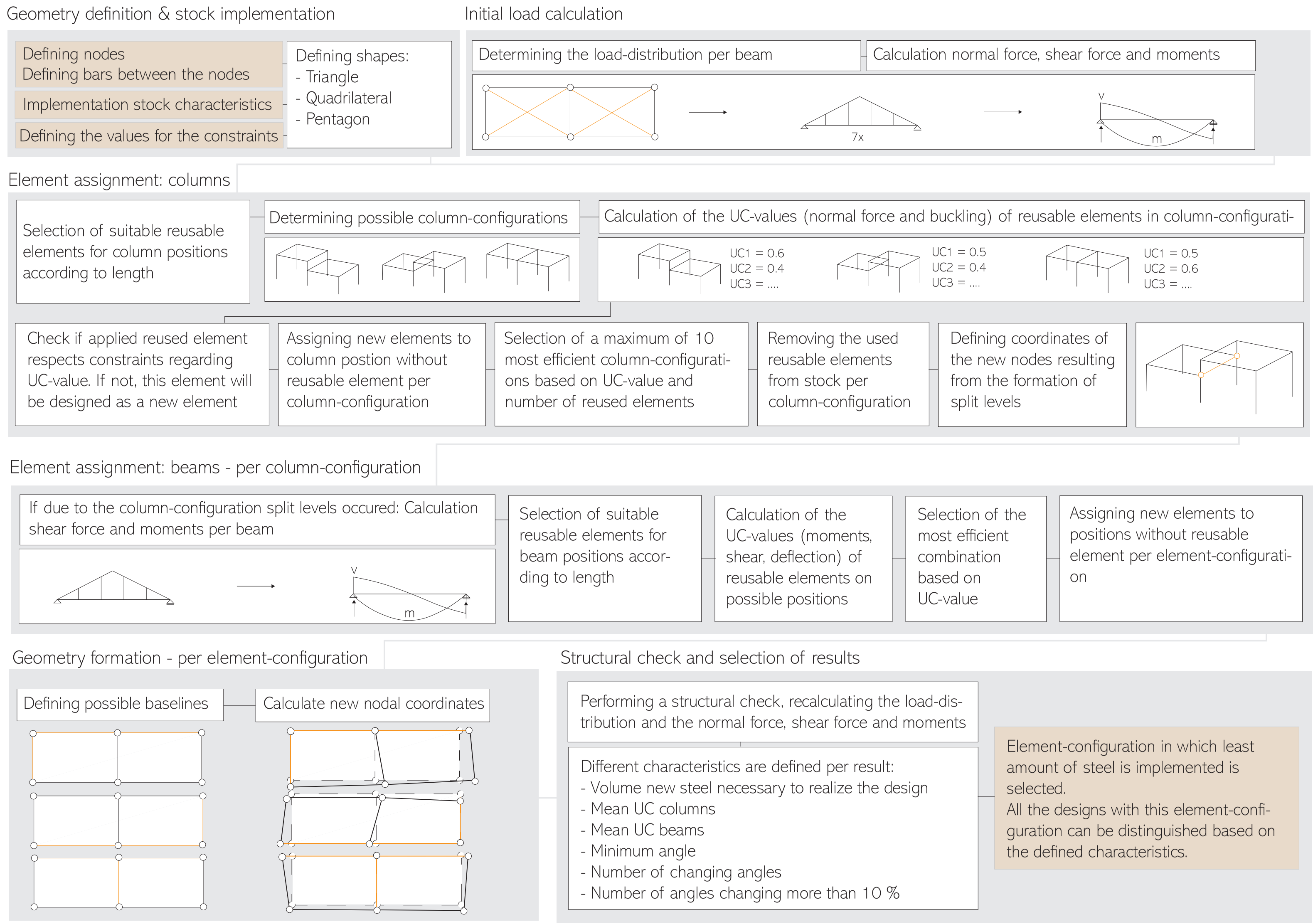


Figure 5.1: Steps in the model

5.1. Optimization objective, design variables and constraints

As discussed in Chapter 4, the three fundamental points of an optimization problem are the objective function, the design variables and the constraints [24]. For this study, these fundamental points can be formulated as follows:

- **Objective function** To minimize the amount of new steel necessary to realize the design of a steel load-bearing structure.
- **Design variables**
  - Nodal coordinates of the geometry: The nodal coordinates are continuous design variables since every possible position is allowed.
  - The cross-sectional areas of the structural members implemented in the design: The cross-sectional areas are discrete variables. At first, the aim is to assign available structural reusable elements in stock to different positions in the geometry. Therefore, not every cross-sectional area is available. If there is no suitable reusable element available for a position in the geometry, a new element will be assigned to this position. The range of possible cross-sectional areas increases. However, this range is still dependent on the profiles available on the market, and therefore this is still a discrete design variable.
- **Constraints**
  - Structural constraints: the UC-values of the elements implemented in the design have to be below 1.
  - Architectural constraints:
    - ◇ The minimum UC-value the elements implemented in the design can have.
    - ◇ The maximum percentage the length of a potentially applicable reusable element available in stock can deviate from the original element located at this position.

5.2. Geometry definition and stock implementation

5.2.1. Geometry

The beam-configuration of the structure is defined by a list of coordinates. These coordinates represent the nodes in the structure. In the nodes, multiple members of the load-bearing structure are connected. A member is defined by the two nodes which represent its end-points. These two nodes form one entry for the list which defines all the members present in the structure. A simple example of the lists defining the nodes and the members (bars) of the structure is given in Figure 5.2.

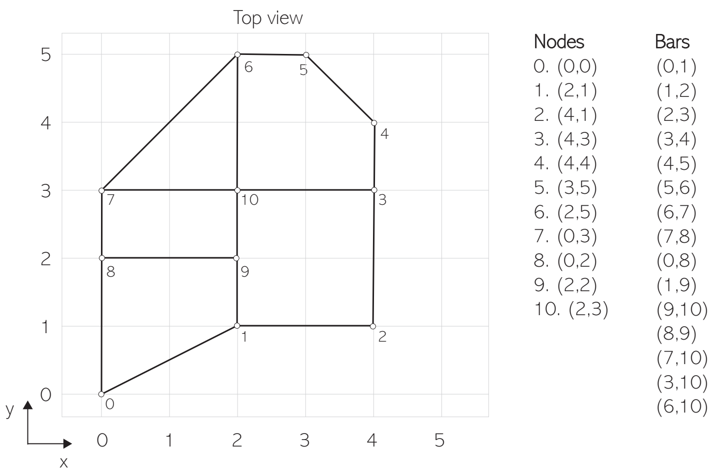


Figure 5.2: Example geometry - beam-configuration

In this study, a structure can consist of one level. The height of this level is defined by a parameter. The resulting structure is a beam-configuration at the height defined by this parameter. Below each node, a column is located.

The example used in this Chapter has the beam-configuration of Figure 5.2. The parameter defining the height of the structure is set to 3 meters resulting in the structure displayed in Figure 5.3. On the structure acts a permanent distributed load G of 3.58 (0.2 kN/m^2 self weight steel, 3.08 kN/m^2 self weight concrete slab, 0.3 kN/m^2 insulation + roof coverage) and a distributed variable load Q of 1 kN/m^2 (maintenance). For calculations related to the Serviceability Limit State (SLS), a load of $G+Q$ is used. In this study, this load-combination is used when calculating the deflection in each beam. For all other calculations the load-combinations related to the Ultimate Limit State (ULS) is used, resulting in a load of $1.2*G+1.5*Q$.

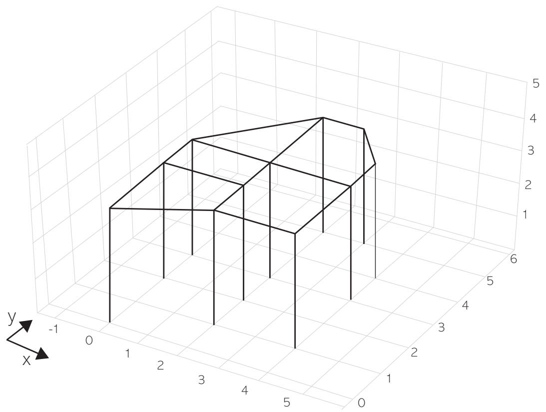


Figure 5.3: Example geometry - actual structure

Besides the implementation of the geometry, the architectural constraints discussed in Section 5.1 need to be defined in this stage. For the example presented in this Chapter, the following values for the parameter have been chosen.

- **Minimum UC-value** 0.01
- **Maximum deviation in length between the original member and the reusable element** 10%

After the geometry and the constraints have been specified, the different shapes in the beam-configuration need to be defined to be able to follow the method which will be described in Section 5.6. A distinction is made between a triangle, a quadrilateral and a pentagon.

The method used to distinguish the different shapes is based on studying the connections between the different nodes. To define a triangle, a closed loop of three different nodes has to be identified. For this example, the loop looks as follows: 6 - 7 - 10 - 6. To determine if a shape is a quadrilateral, a closed loop of four different nodes is necessary, for this particular case 8 - 7 - 9 - 10 - 8 and 0 - 1 - 9 - 8 - 0. For the pentagons, a closed loop of five different nodes needs to be retrieved, 10 - 3 - 4 - 5 - 6 - 10 and 10 - 3 - 2 - 1 - 9 - 10. The different shapes and their corresponding loops are displayed in Figure 5.4.

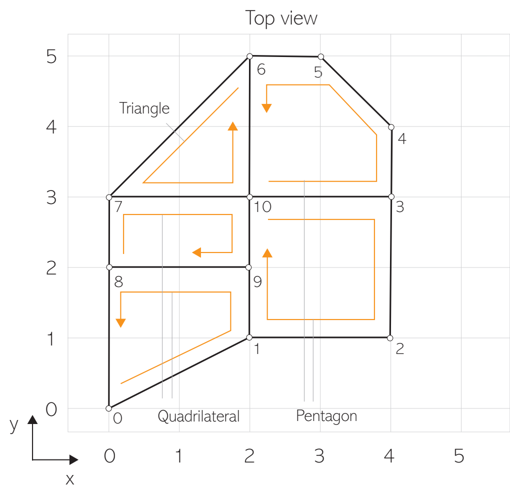


Figure 5.4: Shapes in the beam-configuration

5.2.2. Stock implementation

In the model, the stock is implemented using a .json file. In this file, every group with similar members is defined by their length, profile, structural material and the number of elements. The stock used for the example in this Chapter is displayed in Figure 5.5.


```
[
    {
        "Characteristics": {
            "Code": "B1",
            "Type": "HEA160",
            "Length": 4200,
            "Count": 2,
            "Structural Material": "Staal - S235"
        }
    },
    {
        "Characteristics": {
            "Code": "B1",
            "Type": "HEA200",
            "Length": 3200,
            "Count": 4,
            "Structural Material": "Staal - S235"
        }
    },
    {
        "Characteristics": {
            "Code": "B1",
            "Type": "IPE200",
            "Length": 3700,
            "Count": 2,
            "Structural Material": "Staal - S235"
        }
    },
    {
        "Characteristics": {
            "Code": "B1",
            "Type": "HEA160",
            "Length": 1500,
            "Count": 6,
            "Structural Material": "Staal - S235"
        }
    }
]
```


Figure 5.5: Set up of the .json file representing the available stock

5.3. Initial load calculation

To be able to couple reusable elements to the different members of the structure, it is necessary to specify the magnitude of the loads on the members in the original design. Since the shapes are irregular, finding the exact amount of load carried by one specific beam is challenging. In this study it is therefore assumed that the load carried by the beam is represented by the area between the centroid of the adjacent shape and the ends of the beam. The result is a triangular shaped area. For the geometry displayed in Figure 5.2, the resulting triangles are shown in Figure 5.6.

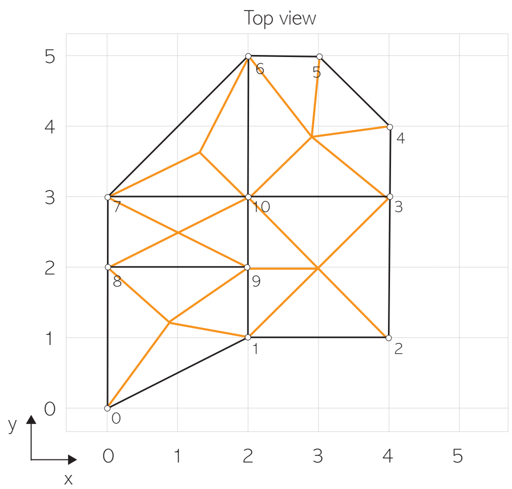


Figure 5.6: Load triangles

To quantify the distributed load and corresponding shear forces and moments acting on each beam different steps have to be performed. Since the area which is carried by each beam is triangular, the resulting distributed load is an unequally distributed, triangular shaped load. The first step is to define a formula that is able to determine the Equation which represents the shape of this distributed load acting on each beam.

The overall formula consists of sub-formulas:

- ***def** SquaredLength(X,Y)*: This sub-formula returns the squared distance between two points. The input are the coordinates (x,y) of two different nodes. As displayed in Equation 5.1 to Equation 5.3 and Figure 5.7 the result of this sub-formula is used in sub-formula ***def** CalculateAngle(A, B, C)*

- ***def** CalculateAngle(A, B, C)*: The function of this sub-formula is to calculate the angles of the triangle resembling the load carried by a beam. This is done by using the Cosine Rule. The input are the different coordinates (x,y) of the three nodes (A, B and C) of which the triangle exists.

$$\cos A = \frac{b^2 + c^2 - a^2}{2bc} \tag{5.1}$$

$$\cos B = \frac{c^2 + a^2 - b^2}{2ac} \tag{5.2}$$

$$\cos C = \frac{a^2 + b^2 - c^2}{2ab} \tag{5.3}$$

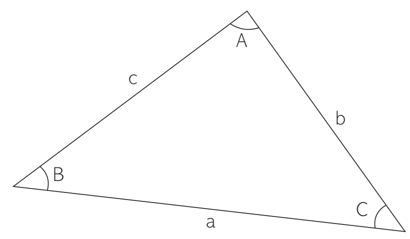


Figure 5.7: Different angles in a triangle

- ***def*** *CalculateArea(x,y)* This sub-formula (Equation 5.4) gives the area of the triangle as a result. The input are the three x-coordinates (x_A, x_B, x_C) and the three y-coordinates (y_A, y_B, y_C) corresponding to the corners of the triangle.

$$area = 0.5abs(x_A(y_B - y_C) + x_B(y_C - y_A) + x_C(y_A + y_B)) \tag{5.4}$$

- ***def*** *CalculateLoad(shape, array)* This is the final sub-formula. As an input, this formula has the coordinates of the shape, and the array which includes the coordinates of the corresponding nodes. First, the different x- and y-coordinates of the shape put in an seperate new array. With these coordinates, a polygon is created. By doing this, the centroid of the Polygon can be identified.
After, every subset of nodes is distinguished. If these nodes are connected to each other by a bar, a triangle will be created between these nodes and the centroid of the polygon. This triangle will be used to define the different characteristics for the load on the beam. First, the different distances between the two nodes and the centroid are identified. Using ***def*** *CalculateAngle(A, B, C)*, the different angles of the triangle are identified. The narrowest corner α (displayed in Figure 5.8) is used as a starting point. By performing the calculation $sin(\alpha) * l_1$, the length of the contourline of the triangle (l_2) can be calculated. If l_2 is multiplied with the acting load, the highest value of load carried by the beam in kN/m is determined. By performing the calculation $cos(\alpha) * l_1$, the distance between the intersection of the contour line and the beam to the corresponding angle (l_3) will be determined. When one knows these characteristics, the gradient of the triangle on both sides can be calculated.

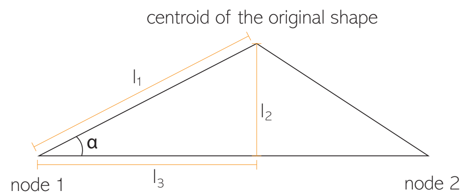
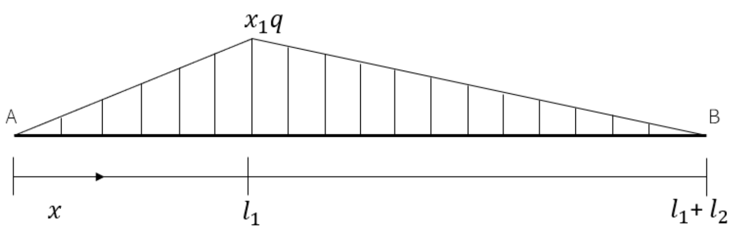


Figure 5.8: Different characteristics of a triangle

Using the method described above, an Equation which represents the shape of the distributed load acting on each beam can be defined. With this Equation, the shear- and moment distribution in each beam can be calculated. For this, a new formula defined.

- ***def*** *CalculateForce(node1, node2, x)* This formula is used for every pair of connected nodes. The Equations displayed in Figure 5.9 form the basis for this formula. For 1000 positions on the beam, the value of moment and shear force on the beam is calculated. In these Equations, q is the distributed load in kN/m, x_1 is the highest load, l_1 is the distance between point A (left end of the beam) and the highest load. l_2 is the distance between point B (right end of the beam) and the highest load. V is the shear force in the beam and M is the moment in the beam.

As mentioned before, the narrowest corner is taken as a starting point of the Equation representing the distributed load (formed by ***def*** *CalculateLoad(shape, array))*. If a beam is carrying load originating from two triangular shapes areas, as displayed in Figure 5.10, the starting point has to be the same to be able to calculate the correct shear forces and moments acting on the beam. When the starting points of the Equations are not equal, the value of the x is transformed into $L-x$ (where L represents the total length) for one of the two Equations representing the shape of one of the two distributed loads acting on the beam.



$$q_x = \frac{qx_1}{l_1}x \qquad 0 < x \leq l_1$$

$$q_x = \frac{-qx_1}{l_2}(x-l_1) + qx_1 \qquad l_1 < x < l_1 + l_2$$

$$V_A = \frac{0.5\, l_1 qx_1\left(\frac{1}{3}l_1 + l_2\right) + 0.5 l_2 qx_1\left(\frac{2}{3}l_2\right)}{l_1 + l_2} \qquad V_B = 0.5\, l_1 qx_1 + 0.5 l_2 qx_1 - V_A$$

Shear

$$V = V_A - 0.5q_x x \qquad 0 < x \leq l_1$$

$$V = V_A - 0.5x_1 ql_1 - 0.5(x_1 q + q_x)(x - l_1) \qquad l_1 < x < l_1 + l_2$$

Moment

$$M = V_A x - \frac{1}{6}q_x x^2 \qquad 0 < x \leq l_1$$

$$M = (l_1 + l_2 - x)V_b - (l_1 + l_2 - x)^2 \frac{1}{6}q_x \qquad l_1 < x < l_1 + l_2$$

Figure 5.9: Formulas used to determine the shear- and moment-distribution

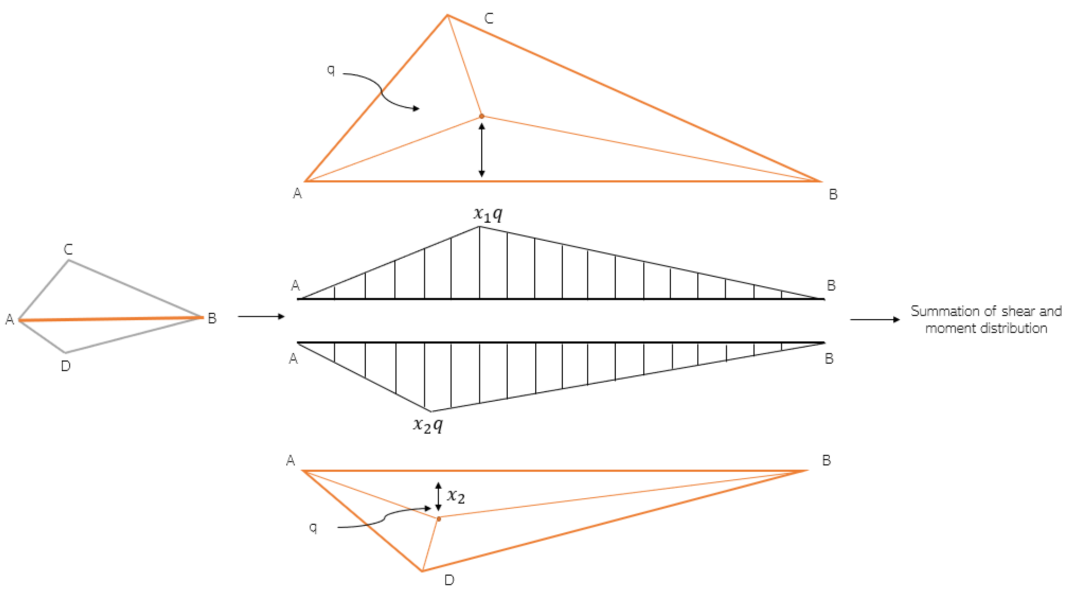


Figure 5.10: The calculation of shear- and moment-distribution in case of two triangles

When the shear- and moment-distribution for each beam is calculated, the shear- and moment-distribution is drawn in a graph. For this example, the lines representing the shear- and moment-distribution are shown in Figure 5.11, where the title of every separate graph is related to the numbers of the nodes between which the member is situated. From these distributions, the maximum value for the shear force and moment in each beam can be determined. Another functionality of the formula is the ability to sum up all the forces going to the columns. In this manner, the normal force in the column can calculated.

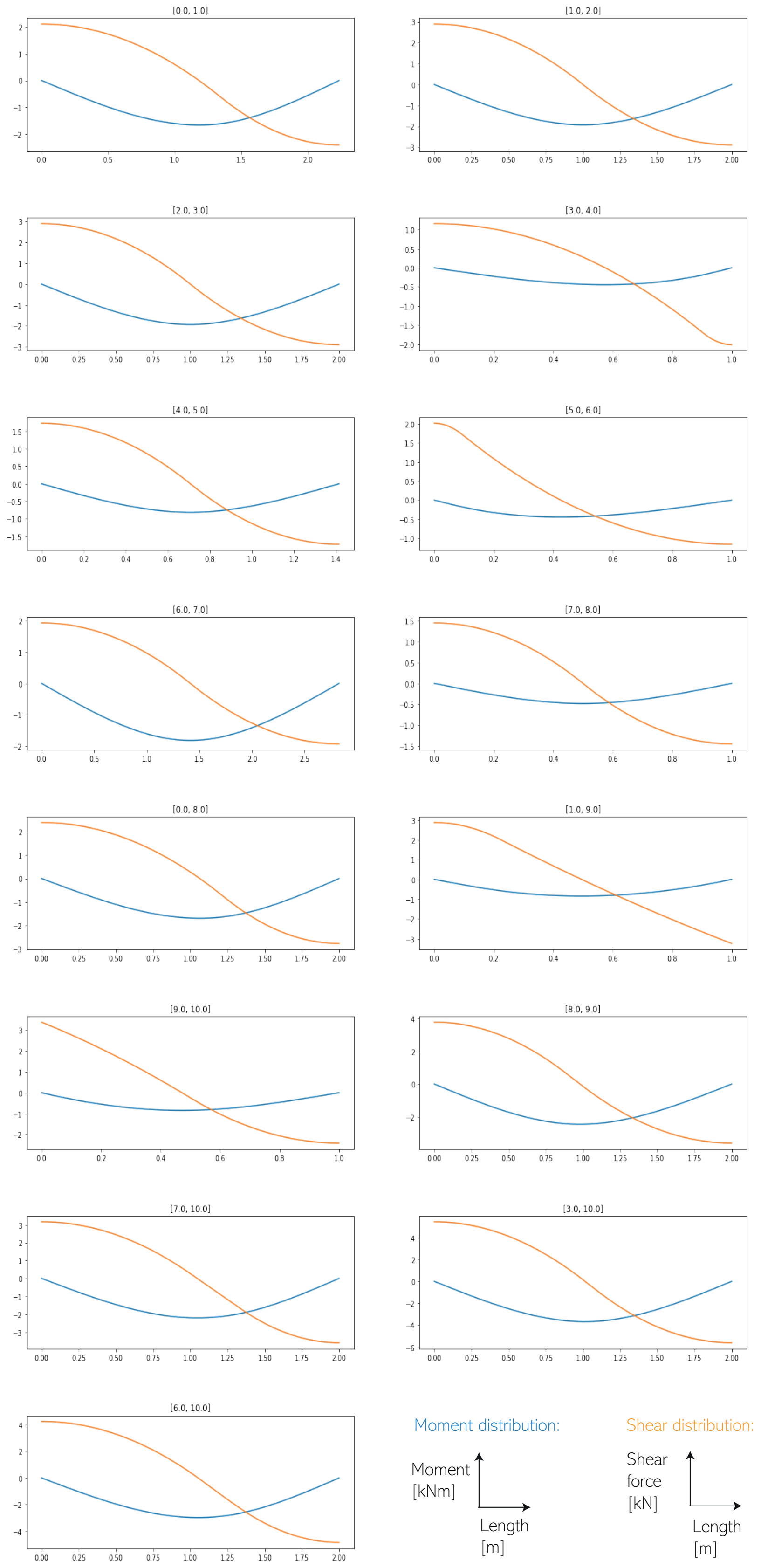


Figure 5.11: Shear- (orange) and moment distribution (blue)

5.4. Element assignment - columns

The first step in the element assignment-process is to determine which of the reusable elements are suitable to function as columns. This is determined by the constraints specified in the beginning of the process; the maximum difference in length and the minimum UC-value allowed.

When the available and suitable columns are selected, the next step is to explore potential locations of these columns. Since the horizontal plane of the structure resembles a floor, it is necessary to keep this horizontal. One shape should therefore remain on the same level to avoid inclined floors (Figure 5.12). However, the application of split levels is possible.

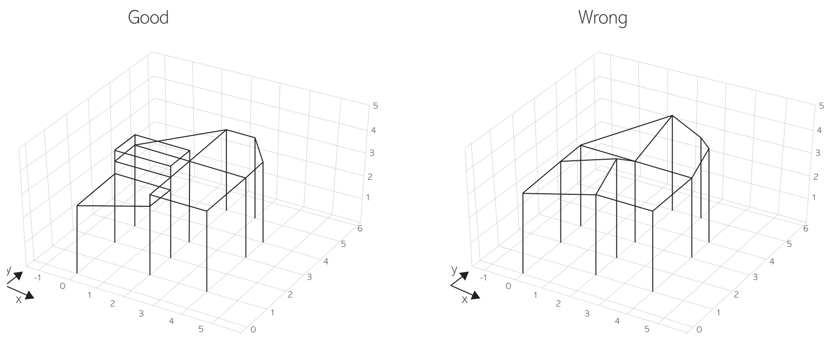


Figure 5.12: Every shape should remain on the same height

To determine which column-configurations fulfill these requirements, the formula ***def*** *PossiblePosition (amount)* is developed.

Before the formula starts to run, it is of importance to sort the selected groups of elements on their length, starting with the longest element. Multiple situations can be distinguished:

1. The number of available elements is lower than the number of columns in the structure.

2. The number of available elements is equal to the number of columns in the structure.

3. The number of available elements is higher than the number of columns in the structure.

For situation 1 and 2, initially nothing will happen to the size of the groups. Situation 3 requires an action. For this case, all possible distributions have to be determined. For example, if the structure requires 8 columns and there are two groups available where the first group has 6 available elements and the second group 5 available elements, divisions could be: 6 elements group 1, 2 elements group 2 or 5 elements group 1, 3 elements group 2 or 4 elements group 1, 4 elements group 2, etc. After all possible divisions have been distinguished, the formula ***def*** *PossiblePosition(amount)* is used for every possible division.

First, the formula is used for the size of the first group. The goal is to find a closed loop of this amount of elements. The numbers of the nodes corresponding to the loop are saved. These numbers represent the location of the elements belonging to group 1. The next step is to find a close loop for the summation of the amount of elements of the first group and the second group. When this is possible, the nodes which were not yet found in the first group resemble the location of the elements from group 2. This process continues until all the elements of this potential configuration are assigned to a location represented by a node number.

In the beginning, the preference is to use all available columns. However, when this is not possible, the second step is to try to find a sequence of connected columns with less elements, starting with the first group. This procedure is explained in Figure 5.13.

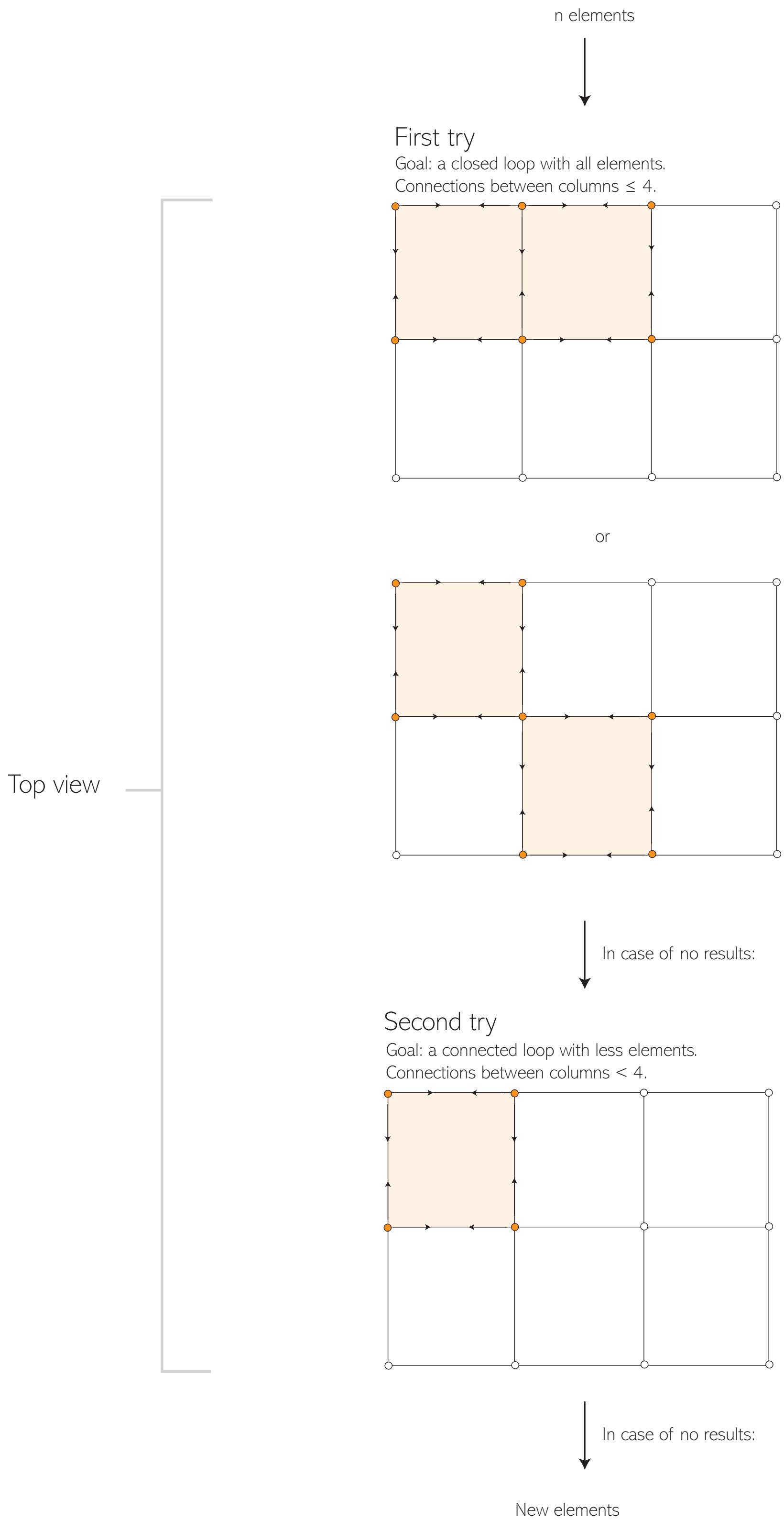


Figure 5.13: Column assignment procedure

This will result in multiple possible column-configurations, and every possibility has to be checked by calculating the corresponding Unity Checks (UC). The UC-values are calculated for normal stress and buckling, by using Equation 5.5 to Equation 5.12 (based on [1]). N_{Ed} is the normal force acting on the column. A is the area of the element assigned to the position of the column. f_y is the yield strength of the column, which is in this case $235N/mm^2$. E is Young's Modulus, which is in this case 210 GPa. I is the second moment of area of the column. Buckling in the strong and weak axis are both calculated. In these calculations, the value for I differs, depending on the axis.

$$\sigma_n = \frac{N_{Ed}}{A} \tag{5.5}$$

$$UC_1 = \frac{\sigma_n}{f_y} \tag{5.6}$$

$$N_{cr} = \frac{\pi^2 EI}{l^2} \tag{5.7}$$

$$\lambda = \sqrt{\frac{Af_y}{N_{cr}}} \tag{5.8}$$

$$\phi = 0.5(1 + \alpha(\lambda - 0.2) + \lambda^2) \tag{5.9}$$

where the value for α is depending on the cross-section of the column. This may vary per axis.

$$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \lambda^2}} \tag{5.10}$$

$$N_{bRd} = \frac{\chi A f_y}{\gamma_{M1}} \tag{5.11}$$

$$UC_2 = \frac{N_{Ed}}{N_{bRd}} \tag{5.12}$$

For every possible configuration, it is checked whether the UC-values respect the architectural and structural constraints. When the number of available reusable elements (respecting the constraints) is known, multiple possibilities can be used for defining the final geometry. These possibilities are explained in Figure 5.14 and Figure 5.15.

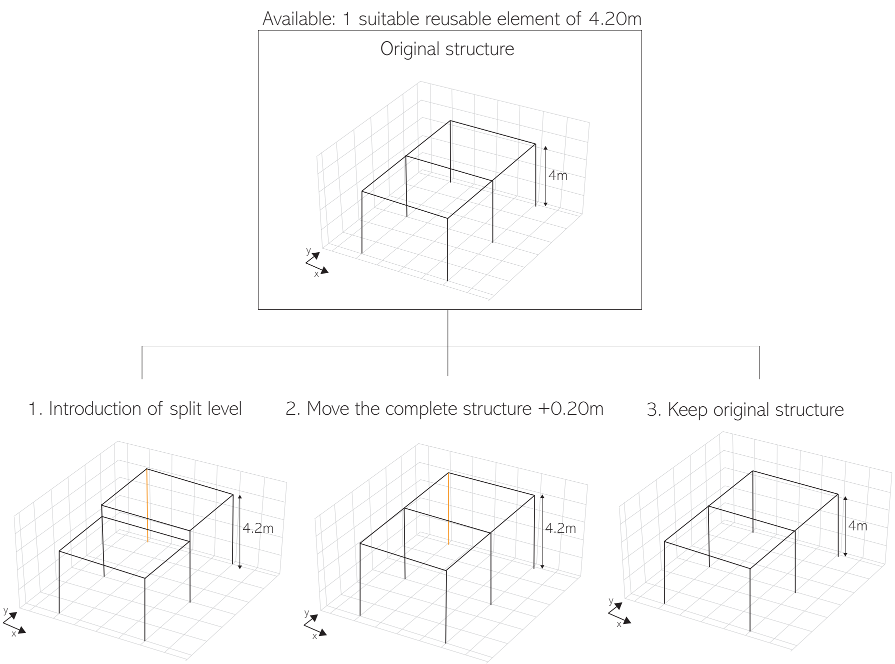


Figure 5.14: Possible column-configurations based on the availability of one reusable element (orange = reused element)

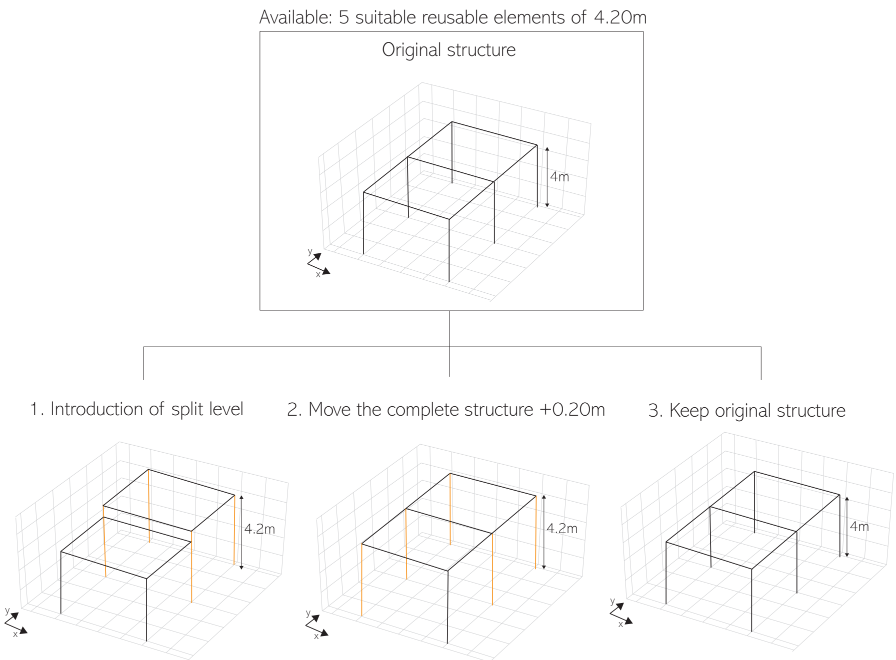


Figure 5.15: Possible column-configurations based on the availability of five reusable elements (orange = reused element)

It is decided to take a look per separate shape. Whenever the length of the reusable element is not equal to the length of the original element, an additional bar may be required because of the creation of a split level. The new steel which is required to create this beam, needs to balance with the amount of new steel saved when replacing the original columns with reused columns. Whether applying a split level results in less required steel, is depending on the geometry (height of columns and length of beams) and the loads acting on the columns and beams (sizes of profiles). In this thesis, it is decided to only apply a split level of all the columns in the shape can be reused elements. However, applying these reused columns still does not guarantee that the amount of new steel required to realize the structure lowers. Therefore it is necessary to include the option where all the columns are made of new elements of the original length.

After all reusable elements are assigned, new elements are assigned to members without a corresponding reused element. The goal is to assign an element which results in an UC-value closest to 1 possible to make sure the profile is suitable for the loads carried by the column, resulting in no waste of steel.

The outcome is a list of potential column-configurations. The goal is to choose the most efficient configurations. To be able to calculate the efficiency of each structure, the UC-values of the elements are summed up. However, for the new elements, a value of -10 is chosen to make sure these are not considered efficient. To limit the computation time in this study, the ten most efficient combinations are used for further calculations.

The elements used for the different column-configurations are removed from the stock. For assigning profiles to the horizontal members, the updated stock is used.

5.5. Element assignment - beams

After the new heights for the columns are defined, new nodes are created and bars (beams) need to be added to the structure to remain the structural feasibility. One possible column-configuration is displayed in Figure 5.16, where the new beams and nodes are indicated. The new indices of the nodes are shown in Figure 5.17.

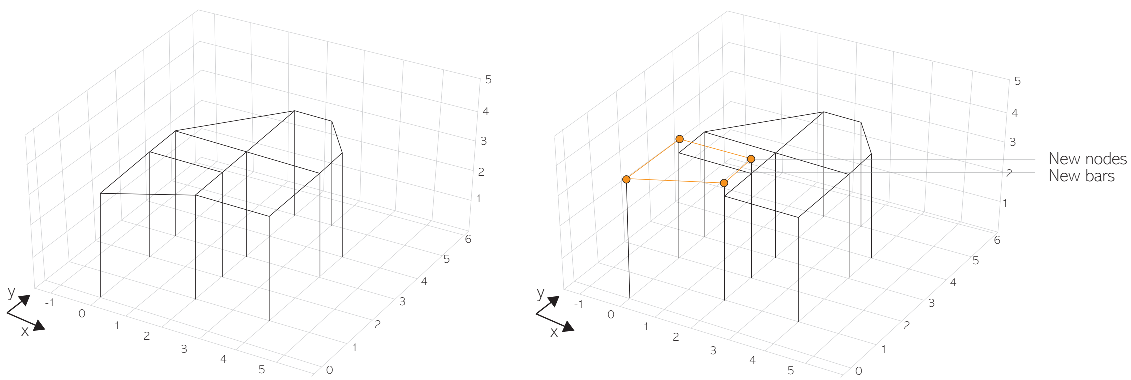


Figure 5.16: New nodes and new beams are created after changing the column-configuration

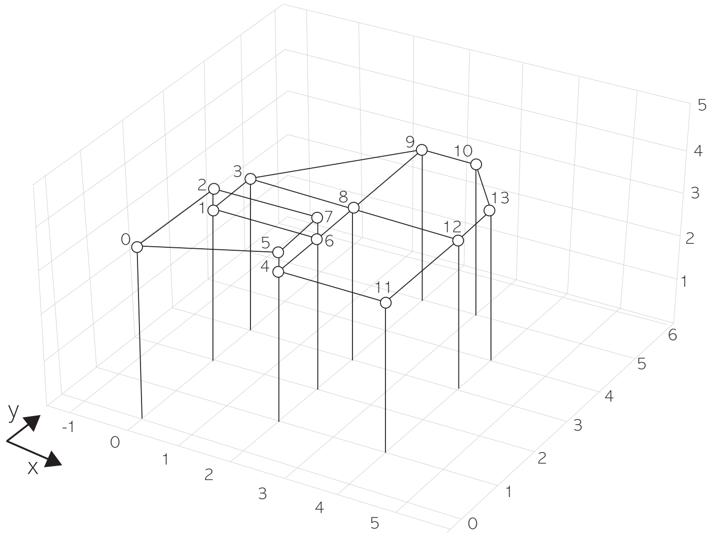


Figure 5.17: New indices corresponding to the nodes

After the new nodes and the new bars are added to the structure, the Formula ***def*** *CalculateForce(node1, node2, x)* is used again. Where originally one beam carried the load of two sides, this is changed due to the addition of the new beam. The new moment and shear-distribution are displayed in Figure 5.18. The title of each subplot indicates the nodes to which the bar is connected.

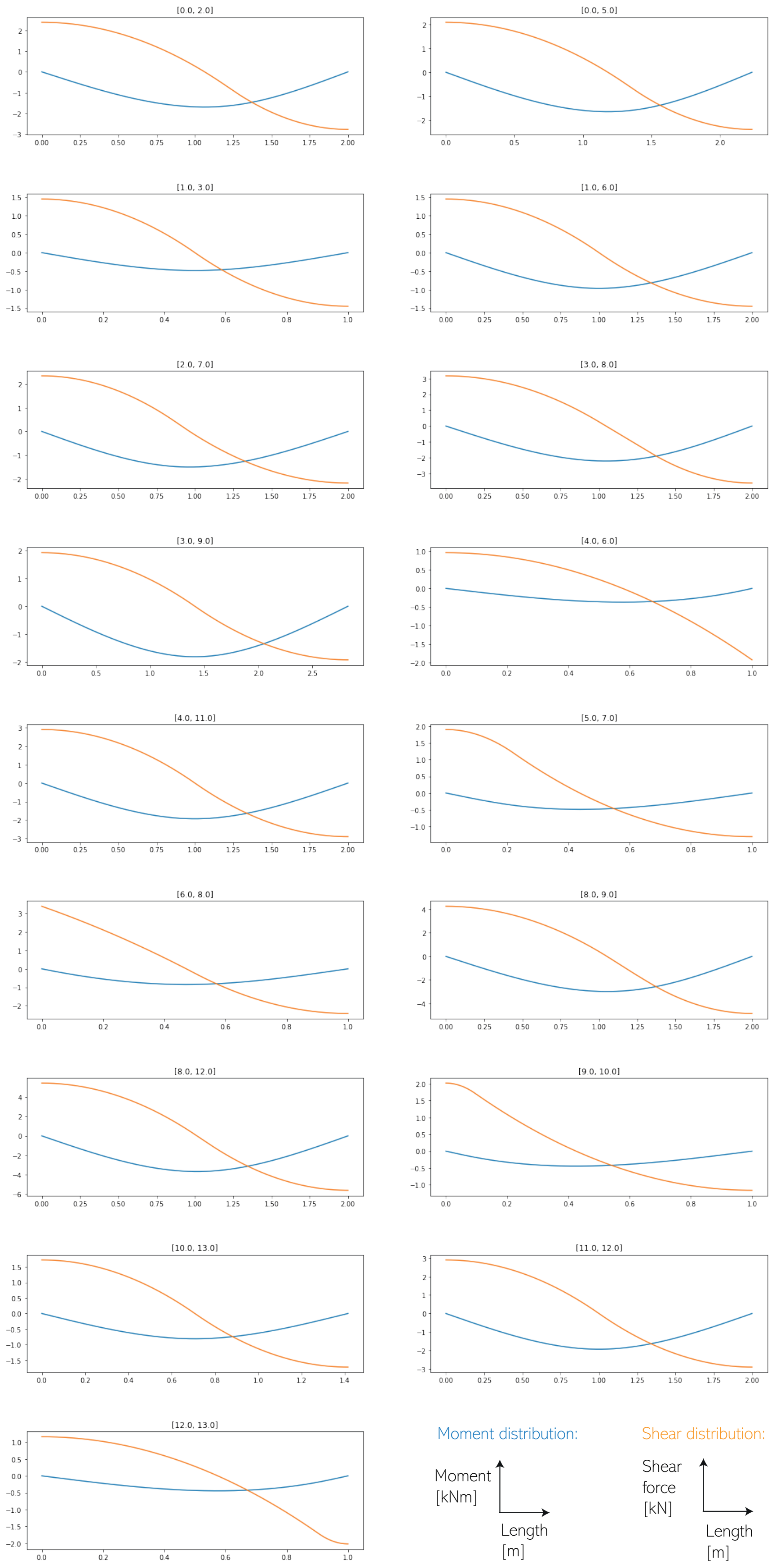


Figure 5.18: Shear- (orange) and moment distribution (blue)

Since the new geometry is known, it can be checked whether there are suitable reusable elements available to replace the original beams in the structure. In the text below, the procedure of element assignment for beams is explained:

- First, suitable reusable elements are selected. To do this, the architectural constraints provided by the designer are used. Per member of the structure, every suitable element is temporarily assigned to this location to calculate the corresponding UC-values for moments, shear forces and deflection using Equation 5.13 to Equation 5.18 (based on [1]). M_{max} is the maximum moment acting on the beam and V_{Ed} the maximum shear force acting on the beam. W is the elastic section modulus of the cross-section assigned to the beam and A_v the shear area in the major axis of the cross-section assigned to the beam. f_y is the yield strength, in this case 235 N/mm^2.

  For the maximum moment:

$$M_{Ed} = M_{max} \tag{5.13}$$

$$\sigma_m = \frac{M_{Ed}}{W} \tag{5.14}$$

$$UC_1 = \frac{\sigma_m}{f_y} \tag{5.15}$$

  For the maximum shear the following formulas are used, where the plastic state of steel is assumed:

$$V_{Ed} = V_{max} \tag{5.16}$$

$$V_{pl,Rd} = \frac{A_v(f_y/\sqrt{3})}{\gamma_{mo}} \tag{5.17}$$

$$UC_2 = \frac{V_{Ed}}{V_{c,Rd}} \tag{5.18}$$

  The third UC-value which will be calculated is related to the beam deflection. Since the load-distribution is triangular, the deflection is calculated using the method described in Figure 5.19 and 5.20 [3]. This method is also checked using the software MatrixFrame, as explained in Appendix B.

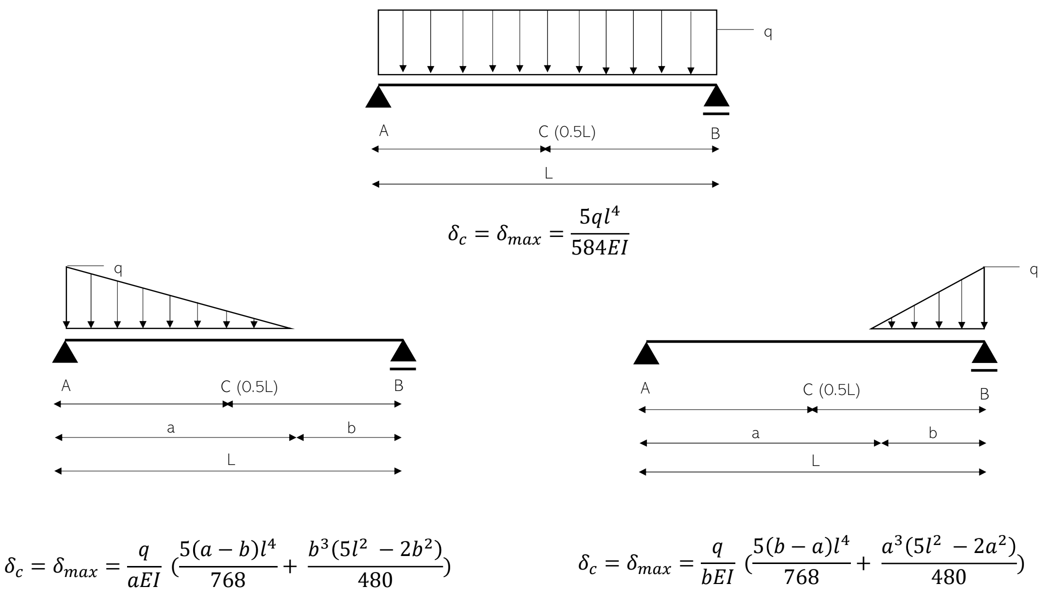


Figure 5.19: Method to calculate displacement, part 1

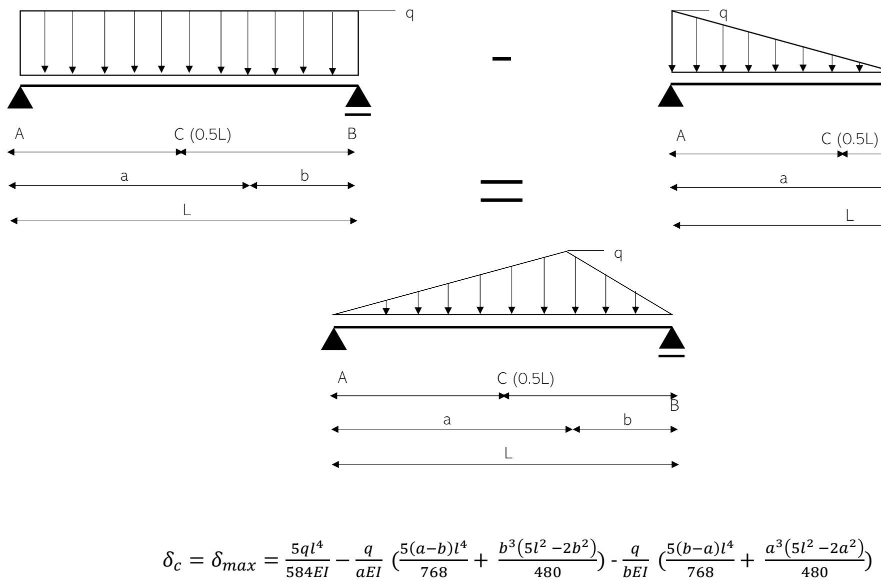


Figure 5.20: Method to calculate displacement, part 2

The result is that the displacement can be calculated by filling in Equation 5.19 [3]. q is the load acting on the beam in kN/m. l is the total length of the beam, which can be divided in a and b, where a is the distance between the left end-point of the beam and the location of the highest load and b is the distance between the right end-point of the beam and the location of the highest load.

$$\delta_c = \frac{5ql^4}{384EI} - \frac{q}{aEI}\left(\frac{5(a-b)l^4}{768} + \frac{b^3(5l^2-2b^2)}{480}\right) - \frac{q}{bEI}\left(\frac{5(b-a)l^4}{768} + \frac{a^3(5l^2-2a^2)}{480}\right) \tag{5.19}$$

The deflection in the beam can has a maximum allowed value of L/250 (based on [2]). Therefore, the third UC-value can be calculated as follows:

$$UC_3 = \frac{\delta_{max}}{\frac{L}{250}} \tag{5.20}$$

- The goal is to assign the reusable elements to the possible positions in the structure in the most efficient way, where the efficiency is related to the UC-value. A UC-value just below 1 indicates that the profile is used to its full capacity. When there are two possible positions for a reusable element where position 1 gives a UC-value of 0.6 and position 2 gives a UC-value of 0.9, it is more efficient to assign the profile to position 2. In this case, a relatively smaller profile made of new steel can be used for position 1. This decreases the amount of steel needed to produce the members of the structure. However, when there are multiple profiles available, the profiles cannot be considered individually. If there are two available profiles and two available positions, a summation of the UC-values is necessary per possible combination. Combination 1: profile 1 on position 1 and profile 2 on position 2 gives the values 0.8 and 0.2 respectively. Combination 2: profile 1 on position 2 and profile 2 on position 1 gives 0.6 and 0.5 respectively. Combination 2 is more efficient, since 0.6 + 0.5 = 1.1 is higher than 0.8 + 0.2 = 1, although the value of 0.8 in combination 1 is the highest UC-value of all.

  To respect the structural and architectural constraints, the highest UC-value has to be above the limit given by the designer and below one. If these requirements are satisfied, the highest of the three UC-values is placed in the UC-matrix. If the requirements are not met, a 0 is placed in the UC-matrix.

  There are three different situations which can occur. The number of horizontal members in the structure can be smaller than the number of suitable profiles, the number of horizontal members in the structure can be equal to the number of suitable profiles or the number of horizontal members in the structure can be bigger than the number of suitable profiles. The procedure differs per situation.

1. **The number of horizontal members in the structure is smaller than the number of suitable profiles** Whenever the number of available profiles is higher than the number of members, there is an element available for every position. The number of horizontal members is therefore guiding for the size of the combinations. As displayed in Figure 5.21, multiple combinations are possible in the case of three possible positions and six available reusable elements. The UC-values corresponding to these positions are summed up after which this number functions as a score representing the efficiency of this combination. The combination which results in the highest score is determines how the available profiles are assigned to the different positions.

Available profiles

Positions	A	B	C	D	E	F
1	UC1A	UC1B	0	UC1D	UC1E	UC1F
2	UC2A	UC2B	UC2C	0	0	UC2F
3	0	UC3B	UC3C	UC3D	UC3E	UC3F

Possible combinations:
1A, 2B, 3C
1B, 2D, 3D
1D, 2B, 3C
1E, 2A, 3F
1F, 2A, 3E
....

Figure 5.21: Number of available profiles is bigger than the number of positions

2. **The number of horizontal members in the structure is equal to the number of suitable profiles** In the case displayed in Figure 5.22, there are three options. There is a profile available for every position, and therefore the size of the combination is equal to the size of both the number of horizontal members in the structure and the number of suitable profiles. The UC-values corresponding to these combinations can be summed up. The highest value represents the most efficient combination and therefore it determines how the available profiles are assigned to the different positions.

Available profiles

Positions	A	B	C
1	UC1A	UC1B	0
2	UC2A	UC2B	UC2C
3	0	UC3B	UC3C

Possible combinations:
1A, 2B, 3C
1A, 2C, 3B
1B, 2A, 3C

Figure 5.22: Number of available profiles is equal to the number of positions

3. **The number of horizontal members in the structure is bigger than the number of suitable profiles** In this case, there is no reusable element available for every position. Therefore, the amount of available profiles is leading for the size of the possible combinations. As one can see in Figure 5.23, there are multiple combinations possible. Again, these UC-values corresponding to each combination are summed up and the combination with the highest score determines how the available profiles are assigned to the different positions.

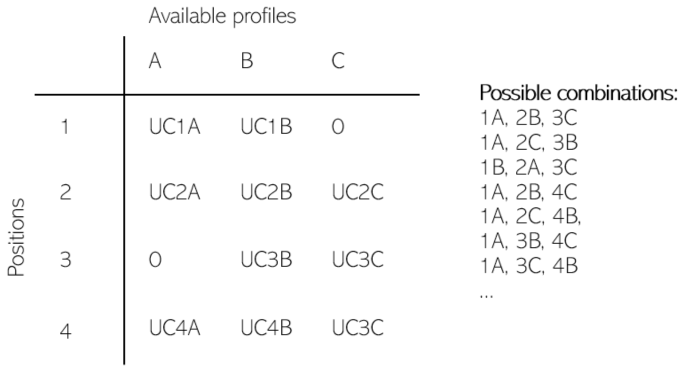


Figure 5.23: Number of available profiles is less than the number of positions

Although is it desirable to explore every possible combination, this can require a high computation time in case of a geometry with a lot of structural members. In that case, a selection of possible combinations is studied and the most efficient one is selected.

- A new element is assigned to every position without an available reusable element which respects the architectural and/or structural constraints. The profile which will result in the UC-value closest to 1 will be assigned, where the UC-values are calculated using Equation 5.13 to Equation 5.19.

5.6. Formulation of the end result

After every bar is coupled to either a new element or reusable element, the formulation of the results can take place. The distance between the different nodes needs to be changed, since the reusable elements assigned to the different beam positions can have a different length from the original distance between the nodes. Therefore, a certain procedure has to be followed in which the coordinates corresponding to the position of the nodes change. This process consists of different steps.

- To align the distance between the nodes with the lengths of the assigned reusable elements, the mathematical formula shown below (Equation 5.21 and 5.22), based on the Pythagorean theorem, can be used. l_1 and l_2 refer to the lengths of the reusable elements. As visible in Equations 5.21 and 5.22 and Figure 5.24, the coordinates of connected two adjacent nodes should be known to be able to calculate the position of the third node.

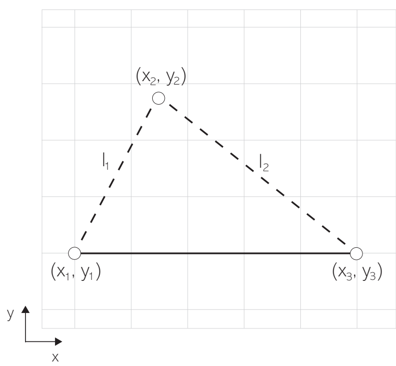


Figure 5.24: Calculation of the nodal coordinates of node 2

$$\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} = l_1 \tag{5.21}$$

$$\sqrt{(x_2 - x_3)^2 + (y_2 - y_3)^2} = l_2 \tag{5.22}$$

When all the positions of the nodes in the complete structure have to be adjusted to match with the assigned reusable elements, a certain amount of nodes with a known position is needed to be able to use the method highlighted in Figure 5.24. To calculate how many nodes are needed of which the position has to be known, Equation 5.23 can be used.

$$\text{number of triangles} * 2 + \text{number of quadrilaterals} * 3 + \text{number of pentagons} * 4 \tag{5.23}$$

In the geometry displayed in Figure 5.2, the amount of nodes with a known position will be sixteen (one triangle, two quadrilaterals and two pentagons). However, some shapes share the same nodes. Duplicate nodes have to be removed. After this has been done, the position of six nodes still have to been known. This will form the basis for the baseline, where the baseline is a line of connected nodes.

The baseline has to fulfill different requirements.

- Per shape, a maximum of one 'single' node (i.e. not connected to another shape) can be left out the baseline. At some point in the process, the two adjacent nodes have to be known to be able to calculate the updated position of the node in between. Yet, if there are two 'single' nodes not in the baseline, this will never happen.

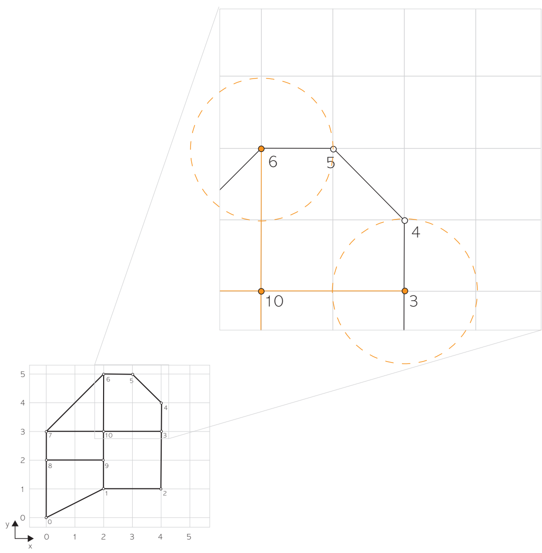


Figure 5.25: Not more than one single node per shape is allowed in the baseline

- Not more than two nodes in the baseline are connected the same separate node. The length of every bar between the separate node and the nodes in the baseline has to equal the length of an available element. However, the probability that the bars with these specific lengths meet in one point is low. In Figure 5.26, the dashed circles around the nodes represent the length of the available reusable element coupled to the bar between the node inside the circle and the separate node. One can see that the circles do not intersect in one point. Therefore, it is not possible to use all the three reusable elements.

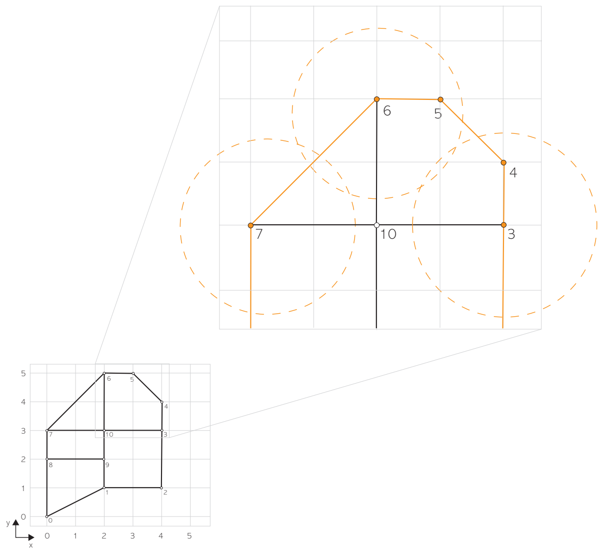


Figure 5.26: Not more than two nodes in the baseline should be connected to the same node outside the baseline

– The nodes in the baseline are connected. However, the baseline cannot include a circular path. The reason for this is that the baseline cannot grow freely, since it is connected on all sides. Therefore, the amount of connections between the different nodes has to be baselinesize$*2-2$. This is illustrated by Figure 5.27.

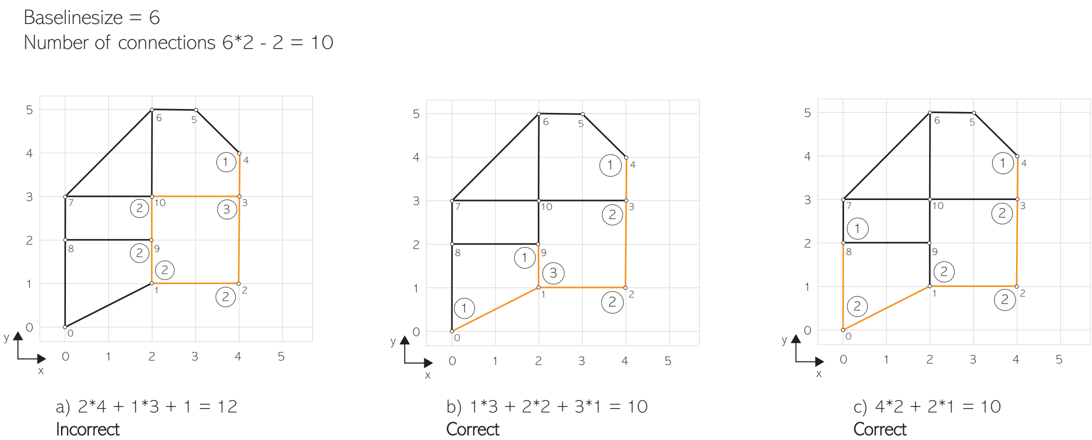


Figure 5.27: A baseline cannot be circular

– There needs to be at least one node which is connected to two nodes in the baseline to start the process. After the process has started, at least one node without a known position should be connected to two nodes with a known position to keep the process going.

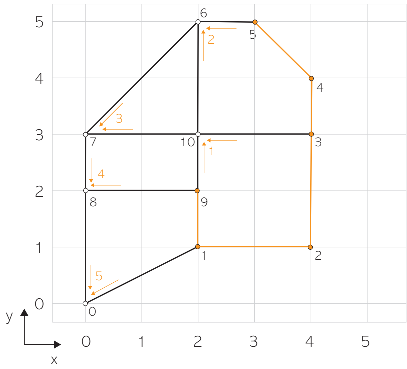


Figure 5.28: Growing process

– During the growing process, two nodes which are calculated apart from each other, should not be connected. This will cause a clash and the distance between the nodes will not be determined by the length of the reusable element, but by the calculation process.

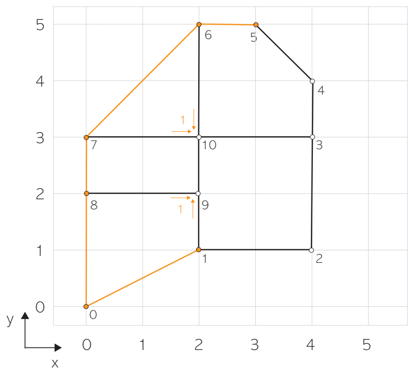


Figure 5.29: The positions of two connected nodes should not be calculated apart from each other

In this example, multiple configurations of the connected nodes within the beam-configuration would fulfill these requirements. All the possibilities are shown in Figure 5.30 and some visualisations of baselines are shown in Figure 5.31.

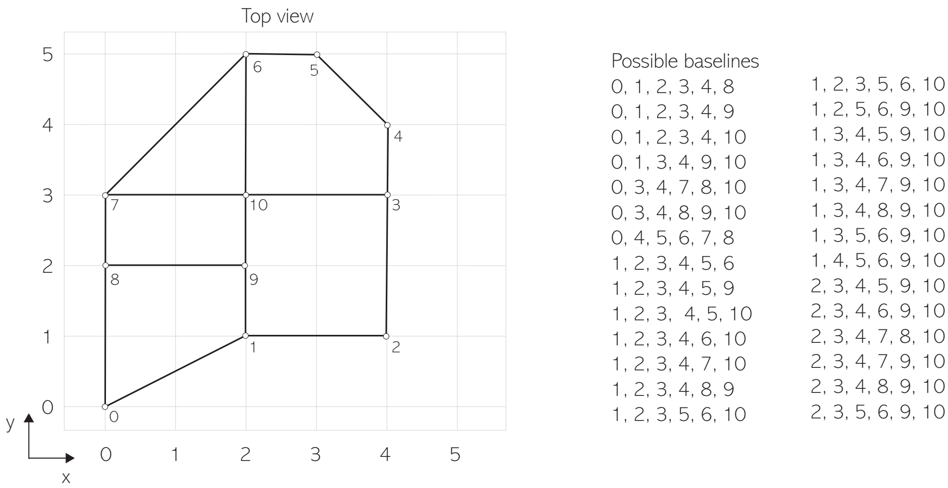


Figure 5.30: All options for the configuration of the baseline for the geometry displayed in Figure 5.2

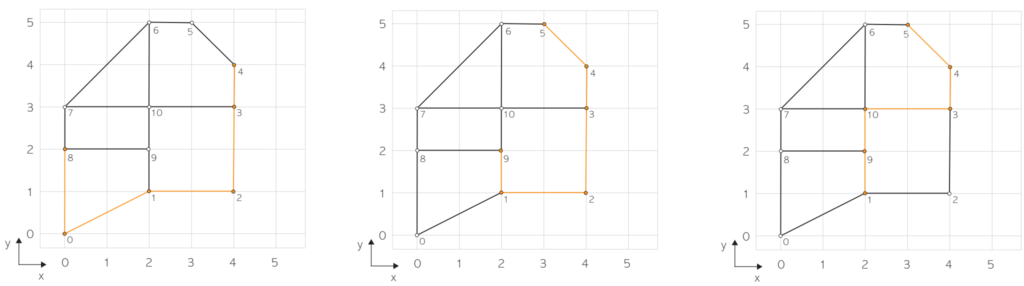


Figure 5.31: Example of baselines for the geometry displayed in Figure 5.2

- When all the baselines are known, it is time to start shifting the nodes in such a way that the distance between the nodes will equal the length between of the assigned reusable elements. This 'growing process' begins at these baselines. For every baseline, the node which the most beam connections is chosen as the 'starting node'. From here, the x- and y-coordinates of the nodes are adjusted so that the distance between the nodes equals the length of the assigned reusable element. The coordinate shifts in the same direction as the direction of the adjacent beam, an example is shown in Figure 5.32.

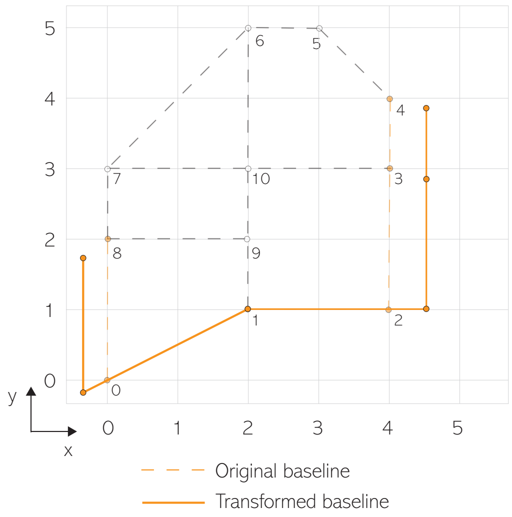


Figure 5.32: Starting point of the 'growing process': adjusting the shape of the baseline

- After this has been done, this 2D-geometry starts 'growing'. When two connections of a node are known, the new position of the node is calculated. This procedure repeats until all the coordinates of all the new nodes are determined.

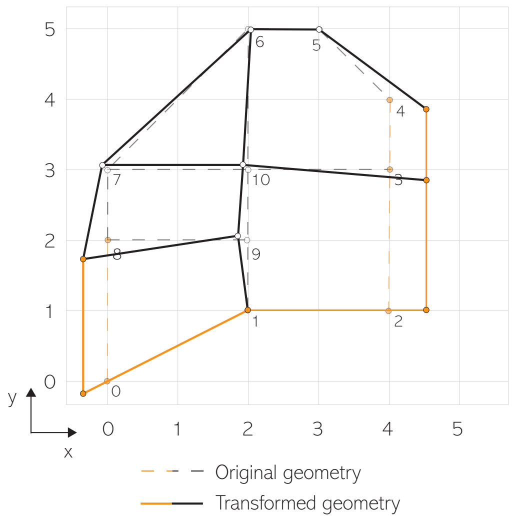


Figure 5.33: Next step: defining the locations of the nodes outside the baseline according to the procedure explained in Equations 5.21 and 5.22

For the geometry displayed in Figure 5.2, 81 possible outcomes, the result of three possible column-configurations (two made of a combination of reused columns and new columns and one with only new columns) and 27 possible baselines. The different possible element-configurations are displayed in Figure 5.34.

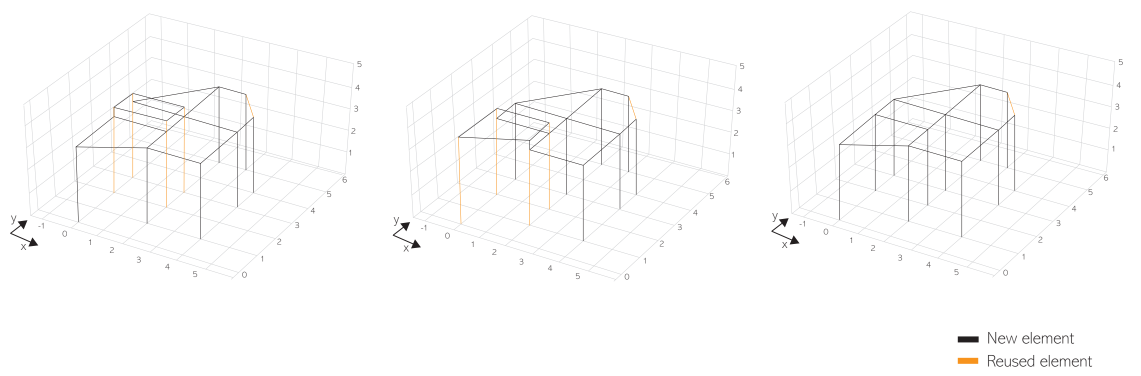


Figure 5.34: The result of the implementation of the geometry displayed in Figure 5.2 in the model

5.7. Structural check

Since the position of the nodes changes after the process is finished, the loads acting on the structure are distributed in a different way. A structural check is necessary to verify the structural safety of these newly created structures. The first step of this structural check is to recalculate the loads using the new geometry. This will be done by reusing the formula ***def*** *CalculateLoad*. With the new numbers, the new equation for the distributed load can be determined. The formula ***def*** *CalculateForce* will be used again, this time using the new load situation, after which the updated moments and shear forces can be calculated per beam. Using Equations 5.13 to 5.20 for beams and Equations 5.5 to 5.12 for the columns, the new UC-values can be calculated for each possible outcome. The result is an overview of the different elements and the corresponding characteristics, including the highest, normative UC-value for each element.

5.8. Characteristics of the different outcomes

The goal of optimization process highlighted in this Chapter, is to develop designs for load-bearing structures for which a low amount of new steel is needed to realize the design.

The developed optimization process produces different results. The results can be distinguished according to Figure 5.35. The number of different element-configurations is the leading factor for the number of results. Per element-configuration all baselines are used to formulate results.

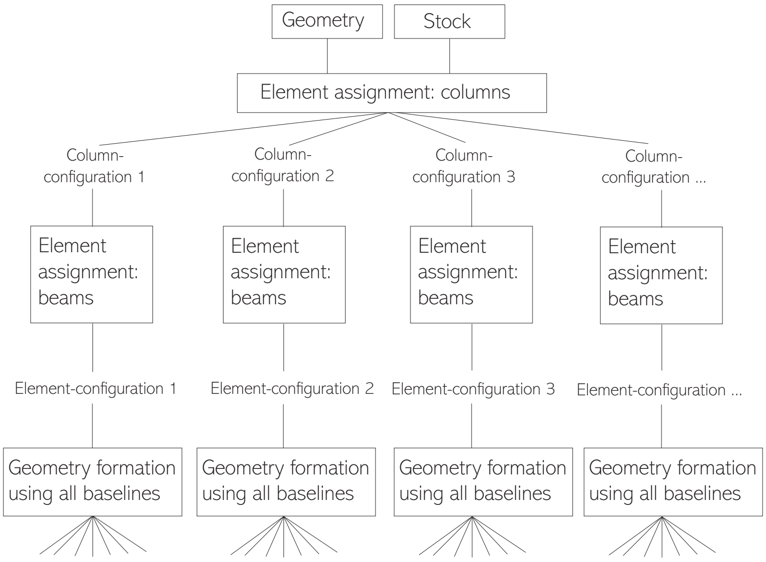


Figure 5.35: Organization of the results

The amount of new steel in a design for a load-bearing structure is determined by the element-configuration. For this element-configuration, one structure is formulated per baseline. Next to the lengths of the reusable elements, the baselines are determining the nodal coordinates of the final designs. Every baseline can cause a different appearance of the design. For this study, 5 different characteristics of the lay-out of every design will be calculated. These characteristics are displayed in Table 5.1.

Characteristic	**Explanation**
Mean UC columns	The mean UC gives an idea of the efficiency of the applied elements.
Mean UC beams	
Minimum angle	This number quantifies the relation of the result to the original geometry concerning the different joints in the construction.
Number of changing angles	
Number of angels changing more than 10 percent	

Table 5.1: Characteristics indicating the difference between all results

6

Case Study

When applying the model described in Chapter 5 on the design of a geometry, the outcome is set of modified designs in which the available reusable elements are implemented in way that respects the constraints. The amount of results the model gives is depending on the geometry, the constraints and the available stock. In this Chapter, the model will be tested and the study will focus on the influence of these parameters.

The model will be used to change the design of a house. The lay-out of the structure is published in the magazine Bouwen met Staal [25], and visible in Figure 6.1.

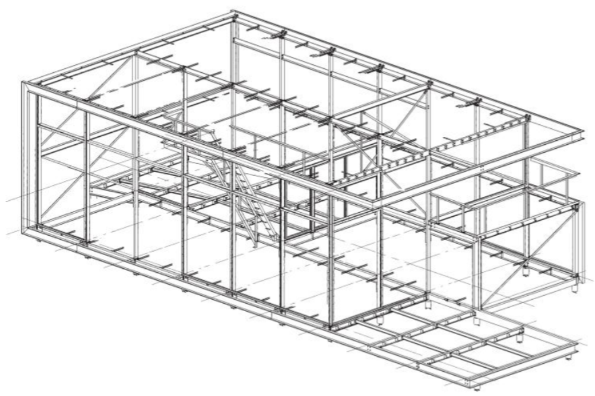


Figure 6.1: Design which served as an inspiration for the geometry used in the Case Study

For this Case Study, the design displayed in Figure 6.1 is simplified. The 3D geometry which will be used for this study is shown in Figure 6.2.

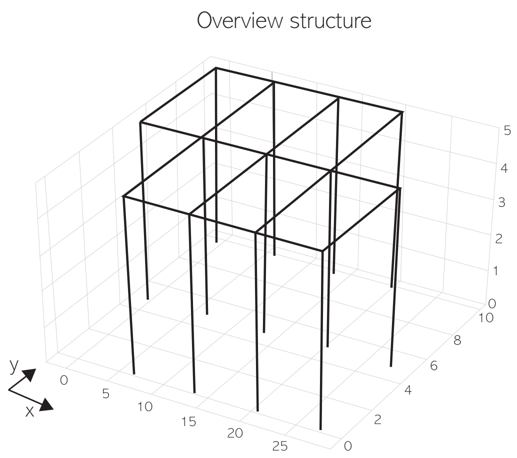


Figure 6.2: 3D overview

The beam-configuration of this geometry is displayed in Figure 6.3.

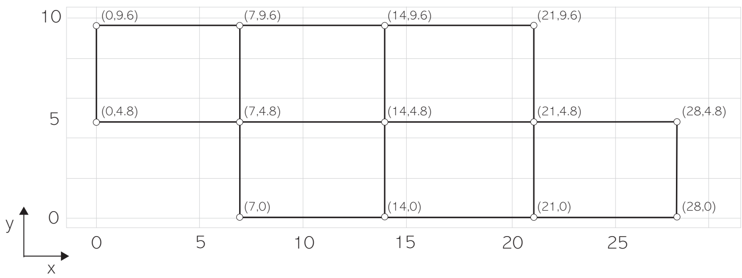


Figure 6.3: Grid

To discover the influence of the stock and the constraints, several analyses will be performed. Three different stocks will be implemented, all with different characteristics. The characteristics of these stocks are displayed in Table 6.1.

Stock	1	2	3
Number of elements	22	32	31
Number of different elements	8	10	6
Sizes of groups	4 x 2 elements 2 x 3 elements 2 x 4 elements	1 x 1 element 2 x 2 elements 1 x 3 elements 6 x 4 elements	1 x 2 elements 2 x 4 elements 1 x 6 elements 1 x 7 elements 1 x 8 elements
Elements within 10% range	15	13	31
Elements within 30% range	22	23	31

Table 6.1: Composition of the different stocks

For each stock, the model will run 4 times. An overview of all analyses is visible in Table 6.2.

Stock 1 consisting of 22 elements			**Stock 2 consisting of 32 elements**			**Stock 3 consisting of 31 elements**		
Analysis	*UC between*	*Maximum deviation (length, %)*	Analysis	*UC between*	*Maximum deviation (length, %)*	Analysis	*UC between*	*Maximum deviation (length, %)*
1.1	0.8 - 1.0	10	2.1	0.8 - 1.0	10	3.1	0.8 - 1.0	10
1.2	0.8 - 1.0	30	2.2	0.8 - 1.0	30	3.2	0.8 - 1.0	30
1.3	0.01 - 1.0	10	2.3	0.01 - 1.0	10	3.3	0.01 - 1.0	10
1.4	0.01 -1.0	30	2.4	0.01 -1.0	30	3.4	0.01 -1.0	30

Table 6.2: Overview of all analyses

In Section 6.1 the original structure will be designed. This design can function as a benchmark to the structures resulting from the different analyses. The results of the analyses referring to the first stock will be discussed in Section 6.2. In Section 6.3, the results of the analyses related to the second stock will be outlined. The results obtained from analyses performed with stock 3 are explained in Section 6.4. In 6.5 the results will be compared, followed by a conclusion.

6.1. Design of the original geometry

The goal of the model is to decrease the amount of new steel needed to realize a certain design. To be able to determine whether this goal is reached using the model described in Chapter 5, the original geometry will first be designed to serve as a benchmark. The aim is to assign profiles to the positions for columns and beams which function most efficiently, represented by a UC-value close but below 1. Every element of the design displayed in Figure 6.4 is numbered and the detailed information about this element can be found in Tables 6.3 and 6.4. The volume of steel needed to realize this design is 0.868 m^3 .

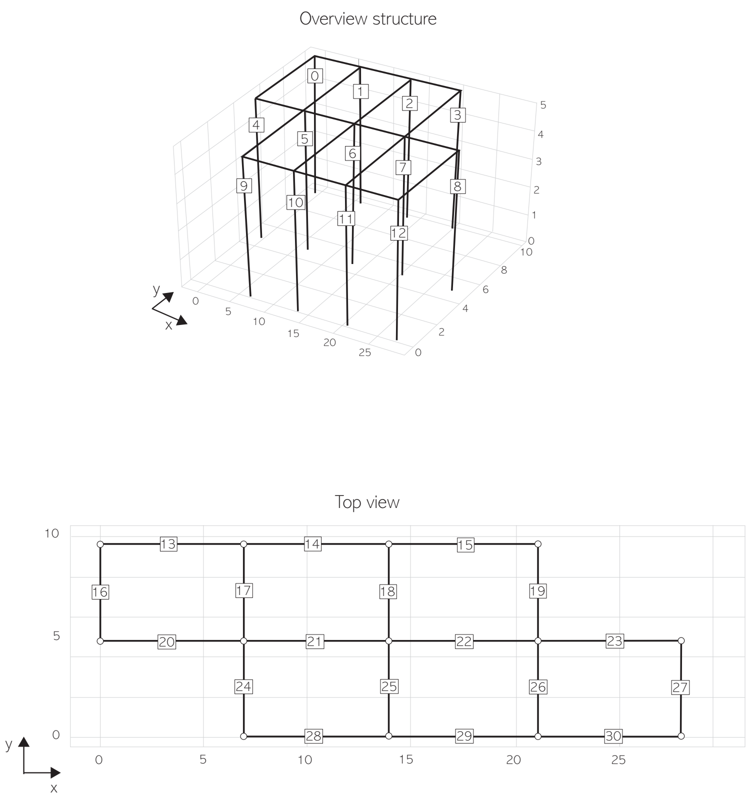


Figure 6.4: Design of the original geometry

	Normalforce [kN]	Length	Profile	UC
0	48.69	5	IPE160	0.97
1	97.37	5	IPE200	0.95
2	97.37	5	IPE200	0.95
3	48.69	5	IPE160	0.97
4	48.69	5	IPE160	0.97
5	146.06	5	UNP240	0.84
6	194.75	5	IPE240	0.99
7	146.06	5	UNP240	0.84
8	48.69	5	IPE160	0.97
9	48.69	5	IPE160	0.97
10	97.37	5	IPE200	0.95
11	97.37	5	IPE200	0.95
12	48.69	5	IPE160	0.97

Table 6.3: Column design of the original geometry

In Table 6.4, the normative value (moment, shear force or deflection) resulting in the highest UC-value is colored gray.

	Node 1	Node2	h[m]	L[m]	Profile	V[kN]	M[kNm]	w[mm]	UC
13	0	1	5	7	HEB180	24.34	56.80	27.34	0.98
14	1	2	5	7	HEB180	24.34	56.80	27.34	0.98
15	2	3	5	7	HEB180	24.34	56.80	27.34	0.98
16	0	4	5	4.8	UNP200	24.34	38.95	17.67	0.92
17	1	5	5	4.8	HEA200	48.69	77.90	18.29	0.95
18	2	6	5	4.8	HEA200	48.69	77.90	18.29	0.95
19	3	7	5	4.8	UNP200	24.34	38.95	17.67	0.92
20	4	5	5	7	HEB180	24.34	56.80	27.34	0.98
21	5	6	5	7	HEM180	48.69	113.60	27.99	1.00
22	6	7	5	7	HEM180	48.69	113.60	27.99	1.00
23	7	8	5	7	HEB180	24.34	56.80	27.34	0.98
24	5	9	5	4.8	UNP200	24.34	38.95	17.67	0.92
25	6	10	5	4.8	HEA200	48.69	77.90	18.29	0.95
26	7	11	5	4.8	HEA200	48.69	77.90	18.29	0.95
27	8	12	5	4.8	UNP200	24.34	38.95	17.67	0.92
28	9	10	5	7	HEB180	24.34	56.80	27.34	0.98
29	10	11	5	7	HEB180	24.34	56.80	27.34	0.98
30	11	12	5	7	HEB180	24.34	56.80	27.34	0.978

Table 6.4: Beam design of the original geometry

N normal force in *kN*
L length in *m*
h height in *m*
V maximum shear force in *kN* (absolute)
M maximum moment in *kNm*
w deflection in *mm*
UC normative UC-value

6.2. Stock 1

In the first analyses, stock 1 will be implemented in the model. The stock can be found in Appendix A. Stock 1 consists of 22 elements. This is less than what the original geometry consists of.

6.2.1. Analysis 1.1

Stock	Original UC between	Maximum deviation in length (%)
1	0.8 - 1.0	10

Table 6.5: Constraints in analysis 1.1

In analysis 1.1, the values for the different parameters as visible in Table 6.5 are implemented. After running the model, it turns out no element in stock is respecting the given constraints and therefore the recommended structure is the original design discussed in Section 6.1.

6.2.2. Analysis 1.2

Stock	Original UC between	Maximum deviation in length (%)
1	0.8 - 1.0	30

Table 6.6: Constraints in analysis 1.2

In analysis 1.2, the values for the different parameters as visible in Table 6.6 are implemented. Again, no elements can be found which respect the given constraints and therefore the output of the model is the original design.

6.2.3. Analysis 1.3

Stock	Original UC between	Maximum deviation in length (%)
1	0.01 - 1.00	10

Table 6.7: Constraints in analysis 1.3

After running the model with the parameters of Table 6.7, multiple results are obtained. The resulting design which consists of the least amount of new steel, is an option in which the level split. One example of a resulting design with this element-configuration is displayed in Figure 6.5. In this Figure, the new positions of the columns and beams are visible. The numbers are connecting the elements in this Figure to the information in Tables 6.8 and 6.9. The amount of steel which is required to realize this design is 0.520 m^3. This therefore saves 0.342 m^3 of new steel, a reduction of 39% compared to the original design.

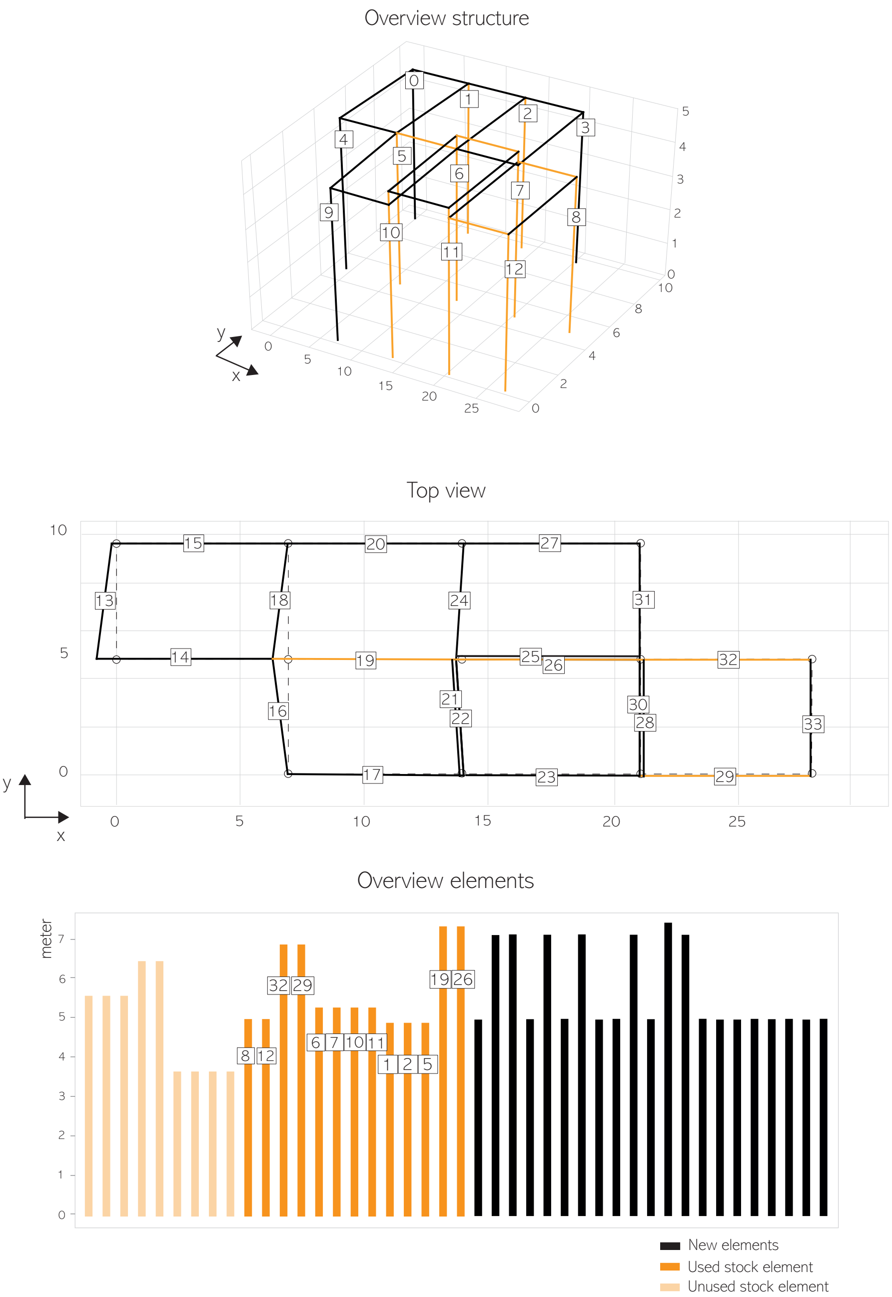


Figure 6.5: A result with the most circular element-configuration of analysis 1.3

	N[kN]	L[m]	Profile	UC	New(0) *or* Reused(1)
0	50.46	4.8	UNP140	1.01	0
1	97.22	4.8	HEB300	0.04	1
2	98.07	4.8	HEB300	0.04	1
3	49.13	4.8	UNP140	1.03	0
4	46.15	4.8	UNP140	0.97	0
5	145.97	4.8	HEB300	0.06	1
6	200.73	5.2	HEM360	0.03	1
7	147.87	5.2	HEM360	0.03	1
8	47.30	4.9	HEB550	0.01	1
9	51.17	4.8	UNP140	1.02	0
10	97.94	5.2	HEM360	0.02	1
11	96.37	5.2	HEM360	0.02	1
12	47.30	4.9	HEB550	0.01	1

Table 6.8: Column design of a result of analysis 1.3

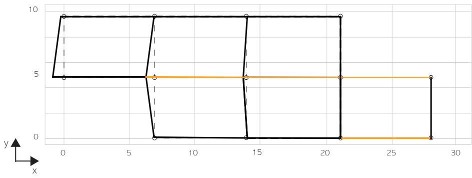
In Table 6.9, the normative value (moment, shear force or deflection) resulting in the highest UC-value is colored gray.

	Node1	Node2	h[m]	L[m]	Profile	V[kN]	M[kNm]	w[mm]	UC	New(0) *or* Reused(1)
13	0	4	4.8	4.8	UNP200	25.62	38.25	17.39	0.91	0
14	4	5	4.8	7.0	HEB180	24.842	56.22	27.07	0.97	0
15	0	1	4.8	7.0	HEB180	24.84	56.22	27.07	0.97	0
16	5	9	4.8	4.8	UNP200	26.23	39.06	17.76	0.93	0
17	9	10	4.8	7.0	HEB180	24.94	56.79	27.34	0.98	0
18	1	5	4.8	4.8	HEA200	48.87	77.10	18.21	0.95	0
19	5	6	4.8	7.3	HEB240	51.21	121.92	21.72	0.74	1
20	1	2	4.8	7.0	HEB180	24.91	56.85	27.37	0.98	0
21	6	10	4.8	4.8	UNP200	25.68	39.51	17.94	0.93	0
22	6	10	5.2	4.8	UNP200	25.56	39.62	17.98	0.94	0
23	10	11	5.2	7.0	HEB180	24.68	57.13	27.50	0.98	0
24	2	6	4.8	4.8	HEA200	49.73	79.10	18.61	0.97	0
25	6	7	4.8	7.3	UNP240	25.35	61.28	34.14	1.17	0
26	6	7	5.2	7.3	HEB240	25.36	61.27	10.91	0.37	1
27	2	3	4.8	7.0	HEB180	24.66	57.13	27.50	0.98	0
28	7	11	4.9	4.8	UNP200	23.65	37.84	17.17	0.89	0
29	11	12	4.9	6.8	IPE270	23.65	53.60	16.11	0.59	1
30	7	11	5.2	4.8	UNP200	24.94	39.77	18.04	0.94	0
31	3	7	4.8	4.8	UNP200	24.91	39.78	18.05	0.94	0
32	7	8	4.9	6.8	IPE270	23.65	53.60	16.11	0.59	1
33	8	12	4.9	4.8	UNP200	23.65	37.84	17.17	0.90	0

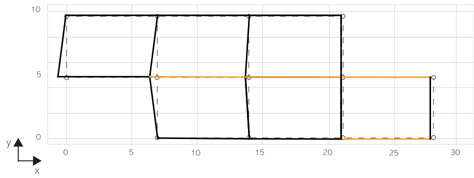
Table 6.9: Beam design of a result of analysis 1.3

N	normal force in *kN*	**M**	maximum moment in *kNm*
L	length in *m*	**w**	deflection in *mm*
h	height in *m*	**UC**	normative UC-value
V	maximum shear force in *kN* (absolute)		

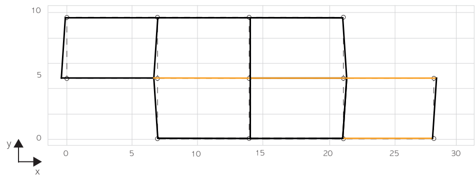
The results with the same element-configuration as the geometry displayed in Figure 6.5, can be distinguished from each other by different characteristics per design. These characteristics are: the nodal coordinates, the mean UC-value, the minimum angle and the number of changing corners. In Figure 6.7, 8 examples are given. The characteristics of per beam-configuration are given. In Appendix D, a full overview of all the results for this beam-configuration are presented.



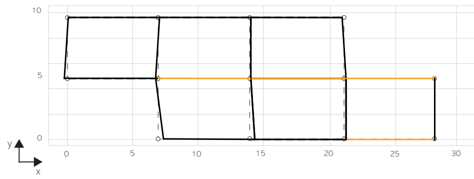
Mean UC columns: 0.328
Mean UC beams: 0.886
Minimum angle: 82.595
Number of changing angles: 19
Number of angles changing more than 10%: 0



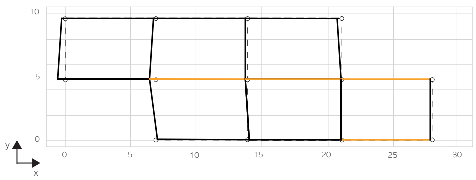
Mean UC columns: 0.328
Mean UC beams: 0.886
Minimum angle: 82.595
Number of changing angles: 19
Number of angles changing more than 10%: 0



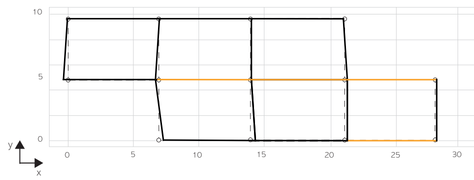
Mean UC columns: 0.329
Mean UC beams: 0.889
Minimum angle: 86.343
Number of changing angles: 21
Number of angles changing more than 10%: 0



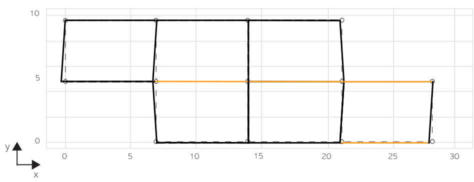
Mean UC columns: 0.330
Mean UC beams: 0.888
Minimum angle: 882.744
Number of changing angles: 17
Number of angles changing more than 10%: 0



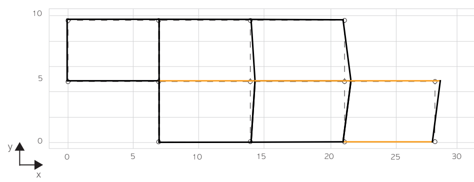
Mean UC columns: 0.330
Mean UC beams: 0.888
Minimum angle: 82.744
Number of changing angles: 17
Number of angles changing more than 10%: 0



Mean UC columns: 0.330
Mean UC beams: 0.888
Minimum angle: 82.744
Number of changing angles: 17
Number of angles changing more than 10%: 0



Mean UC columns: 0.329
Mean UC beams: 0.889
Minimum angle: 86.343
Number of changing angles: 22
Number of angles changing more than 10%: 0



Mean UC columns: 0.329
Mean UC beams: 0.886
Minimum angle: 82.818
Number of changing angles: 18
Number of angles changing more than 10%: 0

Figure 6.6: 8 out of 39 possibilities for the beam-configuration of the most circular result of analysis 1.3

6.2.4. Analysis 1.4

Stock	Original UC between	Maximum deviation in length (%)
1	0.01 - 1.00	30

Table 6.10: Constraints in analysis 1.4

In analysis 1.4, the parameters have the different values displayed in Table 6.10. The best result is the result where only the beams are replaced by reused elements. One example of a resulting design with this element-configuration is displayed in Figure 6.7. The Tables 6.11 and 6.12 give information about the different columns and beams included in this design. For this combination of columns and beams, the resulting designs include $0.1791m^3$ of new steel, due to the new columns. This is a reduction of 79.4% compared to the original design which included $0.868m^3$ of new steel.

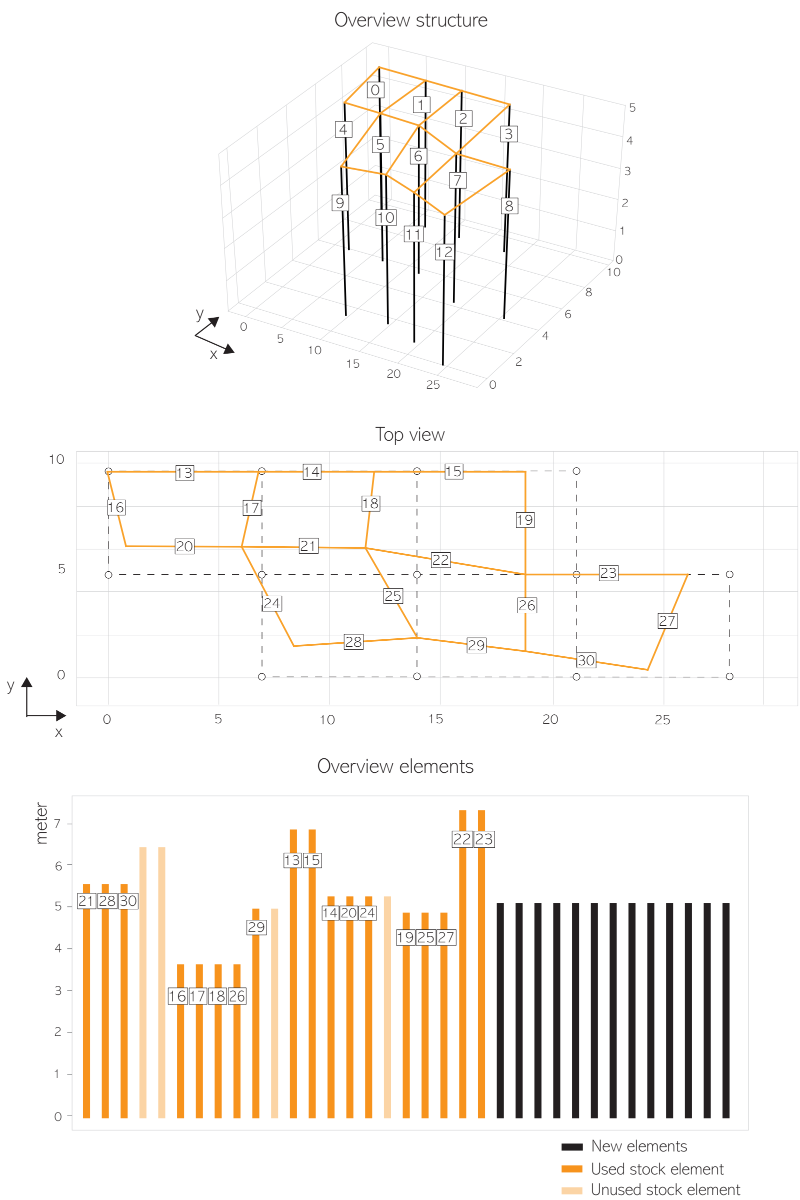


Figure 6.7: A result with the most circular element-configuration of analysis 1.4

	N[kN]	L[m]	Profile	UC	New(0) *or* Reused(1)
0	29.84	5.0	IPE160	0.59	0
1	59.21	5.0	IPE200	0.58	0
2	66.18	5.0	IPE200	0.65	0
3	45.15	5.0	IPE160	0.90	0
4	30.81	5.0	IPE160	0.61	0
5	87.75	5.0	UNP240	0.50	0
6	140.43	5.0	IPE240	0.72	0
7	119.07	5.0	UNP240	0.68	0
8	37.83	5.0	IPE160	0.75	0
9	42.10	5.0	IPE160	0.84	0
10	66.82	5.0	IPE200	0.65	0
11	61.10	5.0	IPE200	0.60	0
12	40.81	5.0	IPE160	0.81	0

Table 6.11: Column design of a result of analysis 1.4

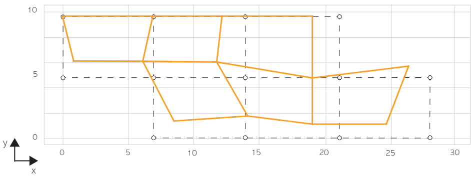
In Table 6.12, the normative value (moment, shear force or deflection) resulting in the highest UC-value is colored gray.

	Node1	Node2	h[m]	L[m]	Profile	V[kN]	M[kNm]	w[mm]	UC	New(0) *or* Reused(1)
13	0	1	5.0	6.8	IPE270	16.47	37.25	11.20	0.41	1
14	1	2	5.0	5.2	HEM360	13.95	23.23	0.28	0.02	1
15	2	3	5.0	6.8	IPE270	21.10	47.51	14.28	0.53	1
16	0	4	5.0	3.582	UNP350	17.03	17.54	0.66	0.10	1
17	1	5	5.0	3.582	UNP350	29.22	33.40	1.27	0.19	1
18	2	6	5.0	3.582	UNP350	33.54	39.16	1.47	0.23	1
19	3	7	5.0	4.8	HEB300	24.05	36.93	1.27	0.09	1
20	4	5	5.0	5.2	HEM360	13.78	23.81	0.29	0.02	1
21	5	6	5.0	5.566	HEM240	34.87	57.46	2.78	0.14	1
22	6	7	5.0	7.3	HEB240	41.06	96.24	17.19	0.59	1
23	7	8	5.0	7.3	HEB240	21.02	49.66	8.85	0.30	1
24	5	9	5.0	5.2	HEM360	21.47	30.49	0.37	0.03	1
25	6	10	5.0	4.8	HEB300	35.09	48.06	1.74	0.12	1
26	7	11	5.0	3.582	UNP350	34.69	39.04	1.48	0.23	1
27	8	12	5.0	4.8	HEB300	22.92	31.44	1.09	0.08	1
28	9	10	5.0	5.556	HEM240	20.63	32.59	1.58	0.08	1
29	10	11	5.0	4.9	HEB550	15.72	21.93	0.15	0.02	1
30	11	12	5.0	5.566	HEM240	17.89	32.07	1.54	0.08	1

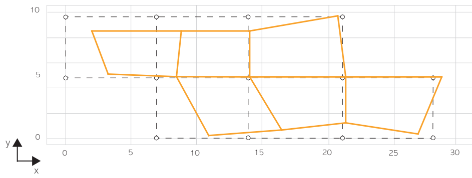
Table 6.12: Beam design of a result of analysis 1.4

N normal force in *kN*
L length in *m*
h height in *m*
V maximum shear force in *kN* (absolute)
M maximum moment in *kNm*
w deflection in *mm*
UC normative UC-value

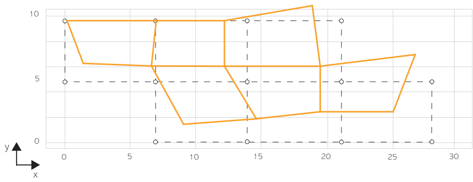
There are several resulting structures in which the same amount of new steel is included. The element-configuration is the same as in the design displayed in 6.7. However, the nodal coordinates can be different, resulting in changing characteristics (mean UC-value beams and columns, minimum angle and number of changing angles). In Figure 6.8, a sample of the beam-configuration of these structures are displayed. In Appendix D, all structures and characteristics are visible.



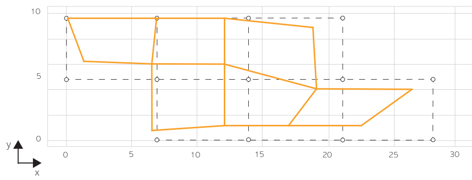
Mean UC columns: 0.677
Mean UC beams: 0.180
Minimum angle: 51.124
Number of changing angles: 22
Number of changing angles more than 10%: 16



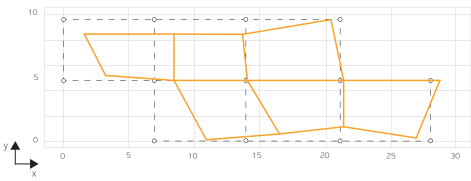
Mean UC columns: 0.685
Mean UC beams: 0.183
Minimum angle: 59.562
Number of changing angles: 20
Number of changing angles more than 10%: 11



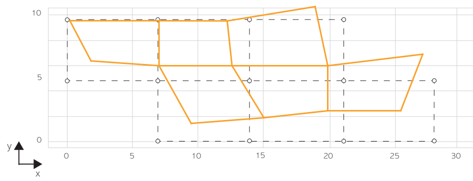
Mean UC columns: 0.681
Mean UC beams: 0.182
Minimum angle: 59.562
Number of changing angles: 20
Number of changing angles more than 10%: 11



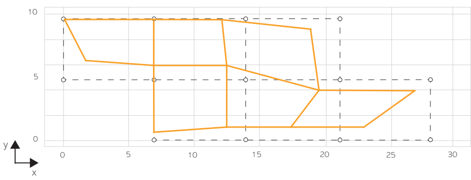
Mean UC columns: 0.641
Mean UC beams: 0.172
Minimum angle: 36.478
Number of changing angles: 22
Number of changing angles more than 10%: 12



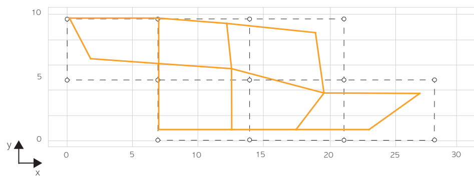
Mean UC columns: 0.682
Mean UC beams: 0.183
Minimum angle: 59.562
Number of changing angles: 20
Number of changing angles more than 10%: 11



Mean UC columns: 0.678
Mean UC beams: 0.181
Minimum angle: 59.562
Number of changing angles: 20
Number of changing angles more than 10%: 11



Mean UC columns: 0.635
Mean UC beams: 0.170
Minimum angle: 36.487
Number of changing angles: 20
Number of changing angles more than 10%: 13



Mean UC columns: 0.636
Mean UC beams: 0.170
Minimum angle: 36.661
Number of changing angles: 22
Number of changing angles more than 10%: 15

Figure 6.8: 8 out of 21 possibilities for the beam-configuration of the most circular result of analysis 1.4

6.3. Stock 2

The second stock consists of 32 elements. This is more than the number of elements in the original design. The complete stock used in analysis 2 is visible in Appendix A.

6.3.1. Analysis 2.1

Stock	**Original UC between**	**Maximum deviation in length (%)**
2	0.8 - 1.0	10

Table 6.13: Constraints in analysis 2.1

Stock 2 in combination with the values for the parameters as displayed in Table 6.13 does not result in designs including reusable elements. Therefore, the original geometry including only new elements is the recommended design.

6.3.2. Analysis 2.2

Stock	**Original UC between**	**Maximum deviation in length (%)**
2	0.8 - 1.0	30

Table 6.14: Constraints in analysis 2.2

The values displayed in Table 6.14 in combination with stock 2 does not result in the implementation of reusable elements in the original structure. Therefore, the original geometry including only new elements is the recommended design.

6.3.3. Analysis 2.3

Stock	Original UC between	Maximum deviation in length (%)
2	0.01 - 1.0	10

Table 6.15: Constraints in analysis 2.3

The values for the parameters shown in Table 6.15 in combination with stock 2 do result in modified designs in which reusable elements are included. Comparable to analysis 1.3, the design in which the least amount of new steel is included is a design in which the beam-configuration consists of a split level. An example of such a design is visible in Figure 6.9. For this design, information about the beams and columns is shown in Tables 6.16 and 6.17. The amount of new steel included in designs with this element-configuration is $0.7230m^3$. Compared to the original design, this is a reduction of 16.1%.

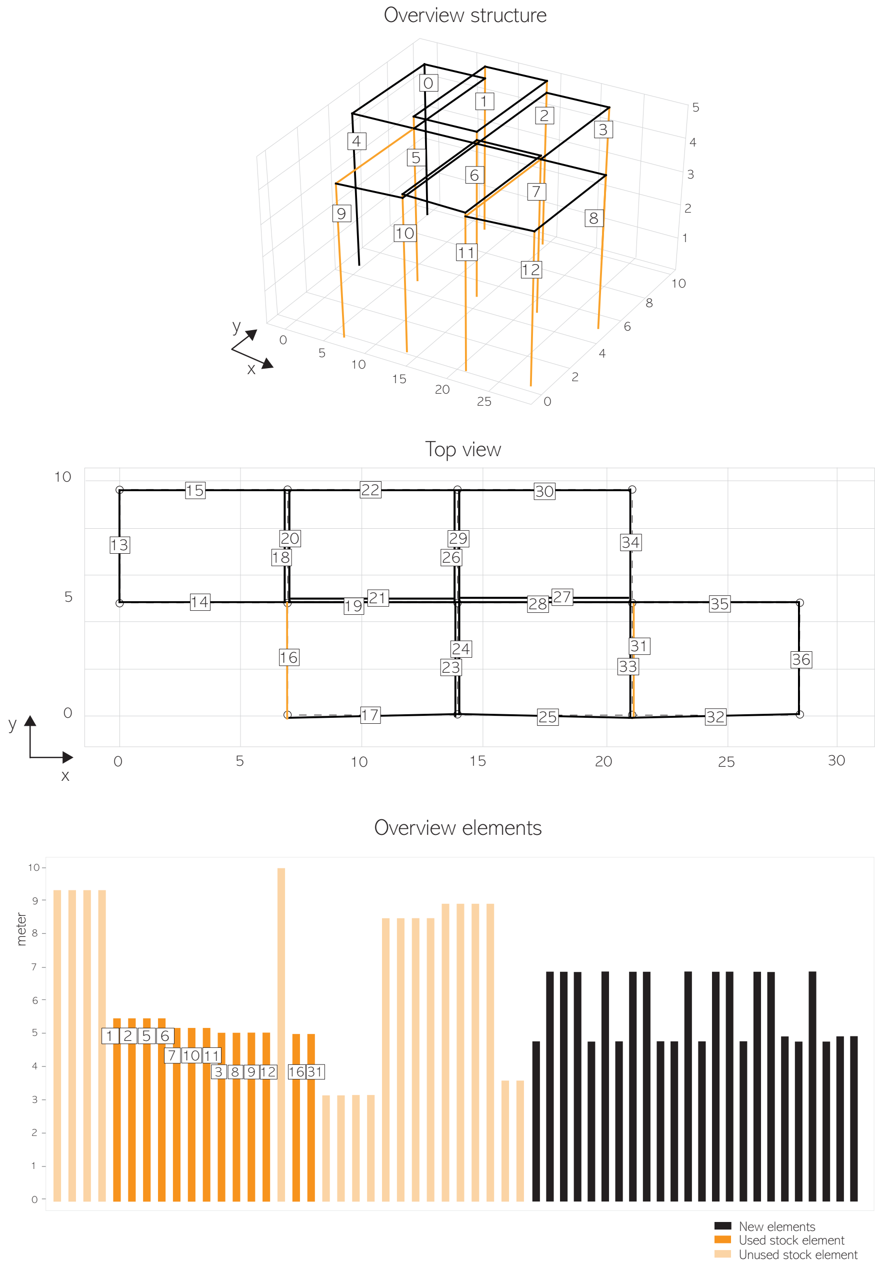


Figure 6.9: A result with the most circular element-configuration of analysis 2.3

	N[kN]	L[m]	Profile	UC	New(0) *or* Reused(1)
0	48.69	4.964	IPE160	0.95	0
1	97.37	5.331	HEM550	0.02	1
2	97.37	5.331	HEM550	0.02	1
3	48.69	4.964	UNP180	0.58	1
4	48.69	4.964	IPE160	0.95	0
5	147.31	5.331	HEM550	0.02	1
6	195.46	5.331	HEM550	0.03	1
7	148.59	5.077	HEA240	0.14	1
8	49.04	4.964	UNP180	0.62	1
9	49.56	4.964	UNP180	0.62	1
10	98.89	5.077	HEA240	0.09	1
11	99.09	5.077	HEA240	0.09	1
12	49.45	4.964	UNP180	0.62	1

Table 6.16: Column design of a result of analysis 2.3

In Table 6.17, the normative value (moment, shear force or deflection) resulting in the highest UC-value is colored gray.

	Node1	Node2	h[m]	L[m]	Profile	V[kN]	M[kNm]	w[mm]	UC	New(0) *or* Reused(1)
13	0	4	4.964	4.8	UNP200	24.34	38.95	17.67	0.92	0
14	4	5	4.964	7.0	HEB180	24.34	56.80	27.34	0.98	0
15	0	1	4.964	7.0	HEB180	24.34	56.80	27.34	0.98	0
16	5	9	4.964	4.961	HEM360	25.14	41.37	0.45	0.04	1
17	9	10	4.964	7.0	HEB180	24.83	57.74	27.79	0.99	0
18	1	5	4.964	4.8	UNP200	24.34	38.95	17.67	0.92	0
19	5	6	4.964	7.0	HEB180	24.80	57.76	27.80	0.99	0
20	1	5	5.331	4.8	UNP200	24.34	38.95	17.67	0.92	0
21	5	6	5.331	7.0	HEB180	24.34	56.80	27.34	0.98	0
22	1	2	5.331	7.0	HEB180	24.34	56.80	27.34	0.98	0
23	6	10	4.964	4.8	UNP200	24.61	39.16	17.76	0.93	0
24	6	10	5.077	4.8	UNP200	24.62	39.15	17.76	0.93	0
25	10	11	5.077	7.0	HEB180	24.84	57.74	27.79	0.99	0
26	2	6	4.964	4.8	UNP200	24.34	38.95	17.67	0.92	0
27	6	7	4.964	7.0	HEB180	24.34	56.80	27.34	0.98	0
28	6	7	5.077	7.0	HEB180	24.80	57.76	27.80	0.99	0
29	2	6	5.331	4.8	UNP200	24.34	38.95	17.67	0.92	0
30	2	3	4.964	7.0	HEB180	24.34	56.80	27.34	0.98	0
31	7	11	4.964	4.961	HEM360	25.15	41.37	0.45	0.04	1
32	11	12	4.964	7.0	HEB180	24.84	57.74	27.79	0.99	0
33	7	11	5.077	4.961	UNP200	25.15	41.37	20.05	1.01	0
34	3	7	4.964	4.8	UNP200	24.34	38.95	17.67	0.92	0
35	7	8	4.964	7.0	HEB180	24.80	57.76	27.80	0.99	0
36	8	12	4.964	4.8	UNP200	24.62	39.15	17.76	0.93	0

Table 6.17: Beam design of a result of analysis 2.3

N	normal force in *kN*	**M**	maximum moment in *kNm*
L	length in *m*	**w**	deflection in *mm*
h	height in *m*	**UC**	normative UC-value
V	maximum shear force in *kN* (absolute)		

The different structures which include the same amount of new steel have the same element-configuration. However, the nodal coordinates can be different, resulting in different characteristics. Eight structures with the same elements but in a different position are displayed in Figure 6.10. All possible beam-configurations with this element-configuration are displayed in Appendix D. As visible in Figure 6.10, some of the beam-configuration have slightly different nodal-coordinates. However, the characteristics are almost the same.

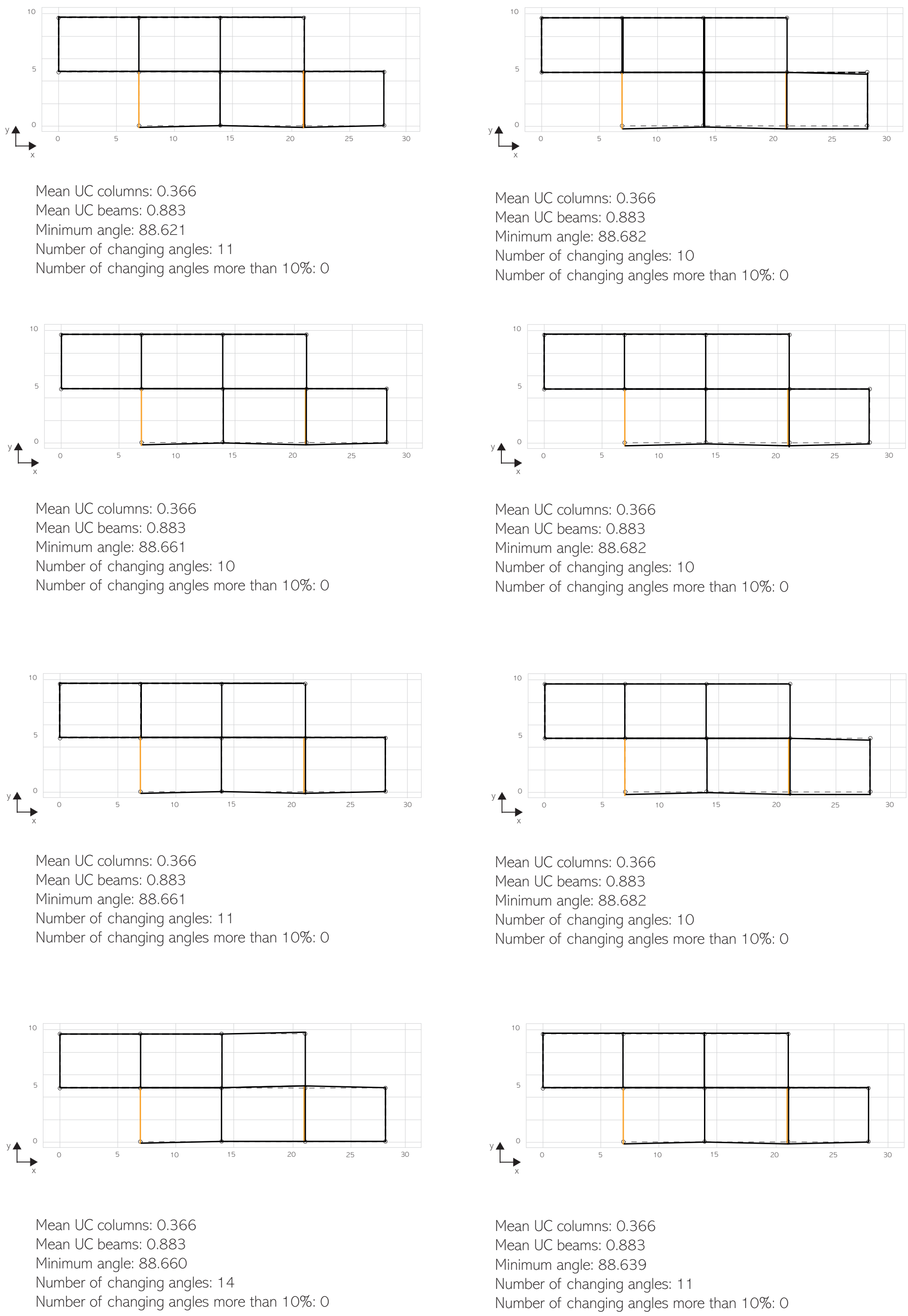


Figure 6.10: 8 out of 39 possibilities for the beam-configuration of the most circular result of analysis 2.3

6.3.4. Analysis 2.4

Stock	Original UC between	Maximum deviation in length (%)
2	0.01 - 1.0	30

Table 6.18: Constraints in analysis 2.4

With the values for the parameters as displayed in Table 6.18, multiple structures serve as an output. As in analysis 1.4, the structure in which the least amount of new steel is included is the selection in which only beams are replaced by reusable elements. An example is shown in Figure 6.11. The corresponding information about the beams and columns is displayed in Tables 6.19 and 6.20. The amount of new steel in structures including these elements is $0.225m^3$, a reduction of 74% compared to the original structure.

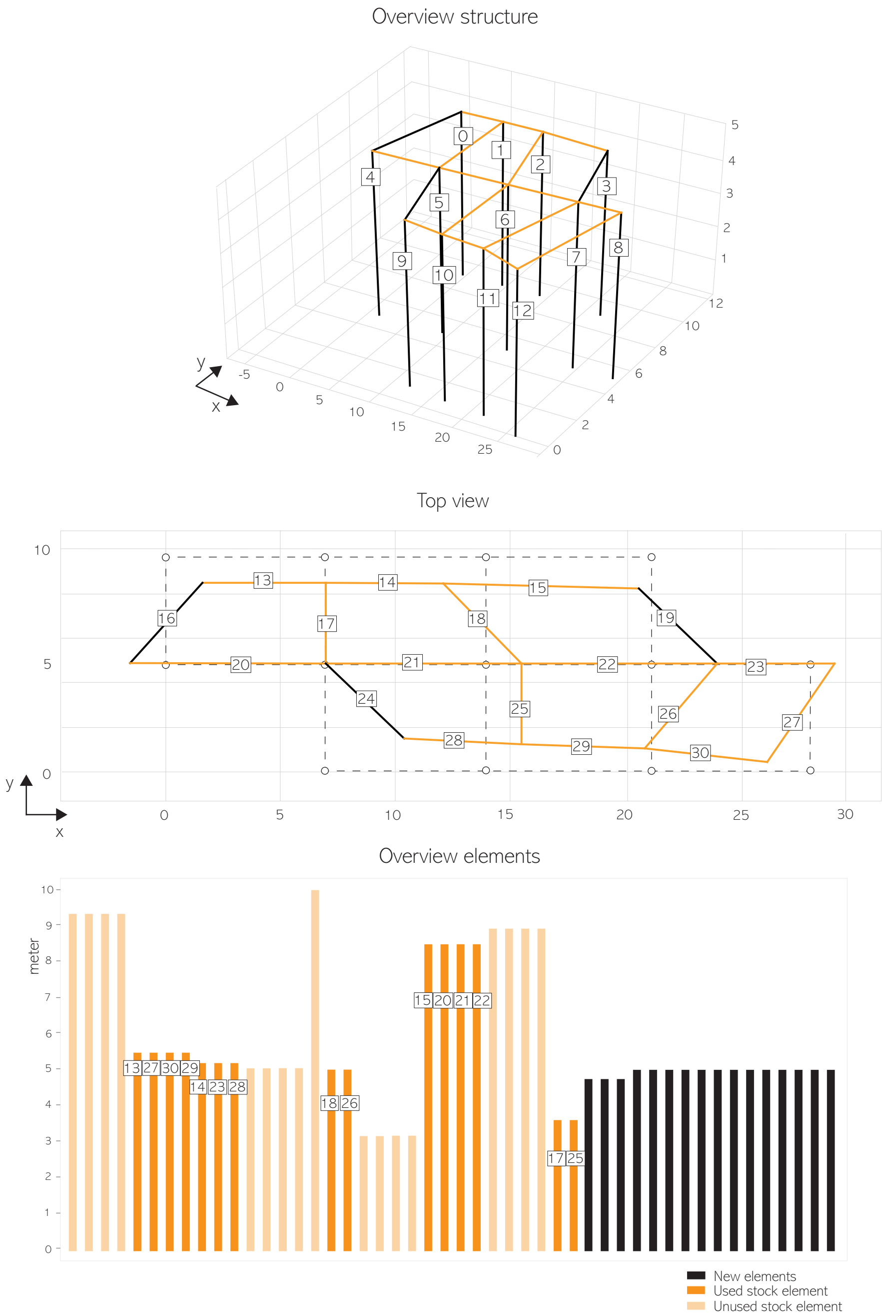


Figure 6.11: A result with the most circular element-configuration of analysis 2.4

	N[kN]	L[m]	Profile	UC	New(0) *or* Reused(1)
0	40.71	5.0	IPE160	0.81	0
1	62.21	5.0	IPE200	0.61	0
2	71.19	5.0	IPE200	0.70	0
3	48.58	5.0	IPE160	0.96	0
4	32.65	5.0	IPE160	0.65	0
5	111.48	5.0	UNP240	0.64	0
6	164.67	5.0	IPE240	0.84	0
7	102.39	5.0	UNP240	0.59	0
8	26.84	5.0	IPE160	0.53	0
9	37.95	5.0	IPE160	0.75	0
10	62.02	5.0	IPE200	0.61	0
11	68.72	5.0	IPE200	0.67	0
12	39.55	5.0	IPE160	0.78	0

Table 6.19: Column design of a result of analysis 2.4

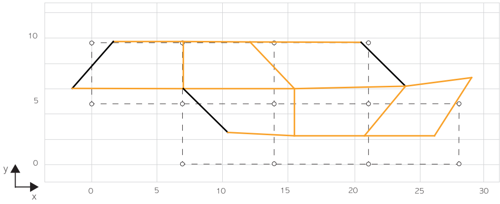
In Table 6.20, the normative value (moment, shear force or deflection) resulting in the highest UC-value is colored gray.

	Node1	Node2	h[m]	L[m]	Profile	V[kN]	M[kNm]	w[mm]	UC	New(0) *or* Reused(1)
13	0	1	5.0	5.331	HEM550	16.76	26.18	0.14	0.02	1
14	1	2	5.0	5.077	HEA240	16.24	23.59	2.97	0.15	1
15	2	3	5.0	8.459	HEB300	23.91	56.74	6.12	0.18	1
16	0	4	5.0	4.8	UNP200	23.95	24.21	11.21	0.58	0
17	1	5	5.0	3.661	HEB360	37.87	44.92	0.52	0.08	1
18	2	6	5.0	4.961	HEM360	39.69	48.55	0.58	0.05	1
19	3	7	5.0	4.8	UNP200	24.67	21.98	11.80	0.61	0
20	4	5	5.0	8.459	HEB300	21.88	57.84	6.20	0.18	1
21	5	6	5.0	8.459	HEB300	40.25	111.71	12.03	0.36	1
22	6	7	5.0	8.459	HEB300	46.88	117.18	12.61	0.37	1
23	7	8	5.0	5.077	HEA240	18.67	24.06	3.07	0.15	1
24	5	9	5.0	4.8	UNP200	22.44	21.31	9.82	0.51	0
25	6	10	5.0	3.661	HEB360	37.86	44.82	0.52	0.08	1
26	7	11	5.0	4.961	HEM360	37.12	49.38	0.57	0.05	1
27	8	12	5.0	5.331	HEM550	19.84	28.28	0.15	0.02	1
28	9	10	5.0	5.077	HEA240	15.51	22.33	2.81	0.14	1
29	10	11	5.0	5.331	HEM550	17.38	27.31	0.15	0.02	1
30	11	12	5.0	5.331	HEM550	19.71	28.20	0.15	0.02	1

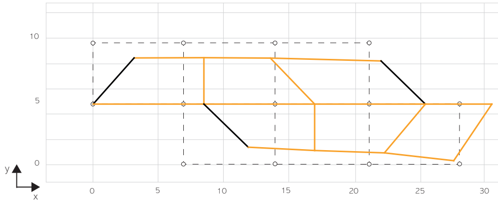
Table 6.20: Beam design of a result of analysis 2.4

N	normal force in *kN*	**M**	maximum moment in *kNm*
L	length in *m*	**w**	deflection in *mm*
h	height in *m*	**UC**	normative UC-value
V	maximum shear force in *kN* (absolute)		

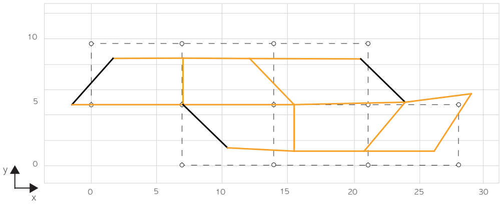
In this case, there are three structures with the same element-configuration. However, the nodal coordinates change. This possibly results in different characteristics (mean UC-value columns, mean UC-value beams, minimum angle and number of changing angles). The resulting beam-configurations are the corresponding characteristics shown in Figure 6.12.



Mean UC columns: 0.694
Mean UC beams: 0.198
Minimum angle: 45.091
Number of changing angles: 20
Number of changing angles more than 10%: 16



Mean UC columns: 0.702
Mean UC beams: 0.198
Minimum angle: 45.091
Number of changing angles: 20
Number of changing angles more than 10%: 16



Mean UC columns: 0.694
Mean UC beams: 0.198
Minimum angle: 45.091
Number of changing angles: 20
Number of changing angles more than 10%: 16

Figure 6.12: all possibilities for the beam-configuration of the most circular result of analysis 2.4

6.4. Stock 3

6.4.1. Analysis 3.1

Stock	Original UC between	Maximum deviation in length (%)
3	0.8 - 1.0	10

Table 6.21: Constraints in analysis 3.1

Analysis 3.1 is the first analysis where the constraints with the values as displayed in Table 6.21 give the model the ability to find results. A design with the element-configuration related to the element-configuration which requires the least amount of new steel to be realized, is displayed in Figure 6.13. The numbers in this Figure indicate the beams and columns. The related characteristics of these elements are displayed in Table 6.22 and Table 6.23. The amount of new steel which is required to realize this design is $0.61m^3$. Compared to the original design with a required amount of $0.87m^3$, this is a reduction of 30%.

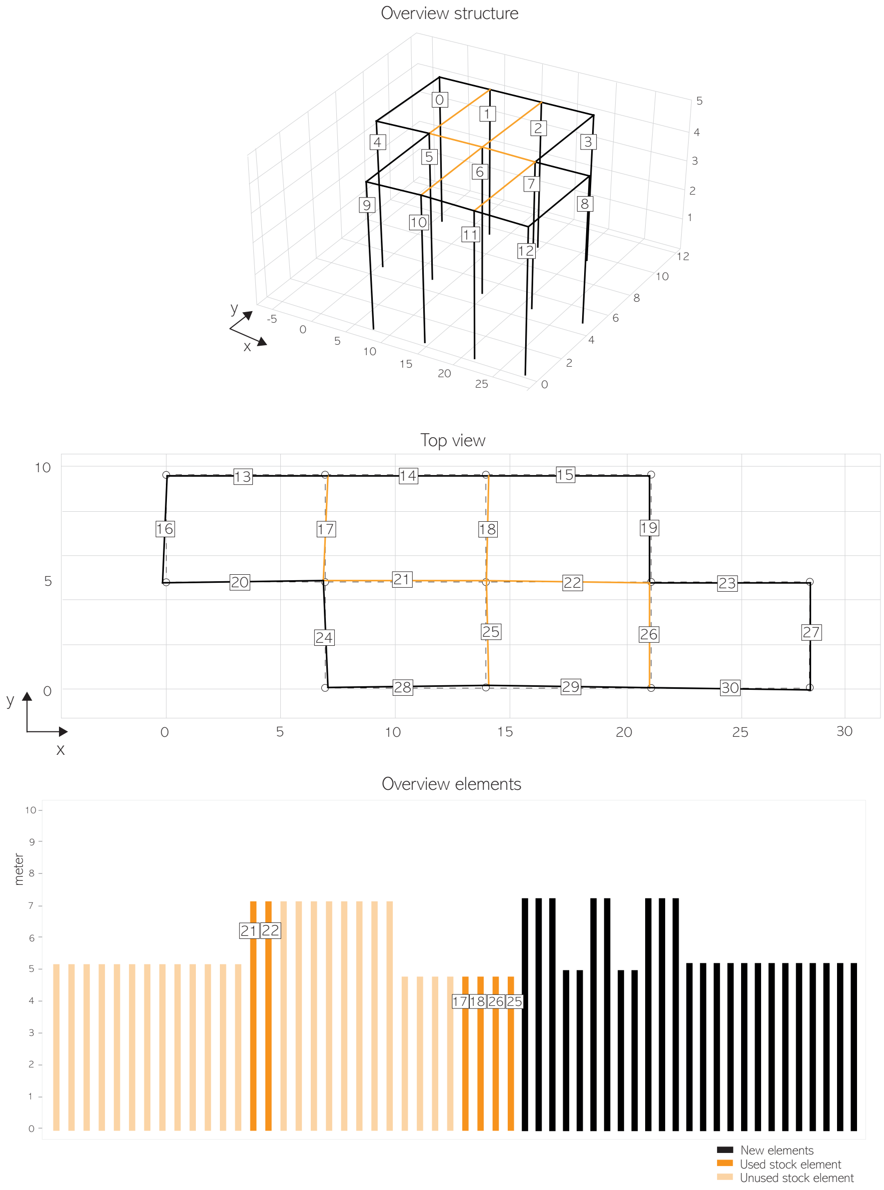


Figure 6.13: A result with the most circular element-configuration of analysis 3.1

	N[kN]	L[m]	Profile	UC	New(0) *or* Reused(1)
0	48.91	5.0	IPE160	0.97	0
1	95.91	5.0	IPE200	0.94	0
2	96.08	5.0	IPE200	0.94	0
3	48.36	5.0	IPE160	0.96	0
4	47.70	5.0	IPE160	0.95	0
5	144.23	5.0	UNP240	0.82	0
6	193.21	5.0	IPE240	0.98	0
7	145.33	5.0	UNP240	0.83	0
8	48.21	5.0	IPE160	0.96	0
9	49.08	5.0	IPE160	0.97	0
10	96.10	5.0	IPE200	0.94	0
11	95.71	5.0	IPE200	0.94	0
12	48.46	5.0	IPE160	0.96	0

Table 6.22: Column design of a result of analysis 3.1

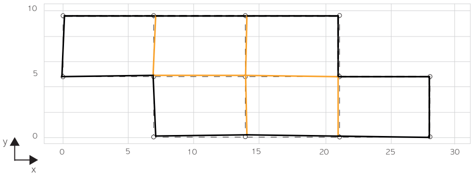
In Table 6.23, the normative value (moment, shear force or deflection) resulting in the highest UC-value is colored gray.

	Node1	Node2	h[m]	L[m]	Profile	V[kN]	M[kNm]	w[mm]	UC	New(0) *or* Reused(1)
13	0	1	5.0	7.0	HEB180	24.32	56.14	27.02	0.96	0
14	1	2	5.0	7.0	HEB180	24.05	55.71	26.81	0.96	0
15	2	3	5.0	7.0	HEB180	24.17	56.34	27.11	0.97	0
16	0	4	5.0	4.8	UNP200	24.80	38.70	17.56	0.91	0
17	1	5	5.0	4.7	HEA200	47.98	74.85	16.87	0.90	1
18	2	6	5.0	4.7	HEA200	48.21	75.31	16.96	0.90	1
19	3	7	5.0	4.8	UNP200	24.50	39.09	17.73	0.92	0
20	4	5	5.0	7.0	HEB180	24.33	56.11	27.01	0.96	0
21	5	6	5.0	7.1	HEB220	48.78	114.70	26.89	0.95	1
22	6	7	5.0	7.1	HEB220	48.63	114.74	26.90	0.95	1
23	7	8	5.0	7.0	HEB180	24.12	56.21	27.05	0.97	0
24	5	9	5.0	4.8	UNP200	24.82	39.04	17.71	0.92	0
25	6	10	5.0	4.7	HEA200	48.29	75.23	16.95	0.90	1
26	7	11	5.0	4.7	HEA200	48.03	75.06	16.90	0.90	1
27	8	12	5.0	4.8	UNP200	24.34	38.81	17.61	0.92	0
28	9	10	5.0	7.0	HEB180	24.27	56.32	27.11	0.97	0
29	10	11	5.0	7.0	HEB180	24.02	55.72	26.82	0.96	0
30	11	12	5.0	7.0	HEB180	24.14	56.21	27.05	0.97	0

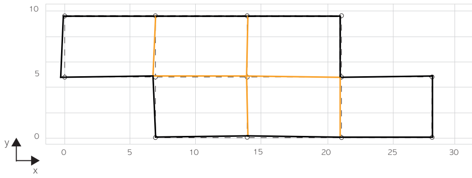
Table 6.23: Beam design of a result of analysis 3.1

N normal force in *kN*
L length in *m*
h height in *m*
V maximum shear force in *kN* (absolute)
M maximum moment in *kNm*
w deflection in *mm*
UC normative UC-value

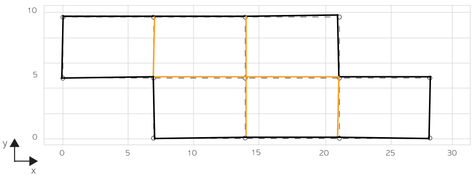
There are multiple results with the same element-configuration. However, the nodal coordinates slightly change. Eight of these beam-configurations are displayed in Figure 6.14. As visible, the characteristics of these beam-configuration are similar.



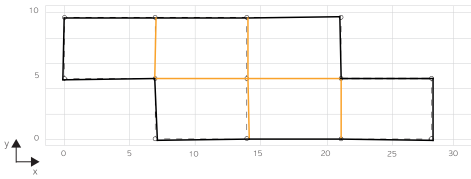
Mean UC columns: 0.94
Mean UC beams: 0.94
Minimum angle: 86.81
Number of changing angles: 22
Number of changing angles more than 10%: 0



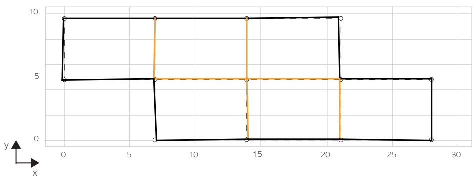
Mean UC columns: 0.93
Mean UC beams: 0.94
Minimum angle: 86.81
Number of changing angles: 22
Number of changing angles more than 10%: 0



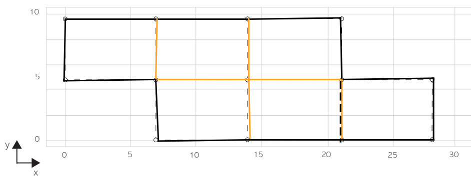
Mean UC columns: 0.94
Mean UC beams: 0.94
Minimum angle: 88.00
Number of changing angles: 21
Number of changing angles more than 10%: 0



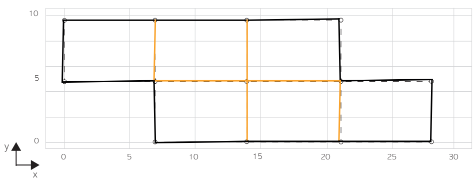
Mean UC columns: 0.94
Mean UC beams: 0.94
Minimum angle: 87.60
Number of changing angles: 20
Number of changing angles more than 10%: 0



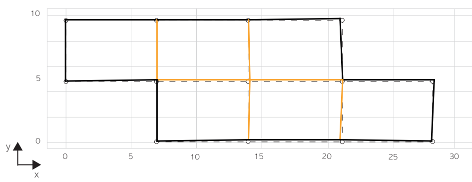
Mean UC columns: 0.94
Mean UC beams: 0.94
Minimum angle: 87.59
Number of changing angles: 21
Number of changing angles more than 10%: 0



Mean UC columns: 0.94
Mean UC beams: 0.94
Minimum angle: 87.60
Number of changing angles: 20
Number of changing angles more than 10%: 0



Mean UC columns: 0.93
Mean UC beams: 0.94
Minimum angle: 88.00
Number of changing angles: 22
Number of changing angles more than 10%: 0



Mean UC columns: 0.93
Mean UC beams: 0.94
Minimum angle: 87.55
Number of changing angles: 21
Number of changing angles more than 10%: 0

Figure 6.14: 8 out of 39 possibilities for the beam-configuration of the most circular result of analysis 3.1

6.4.2. Analysis 3.2

Stock	Original UC between	Maximum deviation in length (%)
3	0.8 - 1.0	30

Table 6.24: Constraints in analysis 3.2

The values displayed in Table 6.24 serve as an input for analysis 3.2. The results are the same as the results of analysis 3.1.

6.4.3. Analysis 3.3

Stock	Original UC between	Maximum deviation in length (%)
3	0.01 - 1.0	10

Table 6.25: Constraints in analysis 3.3

When the constraints as presented in Table 6.25 are implemented in the model, the result is the design presented in Figure 6.15. The numbers in this Figure are corresponding to Table 6.26 and Table 6.27. In this result, all the elements in the structure are reused and therefore the amount on new steel used in the design is $0m^3$.

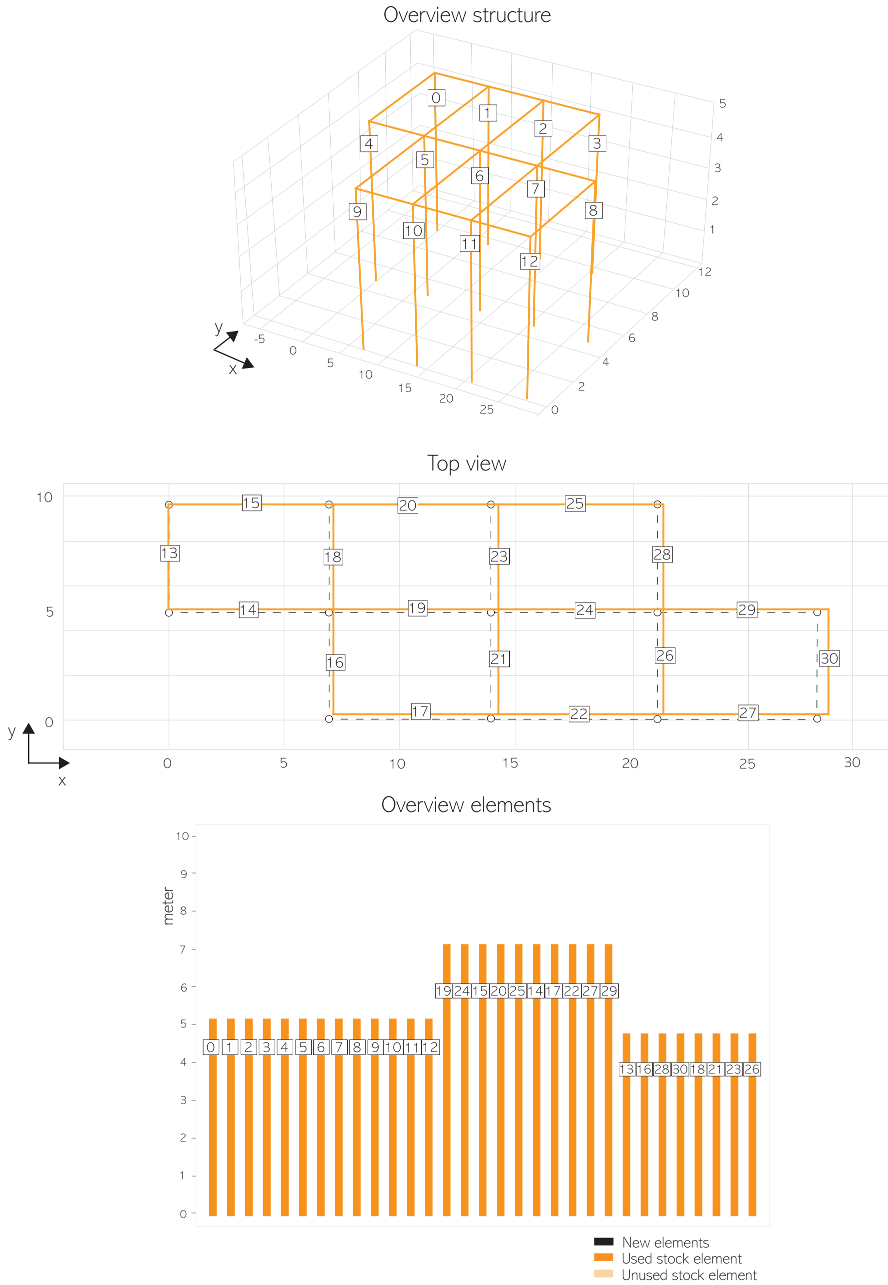


Figure 6.15: A result with the most circular element-configuration of analysis 3.3

	N[kN]	L[m]	Profile	UC	New(0) *or* Reused(1)
0	48.35	5.1	HEA100	0.57	1
1	96.71	5.1	HEA140	0.44	1
2	96.71	5.1	HEA140	0.44	1
3	48.35	5.1	HEA100	0.57	1
4	48.35	5.1	HEA100	0.57	1
5	145.06	5.1	HEA140	0.65	1
6	193.41	5.1	HEA140	0.87	1
7	145.06	5.1	HEA140	0.65	1
8	48.35	5.1	HEA100	0.57	1
9	48.35	5.1	HEA100	0.57	1
10	96.71	5.1	HEA140	0.44	1
11	96.71	5.1	HEA140	0.44	1
12	48.35	5.1	HEA100	0.57	1

Table 6.26: Column design of a result of analysis 3.3

In Table 6.27, the normative value (moment, shear force or deflection) resulting in the highest UC-value is colored gray.

	Node1	Node2	h[m]	L[m]	Profile	V[kN]	M[kNm]	w[mm]	UC	New(0) *or* Reused(1)
13	0	4	5.1	4.7	HEA180	24.18	37.88	12.54	0.67	1
14	4	5	5.1	7.1	HEB200	24.18	57.22	19.05	0.67	1
15	0	1	5.1	7.1	HEB200	24.18	57.22	19.05	0.67	1
16	5	9	5.1	4.7	HEA180	24.18	37.88	12.54	0.67	1
17	9	10	5.1	7.1	HEB200	24.18	57.22	19.05	0.67	1
18	1	5	5.1	4.7	HEA200	48.35	75.75	17.06	0.91	1
19	5	6	5.1	7.1	HEB220	48.35	114.44	26.83	0.94	1
20	1	2	5.1	7.1	HEB200	24.18	57.22	19.05	0.67	1
21	6	10	5.1	4.7	HEA200	48.35	75.75	17.06	0.91	1
22	10	11	5.1	7.1	HEB200	24.18	57.22	19.05	0.67	1
23	2	6	5.1	4.7	HEA200	48.35	75.75	17.06	0.91	1
24	6	7	5.1	7.1	HEB220	48.35	114.44	26.83	0.94	1
25	2	3	5.1	7.1	HEB200	24.18	57.22	19.05	0.67	1
26	7	11	5.1	4.7	HEA200	48.35	75.75	17.06	0.91	1
27	11	12	5.1	7.1	HEB200	24.18	57.22	19.05	0.67	1
28	3	7	5.1	4.7	HEA180	24.18	37.88	12.54	0.67	1
29	7	8	5.1	7.1	HEB200	24.18	57.22	19.05	0.67	1
30	8	12	5.1	4.7	HEA180	24.18	37.88	12.54	0.67	1

Table 6.27: Beam design of a result of analysis 3.3

N normal force in *kN*
L length in *m*
h height in *m*
V maximum shear force in *kN* (absolute)
M maximum moment in *kNm*
w deflection in *mm*
UC normative UC-value

Whatever baseline is used to formulate the geometry, the beam-configuration remains the same. All the angles stay 90 degrees. The mean UC-value of the columns is 0.56 and the mean UC-value of the beams is 0.76.

6.4.4. Analysis 3.4

Stock	Original UC between	Maximum deviation in length (%)
3	0.01 - 1.0	30

Table 6.28: Constraints in analysis 3.4

The results obtained in analysis 3.4 are equal to the results obtained in analysis 3.3. This is due to the fact that there is no improvement possible, since all the amount of new steel required to realize the design is $0m^3$ in analysis 3.3.

6.5. Results

6.5.1. Influence constraints

Analyses 1.1, 1.2, 2.1 and 2.2 do not result in any designs in which reusable elements are included. However, in analysis 1.3, 1.4, 2.3, 2.4 and 3.1 to 3.4 the resulting designs include reused elements. A summary of the results is shown in the Tables 6.29 to 6.31 and Figure 6.16. By looking at the obtained results, it is possible to draw certain conclusions about the influence of the constraints.

- **Minimum UC-value** In analysis 1 and 2, the sub-analyses were only successful when the minimum allowed UC-value was set 0.01. In analysis 3, all different sub-analyses were successful, despite the minimum UC-value being 0.8.

  As visible in Table 6.29, the mean UC-value for the columns was 0.33 for analysis 1.3 and between 0.63 and 0.69 for analysis 1.4. The mean UC-value for the beams was between 0.88 and 0.89 and between 0.17 and 0.18 respectively.

  As visible in Table 6.30, analysis 2 had similar results. The mean UC-value for the columns was 0.37 for analysis 2.3 and between 0.69 and 0.70 for analysis 2.4. The mean UC-value for the beams was 0.88 and 0.20 respectively.

  In analysis 1.3 and 2.3, the mean UC-value of the columns is relatively low compared to the mean UC-value of the beams. This can be explained by the implementation of mainly reused columns. For analysis 1.4 and 2.4, this is opposite. The mean UC-value of the columns is higher than the mean-UC value of the beams. In these results, the reused elements are mostly implemented as beams.

  In analysis 1.3, 1.4, 2.3 and 2.4, the implementation of reusable elements causes very low UC-values in the resulting designs. This is different compared to analysis 3.3 and 3.4, where the mean UC-values for both columns and beams are relatively high (0.56 and 0.75 respectively) despite the complete load-bearing structure being constructed out of reused elements.

- **Maximum deviation in length** The volume of new steel required to realize a design is affected by this parameter. This number decreases for analysis 1 and 2 whenever more deviation is allowed. Although the amount of new steel needed to realize the designs of analysis 1.4 and 2.4 (30% deviation allowed) is lower than in analysis 1.3 and 2.3 (10% deviation allowed), the design also changes more drastically. More irregular shapes are created and the different nodes move further from their original position compared to the results from analysis 1.3 and 2.3 in which the original beam-configuration is still clearly visible. The amount of angles changing more than 10% increases significantly from 0 to a maximum of 19 in analysis 1 and 0 to 16 in analysis 2. Besides, the minimum angle in the results of analysis 1.4 are between 36.48 and 59.56 degrees, while originally every angle was 90 degrees. This also happens in analysis 2.4, where every result has a minimum angle of 45.091 degrees.

  In analysis 3.1 and 3.2, the minimum angle is between 86.81 and 88.78. In these analysis 20 to 22 angles change, of which none more than 10%. In analysis 3.3 and 3.4, more elements can be included which have an equal length. Although the measurements of the design change, all angles remain 90 degrees.

6.5.2. Influence stock

As shown in Table 6.1, stock 1 and stock 2 can be considered more diverse than stock 3 because of the inclusion of more different element groups. Due to the fact that more elements have an equal length, the design changes less. In analysis 1.4 and 2.4, the amount of changing angles is max. 22 and 20 out of 24, and the number of angles changing more than 10% is max. 19 and 16 respectively. In analysis 3.4, the sizes of the angles do not change.

The capacity of the elements in stock 3 matches better with the original design than the elements in stock 1 and 2. This is reflected in the UC-values. Although the UC-values for the columns are relatively high for analysis 1.4 and 2.4, the UC-values related to the beams are low (0.18 and 0.20 respectively in analysis 1.4 and 2.4), mainly due to the implementation of oversized reused elements. This is different in analysis 3.3 and 3.4, where the mean UC-value for the beams is 0.56 and the columns is 0.75, even though this structure is completely constructed from reused elements.

Therefore, stock 3 is more suitable to the original design because of less change in the design and higher UC-values overall. Besides, the need for new steel is zero, since the structure is completely made of reused elements.

Analysis	**1.1**	**1.2**	**1.3**	**1.4**
Maximum deviation in length (%)	10	30	10	30
Minimum UC-value	0.8	0.8	0.01	0.01
Volume new steel (m^3)	-	-	0.52	0.18
UC columns	-	-	0.33	0.63 - 0.69
UC beams	-	-	0.88 - 0.89	0.17 - 0.18
Minimum angle	-	-	82.60 - 86.42	36.48 - 59.56
Number of changing angles	-	-	17 - 22	20 - 22
Number of angles changing more than 10%	-	-	0	11 - 19

Table 6.29: Summary of the results of analysis 1

Analysis	**2.1**	**2.2**	**2.3**	**2.4**
Maximum deviation in length (%)	10	30	10	30
Minimum UC-value	0.8	0.8	0.01	0.01
Volume new steel (m^3)	-	-	0.72	0.23
UC columns	-	-	0.37	0.69 - 0.70
UC beams	-	-	0.88	0.20
Minimum angle	-	-	88.64 - 88.68	45.09
Number of changing angles	-	-	10 - 19	20
Number of angles changing more than 10%	-	-	0	16

Table 6.30: Summary of the results of analysis 2

Analysis	**3.1**	**3.2**	**3.3**	**3.4**
Maximum deviation in length (%)	10	30	10	30
Minimum UC-value	0.8	0.8	0.01	0.01
Volume new steel (m^3)	0.61	0.61	0	0
UC columns	0.93 - 0.94	0.93 - 0.94	0.56	0.56
UC beams	0.94	0.94	0.75	0.75
Minimum angle	86.81 - 88.78	86.81 - 88.78	90	90
Number of changing angles	20 - 22	20 - 22	0	0
Number of angles changing more than 10%	0	0	0	0

Table 6.31: Summary of the results of analysis 3

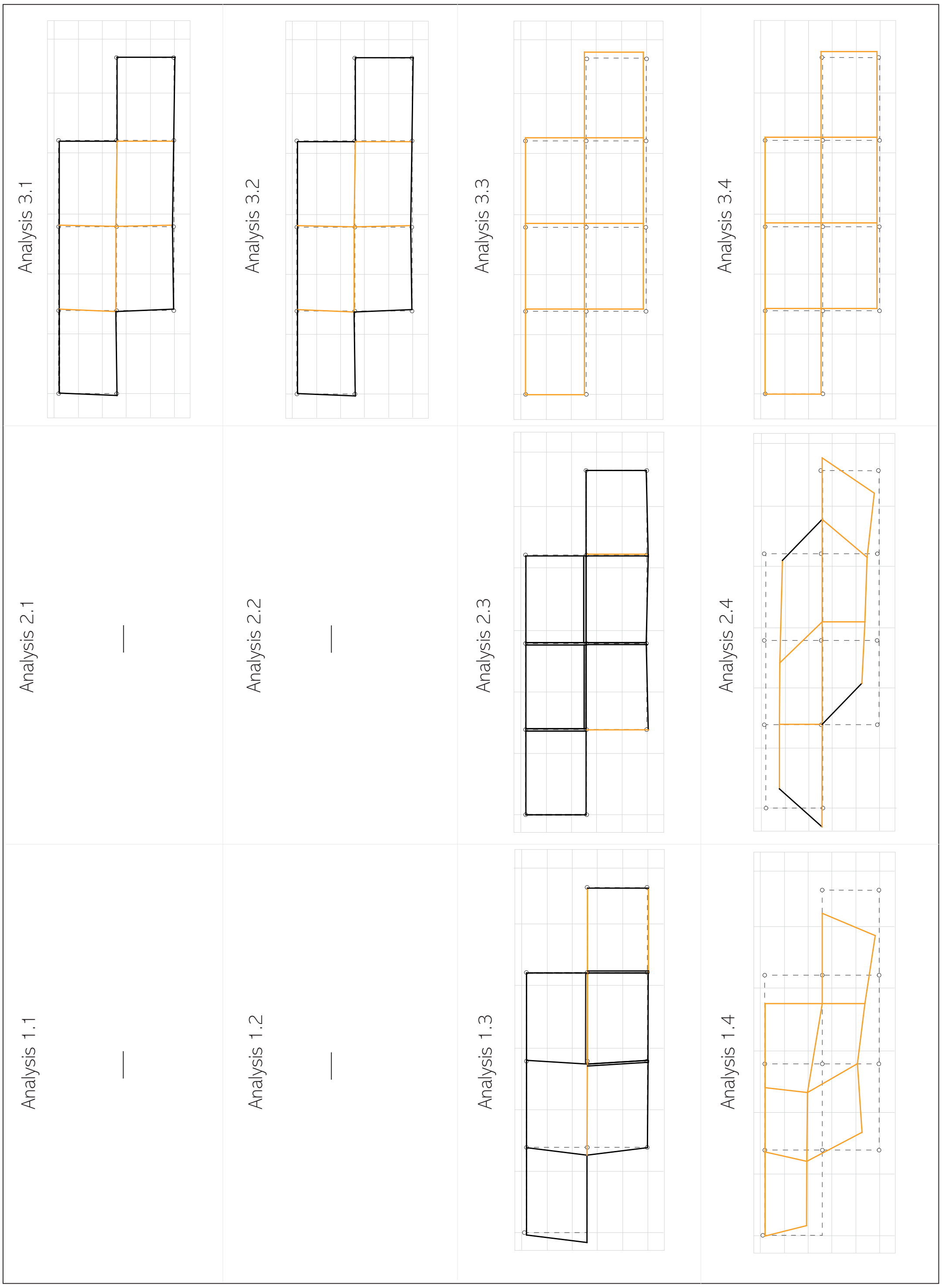


Figure 6.16: Overview of all results

7

Discussion

In this study, literature study has been performed and a model has been developed to be able to answer the research questions. In this Chapter, the limitations of the applied method and the usability of the model will be discussed. Another point of interest is the link between the obtained results and sustainability.

7.1. Limitations

The model results in designs which include reused elements. These reused elements are applied by the method discussed in Chapter 5. However, this method has certain limitations, resulting in the fact that the results do not always reflect reality. These limitations are related to the geometry of the input and output, the element assignment procedure and the structural calculations included in the method.

- **Geometry**
  - The beam-configuration of the geometry which serves as an input for the model can only consists of triangles, quadrilaterals or pentagons.
  - The beam-configurations resulting from the model might not be practical since extra forces can occur due to the unconventional shapes.
- **Element assignment**
  - The cutting of elements is not possible in the model. However, adding this feature might increase the possibility to implement reusable elements and possibly decrease the amount of new steel required to realize the design of a load-bearing structure.
  - Joint designs are not taken into consideration in this study. However, the applicability of reusable elements might be influenced by the lay-out of the required joint. Besides, sharp angles might result in problems in later steps of the design process.
  - Sizes of the elements have not been taken into account. For example, there is no limitation on the height of two adjacent split levels. This may cause a problem if the difference in height is equal to or lower than the height of the applied beams.
  - The placement of the reusable columns to certain positions goes in a specific way as shown in Figure 7.1. However, there are multiple other possibilities, such as splitting the element groups or decreasing the size of an element group (for example; to only use 5 elements when there are 6 elements available). This can increase the amount of possible column-configurations. The latter is now only applied when there is no other column-configuration possible.
  - It is not always possible to connect the two reusable elements assigned to certain positions, as visible in Figure 7.2. The circles represent the reach of the two elements. As visible, the circles do not intersect. Therefore this option is not possible. The more deviation in length between the original and reusable element is allowed, the more often this happens. In these situations where there is no answer, the model places the node where the two reusable elements meet on the wrong location. Therefore, this answer is not correct. The designs in which this happens, are

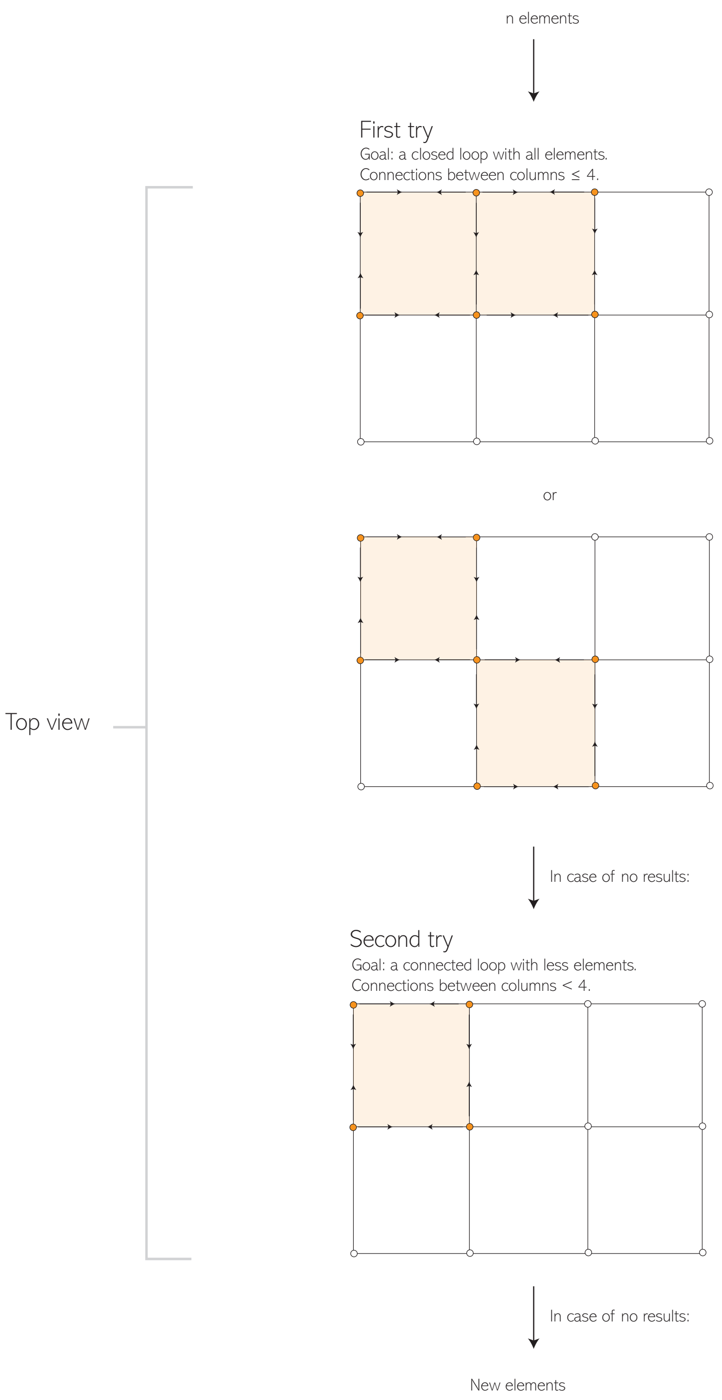


Figure 7.1: The column assignment procedure

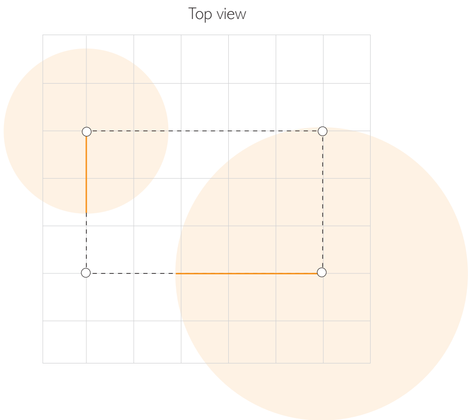


Figure 7.2: No intersection of the two assigned reusable elements

filtered from the batch with all the designs. However, at some point this might result in an analysis without results.

- The beam-assignment procedure does not guarantee to give the optimal result. A certain amount of iterations is performed. Every iteration, the model applies elements on random positions and calculates the total UC-value. Although the final beam-configuration is chosen based on the highest UC-value found, this is not guaranteed to be the optimal solution.

- **Structural calculations**

  - In the model, the load on a floor is divided as visible in Figure 7.3a. The actual load distribution is visible in Figure 7.3b, where the forces acting on the floor go to the beams via the shortest distance (in the case of four equally stiff beams). This means that in real situations, the short beams in the rectangle carry less load than assumed in the model and the longer beams in the rectangle carry more load than assumed in the model.

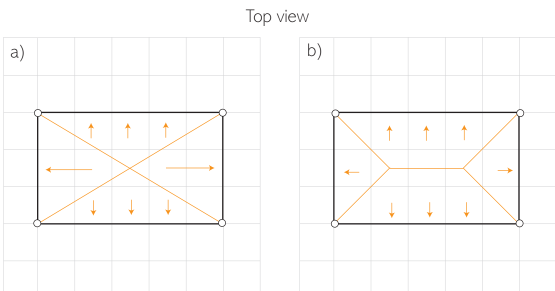


Figure 7.3: The load distribution adopted in the model (a) and the actual load distribution in case of four equally stiff beams (b)

  - For most cases, the formula for deflection works as supposed to (Appendix B). However, when the load is triangular and the highest point of the load is close to the supports, the formula can give wrong results. This is checked in the model. Whenever this happens, the load is considered as displayed in Figure 7.4. The result for deflection might therefore be lower than in reality due to the absence of a small part of the total load.

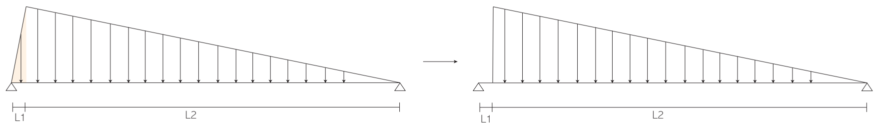


Figure 7.4: Load scheme used for deflection when the highest point of the load-triangle is close to the support

- Horizontal forces such as wind forces are not considered in the model made for this study. The connections between the beams are assumed to be hinged connections. Stability of the resulting designs is therefore not guaranteed. Stability could be guaranteed by applying diagonal members in between two columns and a stiff roof deck.
- Only basic structural calculations are performed. Extra checks could be performed such as lateral torsional buckling. More complex and additional calculations could conclude that the results are not structurally safe.

7.2. Usability

- **Computation time** When the stock is big and there are plenty of suitable elements to function as columns, the computational time of the model is very high (ascending to 24hours).
- **Execution** It is doubtful whether the obtained designs are feasible. Like mentioned before, the resulting structures are not assured to be structurally safe, joint designs are not taken into account and the resulting beam-configurations can be unpractical. Further development of the model is therefore necessary to guarantee feasible designs.

7.3. Sustainability

- **Additional steps** The process before applying the reusable elements in the structure is not taken into account. It is expected that all the elements in the stock are suitable for reuse. These processes might affect the environmental benefit of building with reusable elements. For example, if a reusable element has to be transported over a great distance, the environmental benefit of building with reusable elements can be negatively influenced.
- **Element Assignment** When a new element is needed, the element with a UC-value closest to one is chosen for this position. However, sometimes this element has a bigger cross-section (and thus consists of more steel) than a profile which would lead to an UC-value of for example 0.8. For example, assigning an IPE-profile as a column causes a UC-value close to one because of buckling in the weak axis. The height and width ratio for IPE-profiles is high, and therefore the profile is relatively oversized for buckling in the strong axis. For an HEA-profile, the height and width lie closer to each other. It might be that the buckling in the weak-axis results in a lower UC-value, but buckling in the strong-axis in a higher UC-value. Therefore choosing a HEA-profile might be a more efficient choice.
- **Stock** If the elements are used to their full capacity, the UC-value of this element is one. An element corresponding to a low UC-value can be considered as oversized. Oversized elements can be considered unsustainable since the amount of steel used is more than needed. The weight of the structure increases compared to when suitable profiles would have been used. An increasing weight can result in the need for a bigger foundation, resulting in more material use.

  For this reason, the amount of new steel needed to realize the designs is not the only characteristic of the resulting designs which indicates whether the results are sustainable. Despite the implementation of reusable elements, the structure can increase in weight. Besides, when a UC-value of a reusable element is low, it is more logical to replace it with a new, smaller, element. Implementing a reusable element on a position which results in a UC-value of 0.01 and consequently implementing a new element on a different position where the reusable element would have a UC-value of 0.8 is no sustainable choice. A more logical choice is to implement the reusable element on the second position and implement a smaller new element on the first position, even if both positions are not in the same structure.

As explained in Chapter 6, the UC-values corresponding to the different results are dependent on the stock used as an input. In the different analyses where the constraint for the minimum UC-value is set to 0.01, the actual minimum UC-value of the result differs due to the variety of elements in stock. In analysis 1 and 2, the UC-values are relatively low compared to the UC-values of analysis 3. Therefore, it is depending on composition of the stock whether implementing reusable elements in the structure is an actual sustainable choice.

8
Conclusions and Recommendations

8.1. Conclusions

The main research question of this study was formulated as follows:

How to implement reusable elements in the design of a load-bearing structure in a way that minimizes the amount of steel required to realize the design and which respects the architectural and structural constraints?

Sub-questions following from this main research question were:

1. *How does implementing reusable elements affect the design process of a load-bearing structure?*
2. *How can the optimization problem be defined and modelled?*
3. *How is the amount of new steel in a load-bearing structure affected by the architectural and structural constraints?*

The first sub-question is answered by literature study in Chapter 3. In this Chapter different projects were discussed where structural reusable elements were implemented in the load-bearing structure. After analyzing the design process which led to realizing these buildings, it became clear that constructing and designing with reusable elements comes, compared to the traditional approach, with the inclusion of extra steps:

- After a potential stock of reusable elements have been found, the elements should be checked, tested and measured to identify the different characteristics of the elements. The need to check the different elements is emphasized in the study of Rakshan et al. [30], who state that the reuse potential of a structural element is affected by the potential presence of contaminating, hazardous and banned coatings on the element.
- After the characteristics are known, the conclusion might be that refurbishment of certain elements is necessary.
- Extra transportation of the potential reusable elements might be necessary since it is possible that procedure explained above needs to happen on a different location than the building site.

According to Rakshan et al [30], a different factor influencing the reuse potential of a certain element is the match with a new design. This idea that an element should match the design for the new load-bearing structure, agrees with the study of Gorgolewski et al. [15], which states that if the goal is to implement reusable elements in the load-bearing structure of a building, this should be identified in the beginning of the design process. In that respect, the design can follow from the availability of elements and therefore the stock can be used in the most efficient way. The proof of this statement was the project Biopartner 5, Leiden, where the design had to change after the idea of applying reusable elements came to mind in a later stage in the design process.

Realizing a building with reusable elements also has economical consequences, since more time is needed to realize the project, the process changes and checks on the reusable elements have to be performed. On the other hand, according to the study of Brutting et al [9], the environmental impact of a structure which includes reusable elements lowers.

To answer the second research question, the literature study described in Chapter 4 can be used. As stated in this Chapter, an optimization process should have an objective, variables and constraints. For this study, the objective is to minimize the amount of steel required to realize a design for a load-bearing structure. The variables are the nodal coordinates, who can move based on the lengths of the reusable elements. Furthermore, the cross-sectional areas of the different elements can be considered as variables. However, the cross-sectional areas are first limited by the available elements in stock and later by the elements available in the market. The constraints are different parameters indicating the minimum and maximum UC-value and the deviation in length a reusable element can have compared to the original element.

In different studies in which optimization in combination with applying reusable elements in a load-bearing structure was used, the set-up of the optimization process included the following steps:

1. Geometry definition
2. Element assignment
3. Structural calculations
4. Optimization

These steps have also been applied in the model discussed in this study. The geometry is defined by implementing a list of coordinates which represent the nodes and a list of bars which are located between these nodes. The element assignment-procedure is split up in two different parts: the assignment of columns and the assignment of beams. Columns were assigned in such a way that the roof stayed flat. For assignment of beams, no boundaries were given as to the shapes the beam-configuration could take. For both the beams and columns, basic structural calculations were integrated into the optimization process so that basic structural safety was guaranteed. All the different steps were formulated so that the goal of minimizing the amount of new steel required to realize the design of a load-bearing structure would succeed.

The third research questions was answered by the results following from the model. It turned out that the amount of new steel required to realize the design for a load-bearing structure lowers when the boundary for the minimum UC-value is low. However, it is depending on the available stock how low the actual UC-values will be and what change in design the implementation of reusable elements will cause. The same applies to the maximum deviation in length. In some analysis, increasing the deviation from 10% to 30% granted the number of suitable elements and lowered the amount of new steel required to realize the design. In other analysis, all the elements in stock were already respecting the constraints when the value for the maximum deviation was set to 10% and increasing this value did not matter.

Whenever the stock matches the design (such as in analysis 3 in Chapter 6), the outcome can be a structure in which the mean UC-values are relatively high (0.56 for columns and 0.75 for beams) and in which the angles do not change. Besides, the complete structure can be constructed from reusable elements, so no new steel is needed to realize the design. However, when the stock does not match the original design and the maximum deviation in length of the reusable element compared to the original element is set to 30%, the implementation of reusable elements can cause low UC-values (minimum of 0.17) and a drastic change in design (up to 19 angles changing more than 10%), but the amount of new steel needed to realize the design can also lower up to $0.18m^3$ (analysis 1.4 in Chapter 6).

To answer the main research question: the method described in Chapter 5 and shortly in this Chapter, can change the original design of a load-bearing structure in a way that the amount of new steel needed to realize the design lowers, while respecting the given constraints. However, depending on the values for the constraints and the available stock, it can cause low UC-values and drastic changes in the beam-configuration.

,

8.2. Recommendations

As discussed in Chapter 7, several improvements could be implemented in the model to increase its functionality and remove its limits. The mentioned improvements form the basis for the following recommendations:

- **Improvements in the method** The possibility to use the model for more structural systems will increase its functionality. Besides, the load-path assumed in the model should become more realistic. Joint design can be taken into account, e.g. by considering the angles between two beams and the height difference of two split levels. More (complex) structural calculations can be implemented and horizontal forces should be taken into account.

  Possible improvements of the method could be to allow cutting of the reusable elements. This would avoid the need for split levels in case reusable elements are implemented as columns. Besides, the beam assignment-procedure could be improved by implementing an optimization algorithm. Also, topological optimization could be performed simultaneously to assigning reusable element to avoid very low UC-values and to therefore make the complete method more sustainable. Furthermore, not only the amount of new steel should be minimized but the total environmental burden of the structure, also considering the processes to make an element suitable for reuse.

- **Improvements regarding accessibility** The model could be implemented in a different software, which is easier to use for people unfamiliar to the coding language Python.

A

Stocks

A.1. Stock used in Chapter 5


```
[
    {
        "Characteristics": {
            "Code": "B1",
            "Type": "HEA160",
            "Length": 4200,
            "Count": 2,
            "Structural Material": "Staal - S235"
        }
    },
    {
        "Characteristics": {
            "Code": "B1",
            "Type": "HEA200",
            "Length": 3200,
            "Count": 4,
            "Structural Material": "Staal - S235"
        }
    },
    {
        "Characteristics": {
            "Code": "B1",
            "Type": "IPE200",
            "Length": 3700,
            "Count": 2,
            "Structural Material": "Staal - S235"
        }
    },
    {
        "Characteristics": {
            "Code": "B1",
            "Type": "HEA160",
            "Length": 1500,
            "Count": 6,
            "Structural Material": "Staal - S235"
        }
    }
]
```


Figure A.1: Stock used in Chapter 5

A.2. Stock used in Chapter 6 Analysis 1


```
[
    {
        "Characteristics": {
            "Code": "B1",
            "Type": "HEM240",
            "Length": 5566,
            "Count": 3,
            "Structural Material": "Staal - S235"
        }
    },
    {
        "Characteristics": {
            "Code": "B1",
            "Type": "IPE240",
            "Length": 6423,
            "Count": 2,
            "Structural Material": "Staal - S235"
        }
    },
    {
        "Characteristics": {
            "Code": "B1",
            "Type": "UNP350",
            "Length": 3582,
            "Count": 4,
            "Structural Material": "Staal - S235"
        }
    },
    {
        "Characteristics": {
            "Code": "B1",
            "Type": "HEB550",
            "Length": 4900,
            "Count": 2,
            "Structural Material": "Staal - S235"
        }
    },
```


Figure A.2: Stock used in Chapter 6 Analysis 1 (1/2)


```
    {
        "Characteristics": {
            "Code": "B2",
            "Type": "IPE270",
            "Length": 6800,
            "Count": 2,
            "Structural Material": "Staal - S235"
        }
    },
    {
        "Characteristics": {
            "Code": "B2",
            "Type": "HEM360",
            "Length": 5200,
            "Count": 4,
            "Structural Material": "Staal - S235"
        }
    },
    {
        "Characteristics": {
            "Code": "B3",
            "Type": "HEB300",
            "Length": 4800,
            "Count": 3,
            "Structural Material": "Staal - S235"
        }
    },
    {
        "Characteristics": {
            "Code": "B3",
            "Type": "HEB240",
            "Length": 7300,
            "Count": 2,
            "Structural Material": "Staal - S235"
        }
    }
```


Figure A.3: Stock used in Chapter 6 Analysis 1 (2/2)

A.3. Stock used in Chapter 6 Analysis 2


```
[
    {
        "Characteristics": {
            "Code": "B1",
            "Type": "HEB340",
            "Length": 9293,
            "Count": 4,
            "Structural Material": "Staal - S235"
        }
    },
    {
        "Characteristics": {
            "Code": "B1",
            "Type": "HEM550",
            "Length": 5331,
            "Count": 4,
            "Structural Material": "Staal - S235"
        }
    },
    {
        "Characteristics": {
            "Code": "B1",
            "Type": "HEA240",
            "Length": 5077,
            "Count": 3,
            "Structural Material": "Staal - S235"
        }
    },
    {
        "Characteristics": {
            "Code": "B1",
            "Type": "UNP180",
            "Length": 4964,
            "Count": 4,
            "Structural Material": "Staal - S235"
        }
    },
    {
        "Characteristics": {
            "Code": "B2",
            "Type": "HEB700",
            "Length": 9801,
            "Count": 1,
            "Structural Material": "Staal - S235"
        }
    },
```


Figure A.4: Stock used in Chapter 6 Analysis 2 (1/2)

```
    {
        "Characteristics": {
            "Code": "B3",
            "Type": "HEM360",
            "Length": 4961,
            "Count": 2,
            "Structural Material": "Staal - S235"
        }
    },
    {
        "Characteristics": {
            "Code": "B3",
            "Type": "HEM200",
            "Length": 3022,
            "Count": 4,
            "Structural Material": "Staal - S235"
        }
    },
    {
        "Characteristics": {
            "Code": "B3",
            "Type": "HEB300",
            "Length": 8459,
            "Count": 4,
            "Structural Material": "Staal - S235"
        }
    },
    {
        "Characteristics": {
            "Code": "B3",
            "Type": "IPE100",
            "Length": 8953,
            "Count": 4,
            "Structural Material": "Staal - S235"
        }
    },
    {
        "Characteristics": {
            "Code": "B3",
            "Type": "HEB360",
            "Length": 3661,
            "Count": 2,
            "Structural Material": "Staal - S235"
        }
    }
]
```


Figure A.5: Stock used in Chapter 6 Analysis 2 (2/2)

A.4. Stock used in Chapter 6 Analysis 3


```
[
    {
        "Characteristics": {
            "Code": "B1",
            "Type": "HEA140",
            "Length": 5100,
            "Count": 7,
            "Structural Material": "Staal - S235"
        }
    },
    {
        "Characteristics": {
            "Code": "B1",
            "Type": "HEA100",
            "Length": 5100,
            "Count": 6,
            "Structural Material": "Staal - S235"
        }
    },
    {
        "Characteristics": {
            "Code": "B1",
            "Type": "HEB220",
            "Length": 7100,
            "Count": 2,
            "Structural Material": "Staal - S235"
        }
    },
    {
        "Characteristics": {
            "Code": "B1",
            "Type": "HEB200",
            "Length": 7100,
            "Count": 8,
            "Structural Material": "Staal - S235"
        }
    },
```


Figure A.6: Stock used in Chapter 6 Analysis 3 (1/2)


```
    {
        "Characteristics": {
            "Code": "B1",
            "Type": "HEA180",
            "Length": 4700,
            "Count": 4,
            "Structural Material": "Staal - S235"
        }
    },
    {
        "Characteristics": {
            "Code": "B1",
            "Type": "HEA200",
            "Length": 4700,
            "Count": 4,
            "Structural Material": "Staal - S235"
        }
    }
```


Figure A.7: Stock used in Chapter 6 Analysis 3 (2/2)

B

Structural Verification

For the structural verification of the model, a simple geometry will be used. The beam-configuration is shown in Figure B.1. The height of the structure is 3 meter. The geometry is subjected to distributed load $q = 5kN/m^2$ on the roof. Normally, the load is different due to different safety factors for checks regarding Ultimate Limit State and Serviceability Limit State. However, in this example the load is the same for every check.

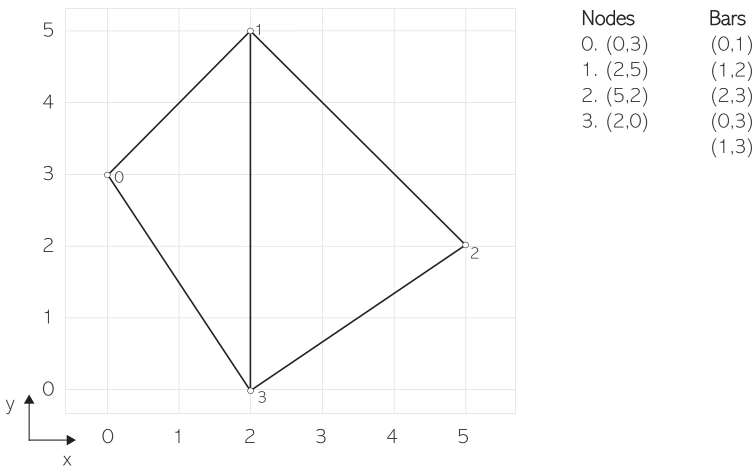


Figure B.1: Beam-configuration of the geometry used in this Appendix

The stock which will serve as in input for this geometry is displayed in Figure B.2. The deviation in length a reusable element can have from the original element is 10% and the minimum UC-value a reusable element can have is 0.01.

```
[
    {
        "Characteristics": {
            "Code": "B1",
            "Type": "HEA100",
            "Length": 3200,
            "Count": 3,
            "Structural Material": "Staal - S235"
        }
    },
    {
        "Characteristics": {
            "Code": "B1",
            "Type": "HEB200",
            "Length": 4500,
            "Count": 1,
            "Structural Material": "Staal - S235"
        }
    }
]
```


Figure B.2: Geometry used for structural verification

The geometry consists of two unequal triangles. To determine the amount of load which is carried by every beam, the formula ***def*** *CalculateLoad* will be used as explained in Chapter 5 of this report. First, the centroids of both the triangles will be calculated to determine which floor-area will be carried by which beam. The centroids of the triangle are visible in Figure B.3.

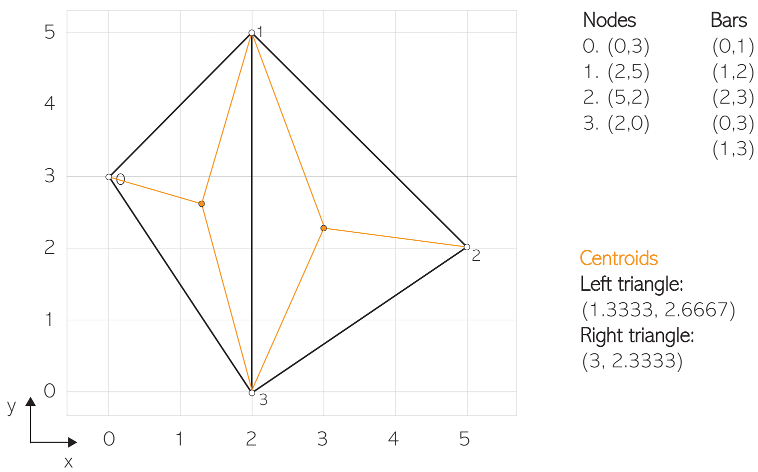


Figure B.3: Division of load

For every triangle, different characteristics are known as later shown in Figure B.5 and B.9. With these characteristics, the Equation representing the load division on the beam can be determined after which the maximum shear force and moment can be calculated per beam. In this Chapter, this process will be explained for the beam between node 1 and 3. After, the normal-force in column 1 will be calculated.

B.1. Beam 13

The load carried by Beam 13 comes from two different triangles, as indicated in orange in Figure B.4.

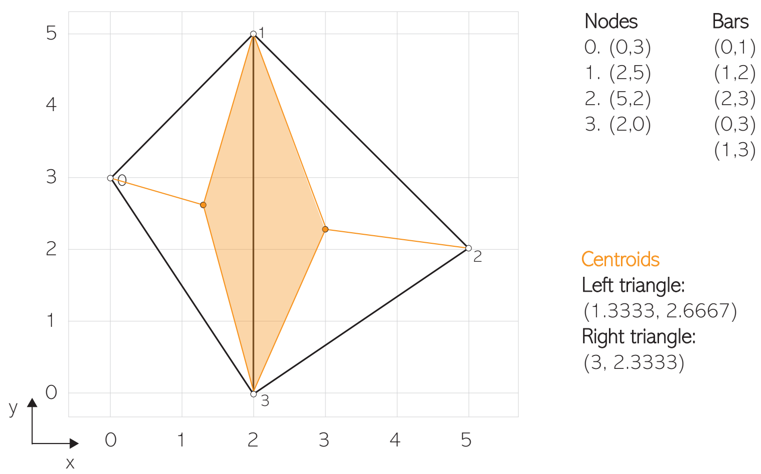


Figure B.4: Floor area carried by Beam 13

In Section B.1.1 the load-division on the beam due to the area covered in the left triangle will be determined and the shear- and moment-distribution will be calculated. In Section B.1.2, the same procedure will be performed for the area covered in the right triangle.

B.1.1. Left triangle

In this Section, the load on Beam 13 due to the area covered in the triangle displayed in Figure B.5 will be determined. After, the support reactions and the size of the moment at mid-span will be calculated. These values will be compared to the values given by the software MatrixFrame.

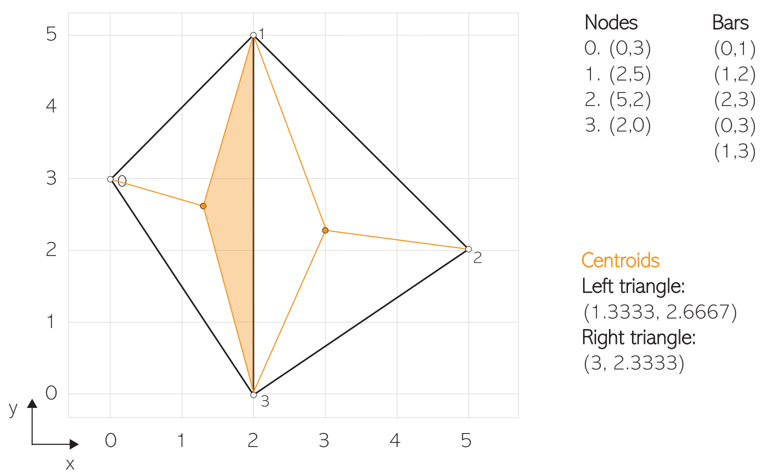


Figure B.5: Left triangle

The characteristics of the triangle displayed in Figure B.5 are visible in Figure B.6.

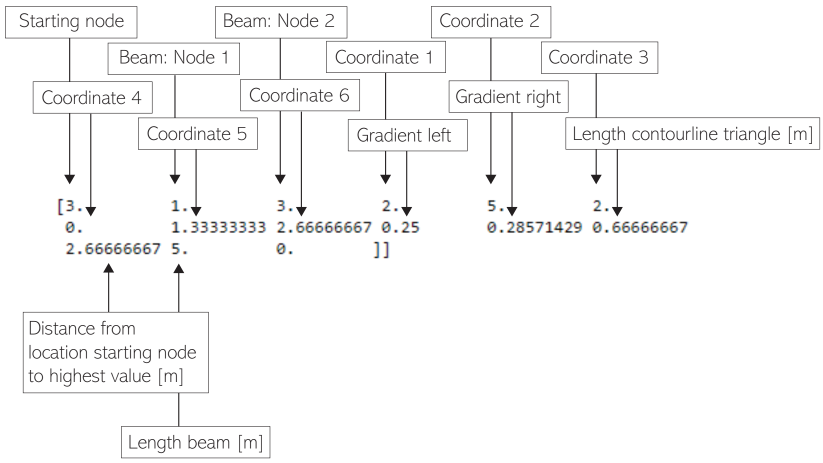


Figure B.6: Characteristics of the orange triangle in Figure B.5

When using the length of the contour line and the given distance between the location of the starting point and the highest point of the triangle, the load scheme in Figure B.7 can be formulated.

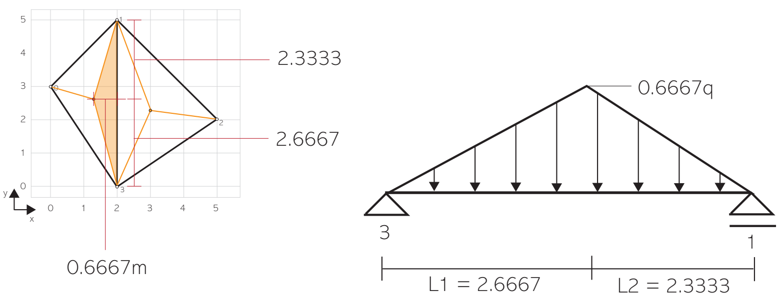


Figure B.7: Load scheme

The highest value of the load has is $0.6667 * 5 = 3.3333$ kN. The support reaction at V_3 can be calculated by using the fact that M_1 is 0, shown in Equation B.1 to B.3.

$$M_1 = \frac{1}{2} * \frac{2}{3} q * \frac{2}{3} * L2^2 + \frac{1}{2} * L1 * \frac{2}{3} * q * (L2 + \frac{1}{3} * L1) - V_3 * (L1 + L2) = 0 \tag{B.1}$$

$$V_3 = \frac{\frac{1}{2} * \frac{2}{3} q * \frac{2}{3} * L2^2 + \frac{1}{2} * L1 * \frac{2}{3} * q * (L2 + \frac{1}{3} * L1)}{(L1 + L2)} \tag{B.2}$$

$$V_3 = \frac{\frac{1}{2} * 3\frac{1}{3} * \frac{2}{3} * 2\frac{1}{3}^2 + \frac{1}{2} * 2\frac{2}{3} * 3\frac{1}{3} * (2\frac{1}{3} + \frac{1}{3} * 2\frac{2}{3}) *}{5} = 4.076kN \tag{B.3}$$

Since there should be a equilibrium in the vertical forces, the support reaction V_3 can be calculated by Equation B.4.

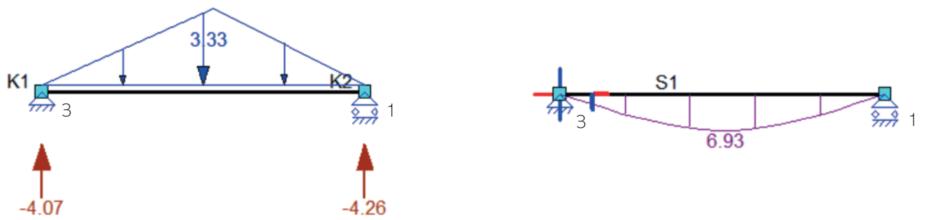
$$V_1 = 0.5 * 3\frac{1}{3} * 5 - V_3 = 4.259kN \tag{B.4}$$

The moment in the middle can be determined by filling in Equation B.5.

$$M_{mid} = V_3 * \frac{L1+L2}{2} - \frac{1}{6} * \frac{\frac{2}{3}q}{L1} * \frac{L1+L2}{2}^3 \tag{B.5}$$

$$M_{mid} = 4.076 * 2.5 - \frac{1}{6} * \frac{3\frac{1}{3}}{2\frac{2}{3}} * 2.5^3 = 6.93kNm \tag{B.6}$$

As visible in Figure B.8, the performing calculations in the software MatrixFrame.



	Label	Type	Beginwaarde	Eindwaarde	Beginafstand	Eindafstand	Richting	Staaf/Knoop	Lasttype	Omschrijving
▶	LD1	qC	3.333	3.333	2.667	2.667	Z'	S1		
*										

Figure B.8: Results obtained from MatrixFrame

B.1.2. Right triangle

In this Section, the load on Beam 13 due to the area covered in the triangle displayed in Figure B.9 will be determined. After, the support reactions and the size of the moment at mid-span will be calculated. These values will be compared to the values given by the software MatrixFrame.

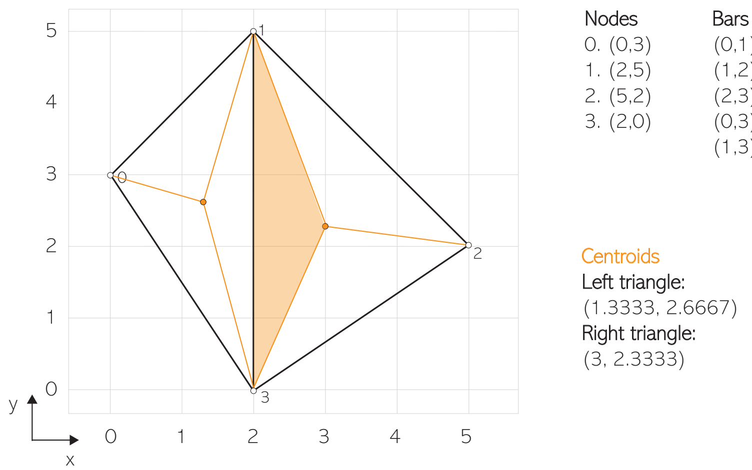


Figure B.9: Right triangle

The characteristics of the orange triangle displayed in Figure B.9 are visible in Figure B.10.

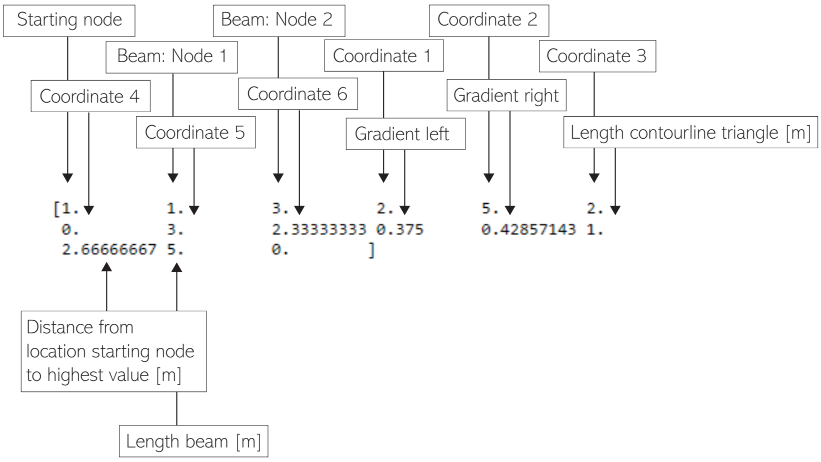


Figure B.10: Characteristics of the orange triangle in Figure B.9

The characteristics shown in Figure B.10 lead to the load scheme in Figure B.11.

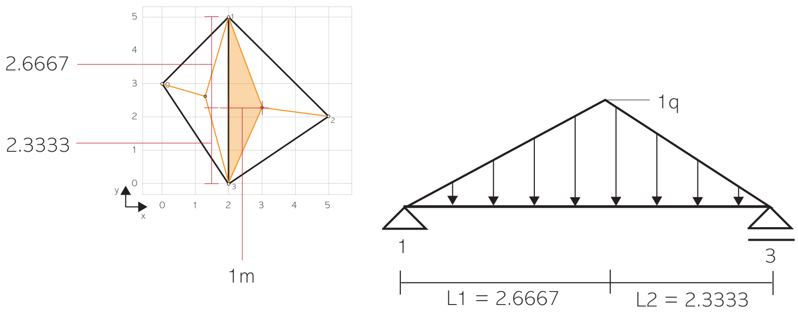


Figure B.11: Load scheme

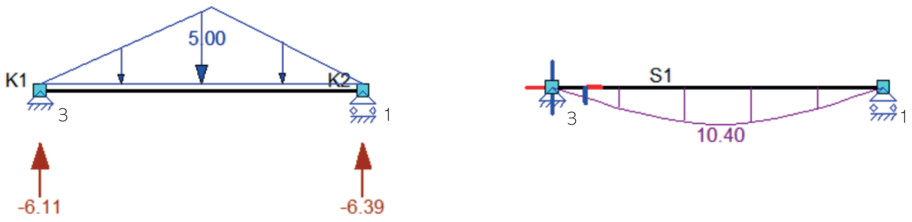
The support reactions can be calculated by the same procedure as used in Section B.1.1. This is shown in Equation B.7 to B.9.

$$V_1 = \frac{\frac{2}{3} * \frac{1}{2} * 5 * 2\frac{1}{3}^2 + (2\frac{1}{3} + \frac{1}{3} * 2\frac{2}{3}) * \frac{1}{2} * 2\frac{2}{3} * 5}{5} = 6.111 kN \tag{B.7}$$

$$V_3 = 0.5 * 5 * 5 - V_1 = 6.389 kN \tag{B.8}$$

$$M_{mid} = 6.111 * 2.5 - \frac{1}{6} * \frac{5}{2\frac{2}{3}} * 2.5 * 2.5^2 = 10.39 kNm \tag{B.9}$$

The same results are obtained when the support reaction and moment is calculated in MatrixFrame, as visible in Figure B.12.



Label	Type	Beginwaarde	Eindwaarde	Beginafstand	Eindafstand	Richting	Staaf/Knoop	Lasttype	Omschrijving
LD1	qC	5.000	5.000	2.667	2.667	Z'	S1		

Figure B.12: Results obtained from MatrixFrame

B.1.3. Summation

The total support reactions and moment can be calculated by summing the results obtained in Section B.1.1 and B.1.2.

The resulting total support reaction for column 1 V_1:

$$V_1 = 4.259 + 6.111 = 10.370 kN \tag{B.10}$$

The resulting total support reaction for column 3 V_3:

$$V_3 = 4.074 + 6.398 = 10.463 kN \tag{B.11}$$

The resulting moment in the middle M_{mid}:

$$M_{mid} = 10.395 + 6.935 = 17.330 kNm \tag{B.12}$$

B.2. Column 1

A part of the normalforce in column 1 is calculated in the previous paragraph. However, the beams 01 and 12 also transfer forces to this columns, as displayed in Figure B.13. The characteristics of the two triangles related to these beams are displayed in Figure B.14 and B.16. The results obtained from the software MatrixFrame are visible in Figure B.15 and B.17.

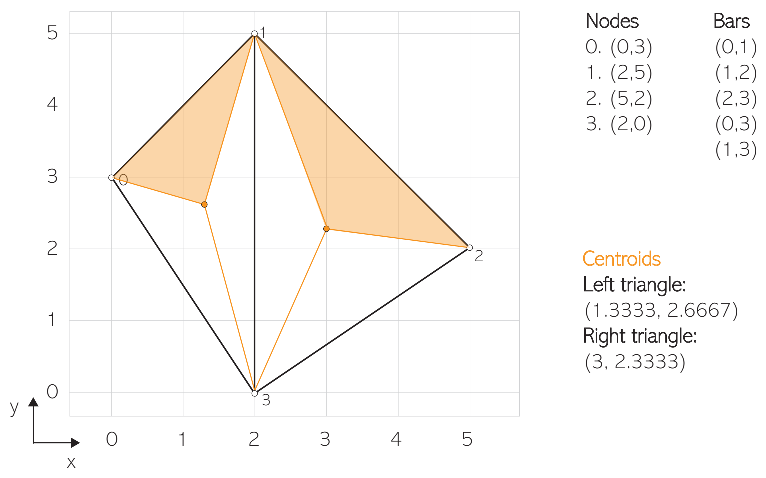


Figure B.13: Two other triangles which cause normalforce in Column 1

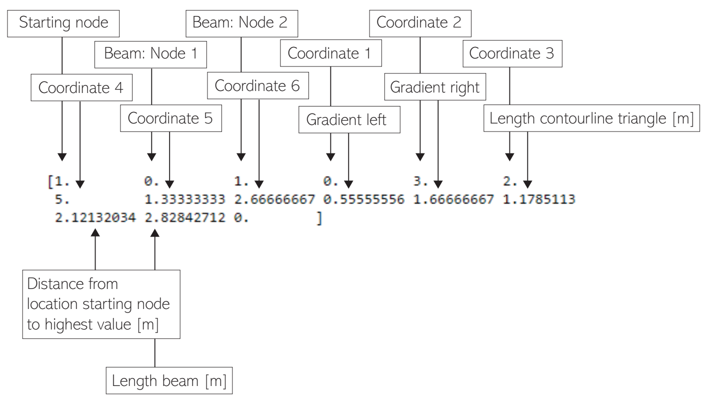
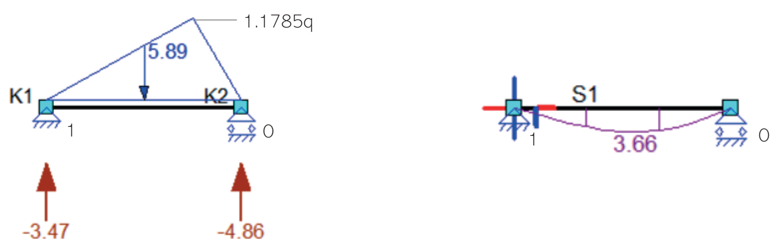


Figure B.14: Characteristics of the load-triangle of beam 01



	Label	Type	Beginwaarde	Eindwaarde	Beginafstand	Eindafstand	Richting	Staaf/Knoop	Lasttype	Omschrijving
▶	LD1	qC	5.893	5.893	2.121	2.121	Z'	S1		
*										

Figure B.15: Results obtained from MatrixFrame

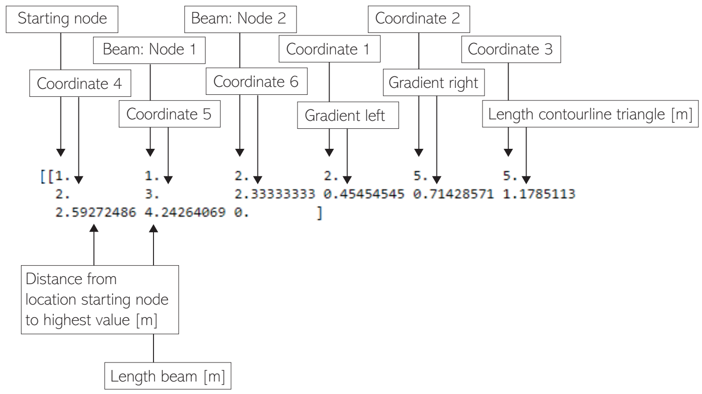


Figure B.16: Characteristics of the load-triangle of beam 13

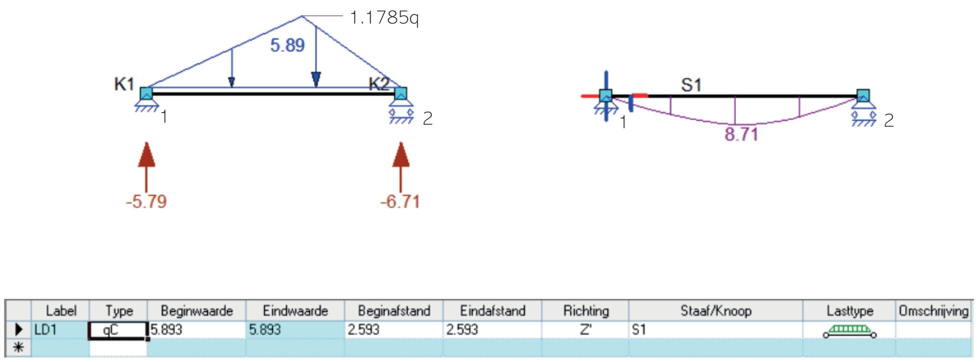


Figure B.17: Results obtained from MatrixFrame

By summing up all the support reactions in column 1, the normalforce N_1 can be calculated as shown in Equation .

$$N_1 = 10.370 + 3.47 + 5.79 = 19.63kN \tag{B.13}$$

B.3. Comparison to model

The different values for support reactions, moments and normal force obtained in the previous Sections are compared to the values found by the model. After comparing Tables B.1 and B.2 with Figure B.18, these values turn out to be the same.

	Beam 13	Beam 01	Beam 12
Maximum shearforce [kN] (absolute)	10.463	4.86	6.71
Maximum moment [kNm]	17.330	3.66	8.71

Table B.1: Values for maximum shearforce and moments in beams

	Column 1
Normalforce [kN]	19.63

Table B.2: Values for normalforce in column 1

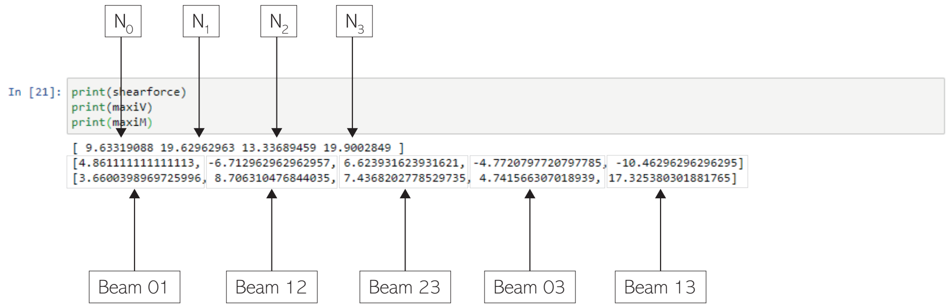


Figure B.18: Values for normalforces, maximum shearforces and moments obtained by the model

The final shear- and moment-distribution per beam is visible in Figure B.19.

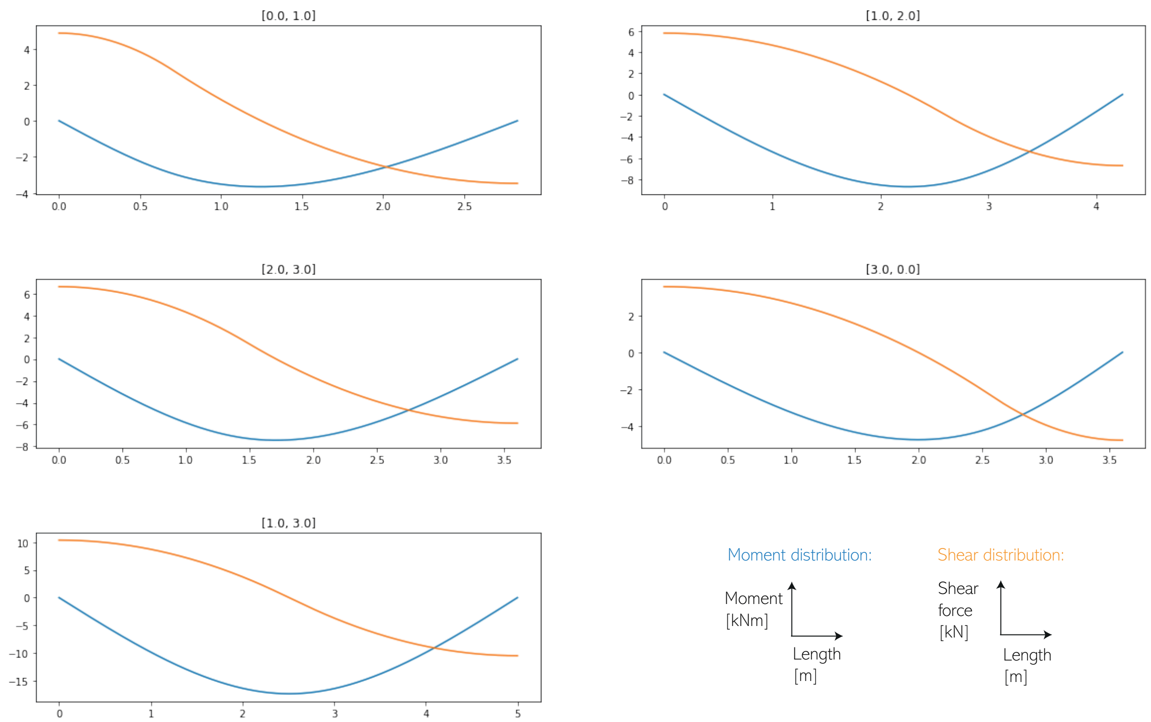


Figure B.19: Shear- and moment-distribution original geometry

B.4. Checks

As visible in Figure B.2, the stock consists of 3 elements which are suitable as columns. Implementing these elements in the geometry causes a split level. The three elements can be assigned to two different sets of members. The extra option is added where all the different columns are made of new elements. These different options are displayed in Figure B.20.

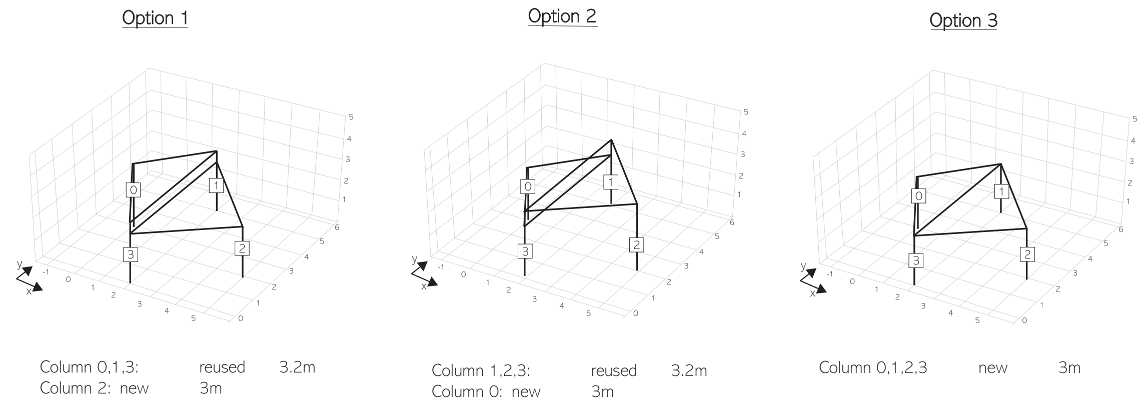


Figure B.20: Different possibilities for the column-configuration

For every option, the two checks explained in Chapter 5 are performed. To check whether the model calculates this correctly, the checks for column 1 are worked out below. As calculated in the Section B.2, the normalforce (N) in column 1 is 19.63 kN. The reusable profile is HEA100 and has an area of $A = 2124mm^2$ and a second moment of inertia around the major axis of $I_{major} = 3.492 * 10^6 mm^4$ and a second moment of interia around the minor axis of $I_{minor} = 1.338 * 10^6 mm^4$. Young's Modulus $E = 210000N/mm^2$

$$\sigma_n = \frac{N}{A} = \frac{19629.629}{2124} = 9.2418 \tag{B.14}$$

$$UC_1 = \frac{\sigma_n}{f_y} = \frac{9.2418}{235} = 0.0393 \tag{B.15}$$

Buckling around the major axis:

$$N_{cr} = \frac{\pi^2 EI}{l^2} = \frac{\pi^2 * 210000 * 3.492 * 10^6}{3200^2} = 706794.75N \tag{B.16}$$

$$\lambda = \sqrt{\frac{Af_y}{N_{cr}}} = \sqrt{\frac{2124 * 235}{706794.75}} = 0.84 \tag{B.17}$$

$\alpha = 0.34$:

$$\phi = 0.5(1 + \alpha(\lambda - 0.2) + \lambda^2) = 0.5(1 + 0.34(0.84 - 0.2) + 0.84^2) = 0.9616 \tag{B.18}$$

$$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \lambda^2}} = \frac{1}{0.9616 + \sqrt{0.9616^2 - 0.84^2}} = 0.69924 \tag{B.19}$$

$$N_{bRd} = \frac{\chi A f_y}{\gamma_{M1}} = \frac{0.69924 * 2124 * 235}{1} = 349133.4233 \tag{B.20}$$

$$UC_2 = \frac{N_{Ed}}{N_{bRd}} = \frac{19629.629}{349133.4233} = 0.0562 \tag{B.21}$$

Buckling around the minor axis:

$$N_{cr} = \frac{\pi^2 EI}{l^2} = \frac{\pi^2 * 210000 * 1.338 * 10^6}{3200^2} = 270816.55N \tag{B.22}$$

$$\lambda = \sqrt{\frac{Af_y}{N_{cr}}} = \sqrt{\frac{2124 * 235}{270816.55}} = 1.36 \tag{B.23}$$

$\alpha = 0.49$:

$$\phi = 0.5(1 + \alpha(\lambda - 0.2) + \lambda^2) = 0.5(1 + 0.49(1.35 - 0.2) + 1.35^2) = 1.71 \tag{B.24}$$

$$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \lambda^2}} = \frac{1}{1.71 + \sqrt{1.71^2 - 1.36^2}} = 0.37 \tag{B.25}$$

$$N_{bRd} = \frac{\chi A f_y}{\gamma_{M1}} = \frac{0.36 * 2124 * 235}{1} = 182374.58 \tag{B.26}$$

$$UC_3 = \frac{N_{Ed}}{N_{bRd}} = \frac{19629.63}{182374.58} = 0.1076 \tag{B.27}$$

The same values are obtained when the calculations are performed by the model, as visible in Figure B.21.

```
0.03932690152989065 0.05624205540278853 0.10763358398259908
```

Figure B.21: Values obtained by the model

After all the checks have been performed and it is determined whether the reusable columns have sufficient capacity, profiles will be chosen for the new columns. After this has been done, it will be calculated which option has the highest total UC-value. However, new elements get a value of -10, to make sure these are seen as inefficient.

Normally, the 10 most efficient options are taken further in the process. However, in this case there are only 3. Therefore, all options continue in the process.

The next step is calculate the forces on the new structure. Since for Option 1 and 2 the level splits, a new beam is added and the loads are redistributed. Where in Section B.1 the forces of the left and right triangle were summed up, they are now considered separately. The normalforce in the columns remains the same. For all options, the shear- and moment-distribution is shown in Figure B.23. The titles in per subplot refer to the newly distributed loads. The indices of these nodes are displayed in Figure B.22.

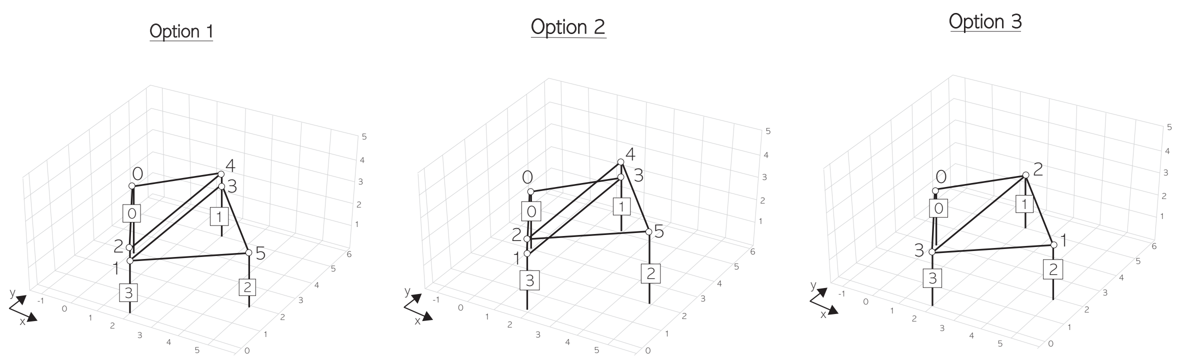


Figure B.22: Different options for the column configuration

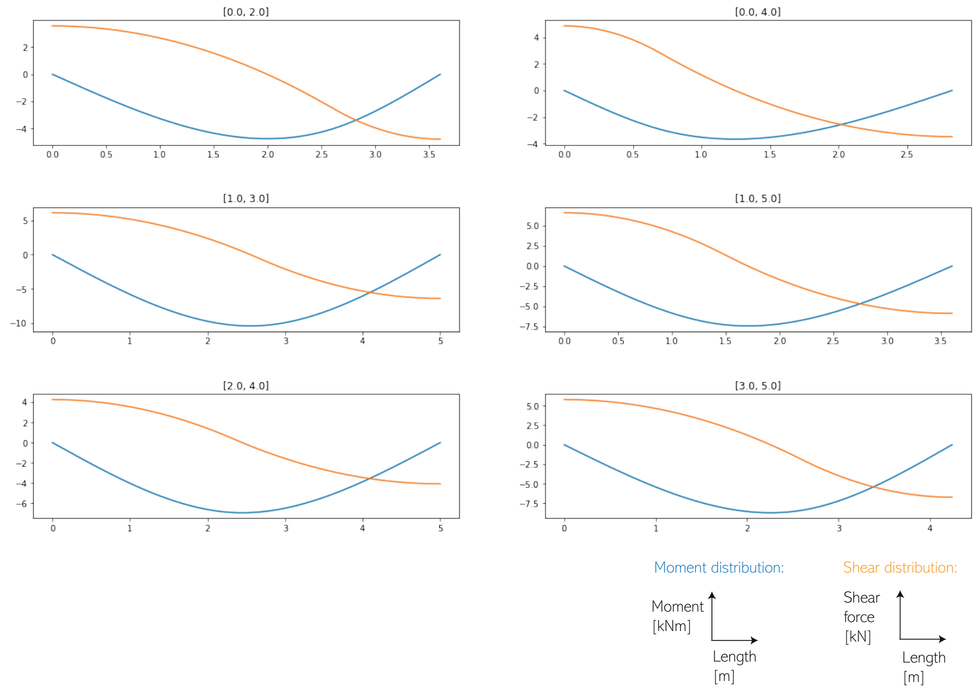


Figure B.23: Shear- and moment-distribution due to option 1

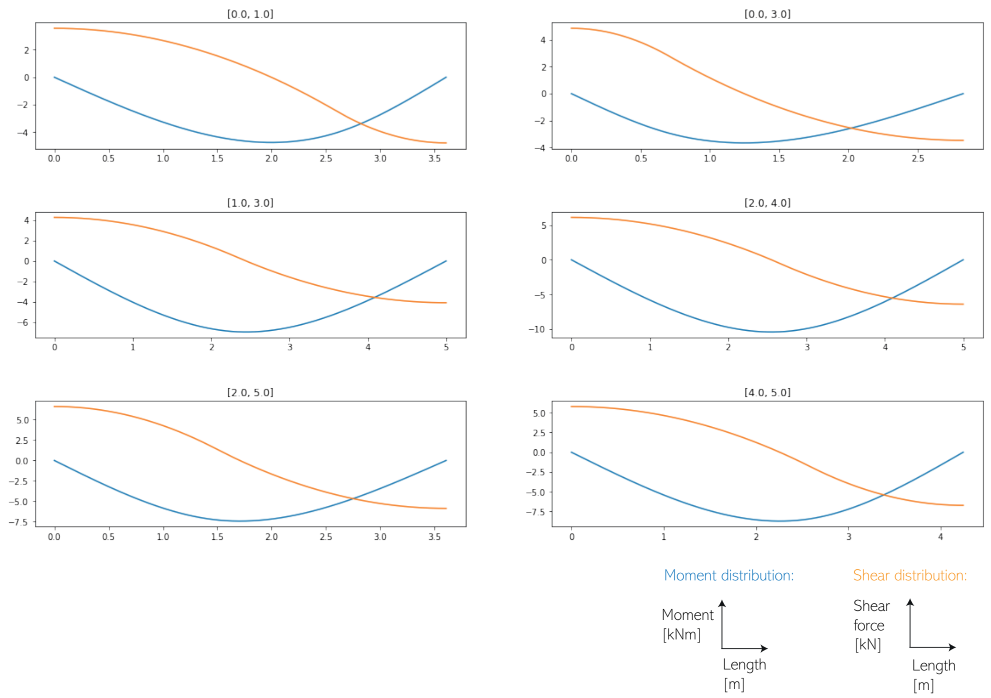


Figure B.24: Shear- and moment-distribution due to option 2

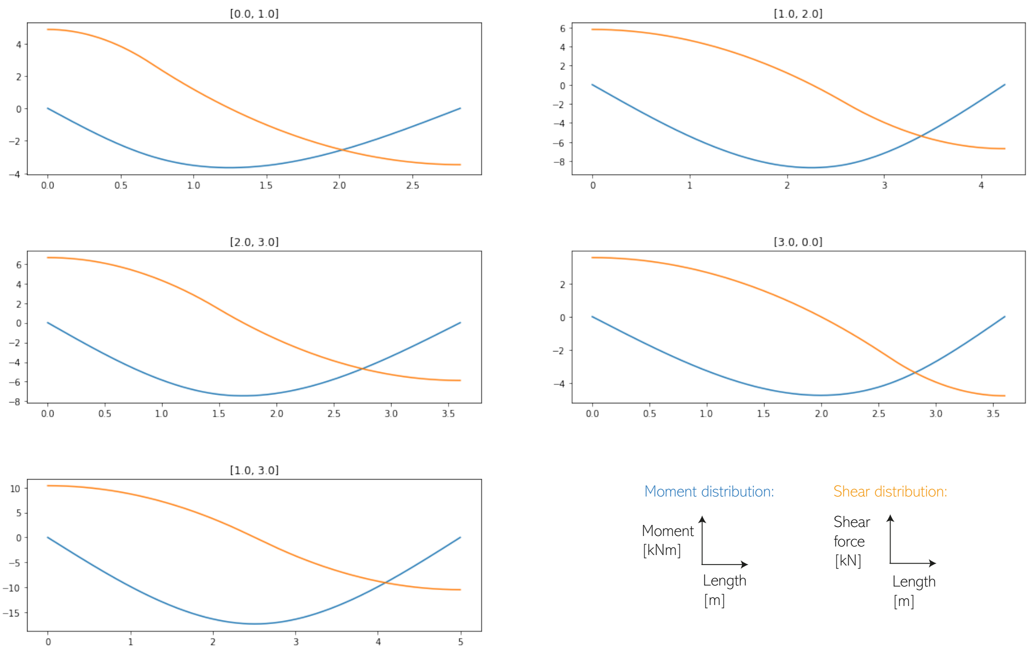


Figure B.25: Shear- and moment-distribution due to option 1

Figure B.26: Values for maximum shearforce and moment

As visible in Figure B.2, the stock consists of one element which is suitable as a beam. To be able to determine where this element is most efficiently, the element is placed on all the suitable positions. For option 1: Beam 13, Beam 24 and Beam 35. For option 2: Beam 13, Beam 24 and Beam 45. For option 3: Beam 13 and Beam 12.

The length of the element is $4.5m$, the profile is HEB200 which has a shear-area in y-y direction A_v of $6000mm^2$ and an elastic section modulus W of $569.6 * 10^3 mm^3$. For Beam 13 in option 1, the maximum moment acting on the beam $M_{max} = 10.401kNm$ and the maximum shear force acting on the beam $abs(V_{max}) = 6.388kN$.

$$\sigma_m = \frac{M_{Ed}}{W} = \frac{10.401 * 10^6}{569.6 * 10^3} = 18.26N/mm^2 \tag{B.28}$$

$$UC_1 = \frac{\sigma_m}{f_y} = \frac{18.26}{235} = 0.077 \tag{B.29}$$

$$V_{pl,Rd} = \frac{A_v(f_y/\sqrt{3})}{\gamma_{mo}} = \frac{6000(235/\sqrt{3})}{1} = 814063.87N \tag{B.30}$$

$$UC_2 = \frac{V_{Ed}}{V_{c,Rd}} = \frac{V_{Ed}}{V_{c,Rd}} = 0.007847 \tag{B.31}$$

For deflection, the parameters are represented by parameters in Figure B.27. As visible, the length is taken as 5m, while the length of the reusable element is 4.5. The reason for this is that the loads are not recalculated yet, and therefore the load-division in the beginning is used, where the length was still 5 meters.

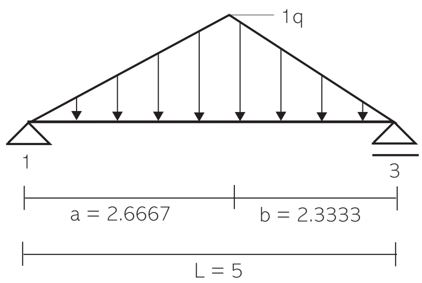


Figure B.27: Values for the parameters in Equation B.32

$$\delta_c = \frac{5ql^4}{384EI} - \frac{q}{aEI}(\frac{5(a-b)l^4}{768} + \frac{b^3(5l^2-2b^2)}{480}) - \frac{q}{bEI}(\frac{5(b-a)l^4}{768} + \frac{a^3(5l^2-2a^2)}{480}) = 2.1747mm \tag{B.32}$$

$$UC_3 = \frac{\delta_{max}}{\frac{L}{300}} = \frac{2.1747}{\frac{4500}{250}} = 0.1208 \tag{B.33}$$

The same values are obtained by the model, as displayed in Figure B.28.

```
0.07770795778346629 0.007848141957069373 0.12081607402364705
```

Figure B.28: Geometry used for structural verification

After the reusable beam has been calculated on every position, the highest UC is selected and the beam will be placed on this location.

The length of the reusable element is different than the original length. Therefore, the coordinates of the original nodes have to change to be able to connect the different elements. This will be done by the procedure described in Chapter 5. After this has been done, the load carried by the different beams is recalculated and the shear- and moment-distributions and the normal-forces are determined. After, the checks are performed with all the new characteristics.

C
Transport of steel elements

Applying reusable steel elements instead of new (or recycled) steel elements in load bearing structures saves the emissions released due to the production of new elements. However, these reusable elements might come from a location far from the building site. In this Appendix, the emissions due to transportation of reusable elements are compared to emissions released during the production of new elements, to be sure that the application of reusable elements in load bearing structures is environmentally beneficial.

For the production of new steel a Blast Furnace or a Blast Oxygen Furnace is used. For the production of recycled steel, an Electric Arc Furnace is used. In the study of Hasanbeigi et al. [17], the average amount of CO_2 emissions (in kg) released during the production process of one ton steel is determined. These amounts are displayed in Table C.1, together with the percentage of steel produced using an Electric Arc Furnace (EAF).

Mexico	**Germany**	**China**	**U.S.**
1080	1708	2148	1736
(69.4% EAF)	(30.2% EAF)	(9.8% EAF)	(61.3% EAF)

Table C.1: The average amount of CO_2 emissions (in kg) released during the production of one ton steel [17]

In the Netherlands, most steel used for construction comes from Germany of Luxembourg [22].

For transportation, a medium-sized inland-vessel is assumed. The total CO_2 emission is 0.031 per ton per km [13]. This inland-vessel can carry 1500 to 3000 ton.

For this situation, 1500 ton cargo is assumed. The emissions due to production would be $1708 * 1500 = 2562000\, kg\, CO_2$.

1500 ton cargo would result in $1500 * 0.031 = 46.5 kg\, CO_2$ per km. This would mean that a distance of $2562000/46.5 = 5510$ km can be travelled before the emissions due to production are equal to the emissions due to transportation.

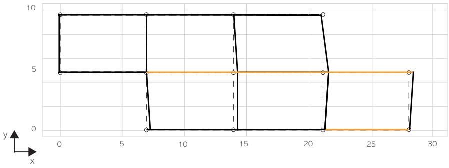
D

Overview of All Beam-Configurations

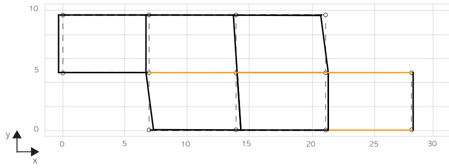
In this Appendix, all possible beam-configurations of the designs which require the least amount of new steel to be realized (per analysis, as explained in Chapter 6) are displayed. Every design is related to a baseline which formed the basis for the growing-process resulting in these nodal coordinates.

D.1. Analysis 1.3

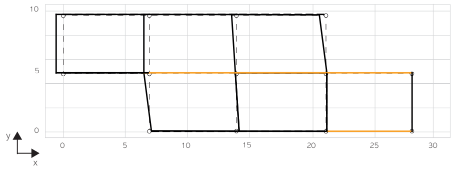
The different results of analysis 1.3 are displayed in Figure D.1 to Figure D.4.



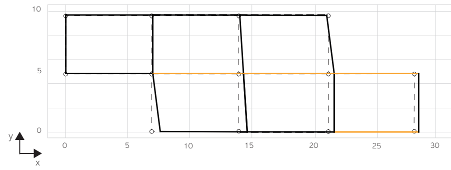
Mean UC columns: 0.33
Mean UC beams: 0.89
Minimum angle: 82.82
Number of changing angles: 17
Number of changing angles more than 10%: 0



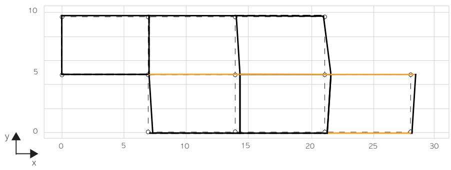
Mean UC columns: 0.33
Mean UC beams: 0.89
Minimum angle: 82.82
Number of changing angles: 14
Number of changing angles more than 10%: 0



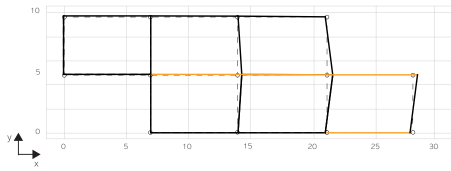
Mean UC columns: 0.33
Mean UC beams: 0.89
Minimum angle: 82.82
Number of changing angles: 14
Number of changing angles more than 10%: 0



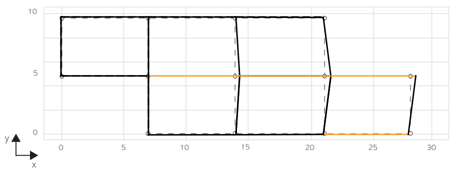
Mean UC columns: 0.33
Mean UC beams: 0.89
Minimum angle: 82.82
Number of changing angles: 14
Number of changing angles more than 10%: 0



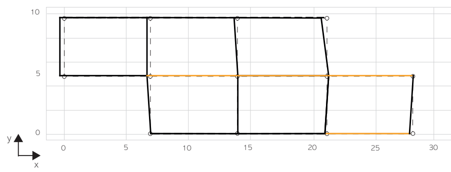
Mean UC columns: 0.33
Mean UC beams: 0.89
Minimum angle: 82.74
Number of changing angles: 17
Number of changing angles more than 10%: 0



Mean UC columns: 0.33
Mean UC beams: 0.89
Minimum angle: 82.60
Number of changing angles: 19
Number of changing angles more than 10%: 0

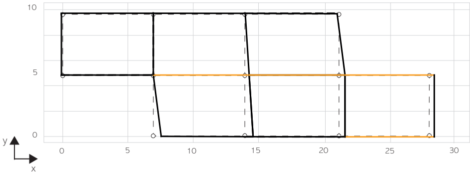


Mean UC columns: 0.33
Mean UC beams: 0.89
Minimum angle: 82.82
Number of changing angles: 18
Number of changing angles more than 10%: 0

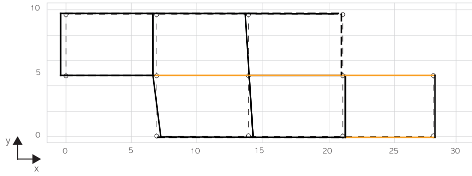


Mean UC columns: 0.33
Mean UC beams: 0.89
Minimum angle: 82.82
Number of changing angles: 17
Number of changing angles more than 10%: 0

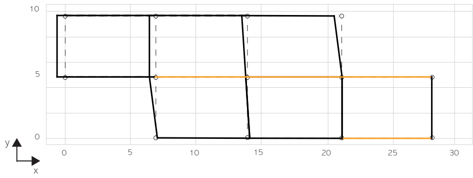
Figure D.1: Overview all possible beam-configurations (1/4)



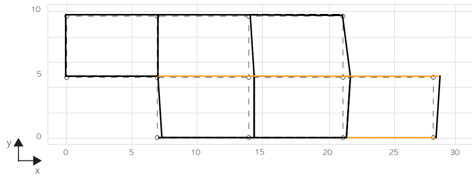
Mean UC columns: 0.33
Mean UC beams: 0.89
Minimum angle: 82.82
Number of changing angles: 14
Number of changing angles more than 10%: 0



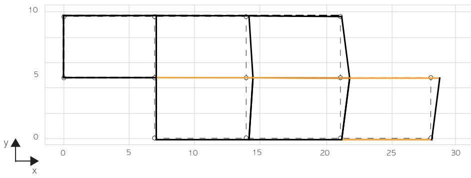
Mean UC columns: 0.33
Mean UC beams: 0.89
Minimum angle: 82.82
Number of changing angles: 14
Number of changing angles more than 10%: 0



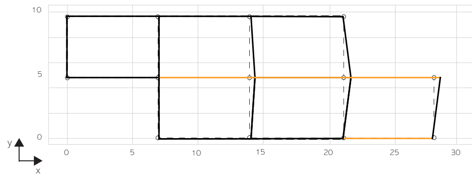
Mean UC columns: 0.33
Mean UC beams: 0.89
Minimum angle: 82.82
Number of changing angles: 14
Number of changing angles more than 10%: 0



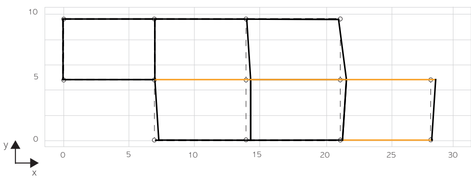
Mean UC columns: 0.33
Mean UC beams: 0.89
Minimum angle: 82.74
Number of changing angles: 17
Number of changing angles more than 10%: 0



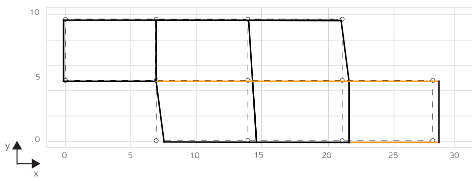
Mean UC columns: 0.33
Mean UC beams: 0.89
Minimum angle: 82.60
Number of changing angles: 19
Number of changing angles more than 10%: 0



Mean UC columns: 0.33
Mean UC beams: 0.89
Minimum angle: 82.82
Number of changing angles: 18
Number of changing angles more than 10%: 0

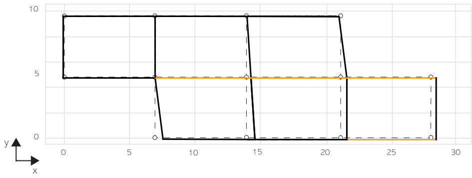


Mean UC columns: 0.33
Mean UC beams: 0.89
Minimum angle: 82.82
Number of changing angles: 17
Number of changing angles more than 10%: 0

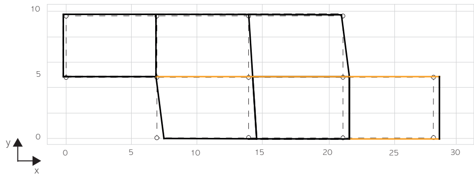


Mean UC columns: 0.33
Mean UC beams: 0.89
Minimum angle: 82.82
Number of changing angles: 14
Number of changing angles more than 10%: 0

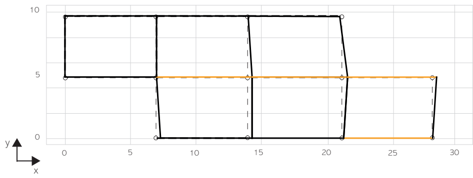
Figure D.2: Overview all possible beam-configurations (2/4)



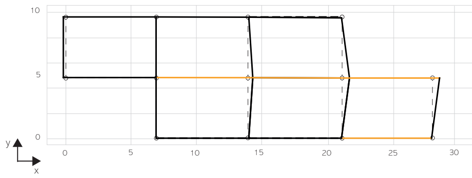
Mean UC columns: 0.33
Mean UC beams: 0.89
Minimum angle: 82.82
Number of changing angles: 14
Number of changing angles more than 10%: 0



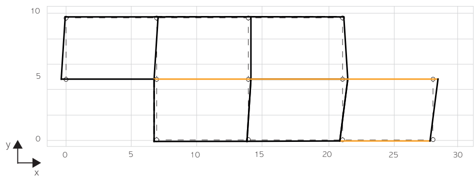
Mean UC columns: 0.33
Mean UC beams: 0.89
Minimum angle: 82.82
Number of changing angles: 14
Number of changing angles more than 10%: 0



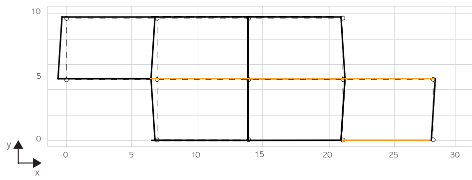
Mean UC columns: 0.33
Mean UC beams: 0.89
Minimum angle: 82.74
Number of changing angles: 17
Number of changing angles more than 10%: 0



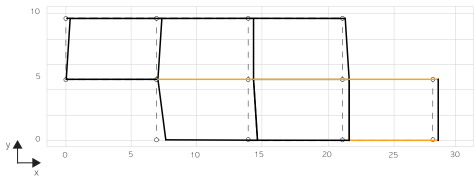
Mean UC columns: 0.33
Mean UC beams: 0.89
Minimum angle: 82.60
Number of changing angles: 19
Number of changing angles more than 10%: 0



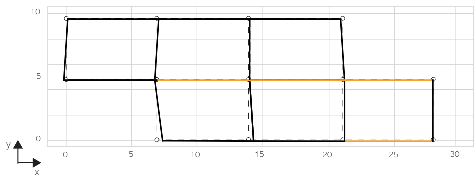
Mean UC columns: 0.33
Mean UC beams: 0.89
Minimum angle: 82.82
Number of changing angles: 21
Number of changing angles more than 10%: 0



Mean UC columns: 0.33
Mean UC beams: 0.89
Minimum angle: 86.41
Number of changing angles: 20
Number of changing angles more than 10%: 0

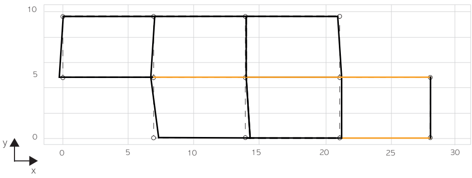


Mean UC columns: 0.33
Mean UC beams: 0.89
Minimum angle: 82.82
Number of changing angles: 17
Number of changing angles more than 10%: 0

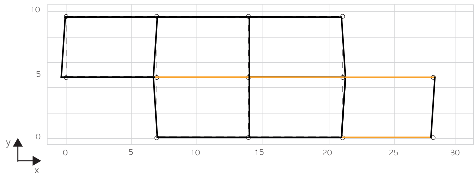


Mean UC columns: 0.33
Mean UC beams: 0.89
Minimum angle: 82.82
Number of changing angles: 17
Number of changing angles more than 10%: 0

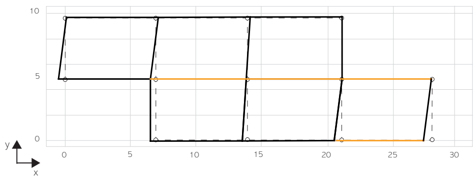
Figure D.3: Overview all possible beam-configurations (3/4)



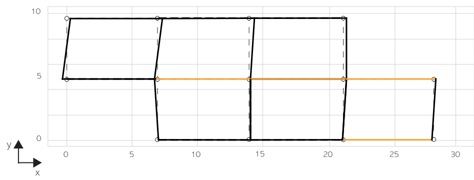
Mean UC columns: 0.33
Mean UC beams: 0.89
Minimum angle: 82.82
Number of changing angles: 17
Number of changing angles more than 10%: 0



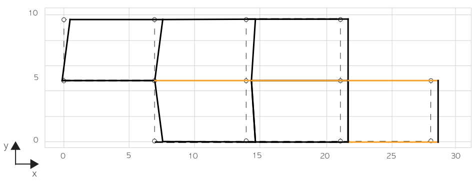
Mean UC columns: 0.33
Mean UC beams: 0.89
Minimum angle: 86.34
Number of changing angles: 21
Number of changing angles more than 10%: 0



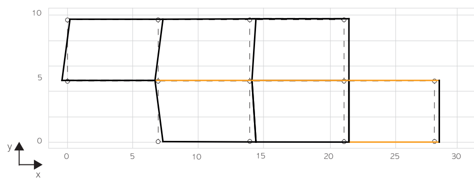
Mean UC columns: 0.33
Mean UC beams: 0.88
Minimum angle: 82.82
Number of changing angles: 22
Number of changing angles more than 10%: 0



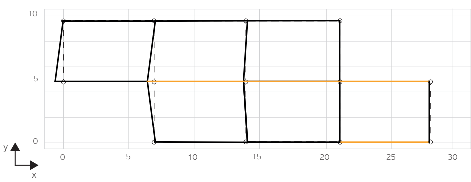
Mean UC columns: 0.33
Mean UC beams: 0.89
Minimum angle: 82.82
Number of changing angles: 21
Number of changing angles more than 10%: 0



Mean UC columns: 0.33
Mean UC beams: 0.89
Minimum angle: 82.82
Number of changing angles: 18
Number of changing angles more than 10%: 0



Mean UC columns: 0.33
Mean UC beams: 0.89
Minimum angle: 82.82
Number of changing angles: 18
Number of changing angles more than 10%: 0

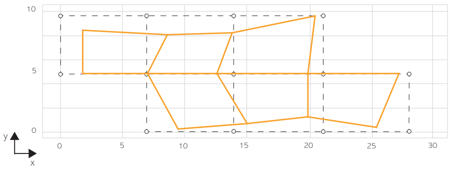


Mean UC columns: 0.33
Mean UC beams: 0.89
Minimum angle: 82.82
Number of changing angles: 18
Number of changing angles more than 10%: 0

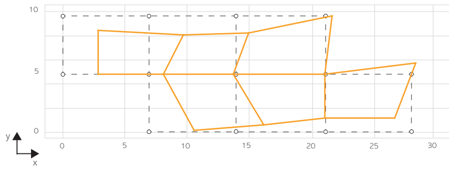
Figure D.4: Overview all possible beam-configurations (4/4)

D.2. Analysis 1.4

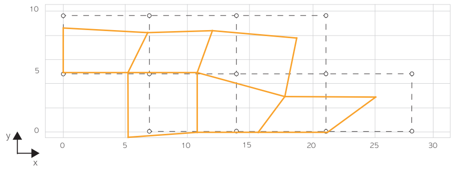
The different results of analysis 1.4 are displayed in Figure D.5 and Figure D.6.



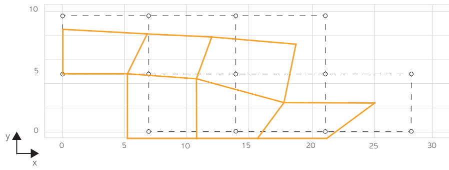
Mean UC columns: 0.66
Mean UC beams: 0.18
Minimum angle: 59.56
Number of changing angles: 21
Number of changing angles more than 10%: 17



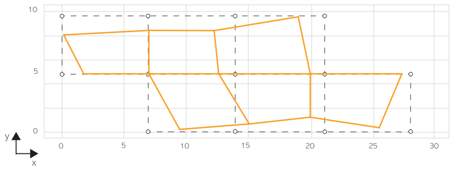
Mean UC columns: 0.66
Mean UC beams: 0.17
Minimum angle: 59.56
Number of changing angles: 21
Number of changing angles more than 10%: 17



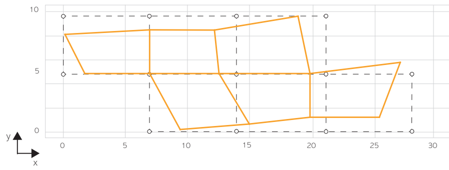
Mean UC columns: 0.63
Mean UC beams: 0.17
Minimum angle: 36.48
Number of changing angles: 21
Number of changing angles more than 10%: 14



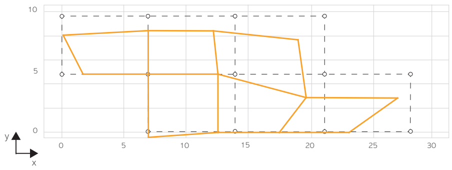
Mean UC columns: 0.64
Mean UC beams: 0.17
Minimum angle: 36.66
Number of changing angles: 22
Number of changing angles more than 10%: 14



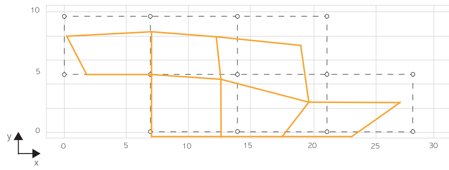
Mean UC columns: 0.68
Mean UC beams: 0.18
Minimum angle: 59.56
Number of changing angles: 20
Number of changing angles more than 10%: 11



Mean UC columns: 0.68
Mean UC beams: 0.18
Minimum angle: 59.56
Number of changing angles: 20
Number of changing angles more than 10%: 11

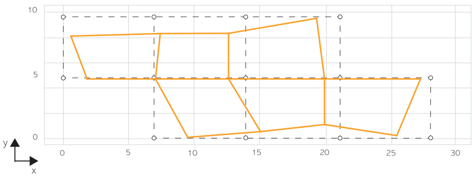


Mean UC columns: 0.64
Mean UC beams: 0.17
Minimum angle: 36.48
Number of changing angles: 20
Number of changing angles more than 10%: 13

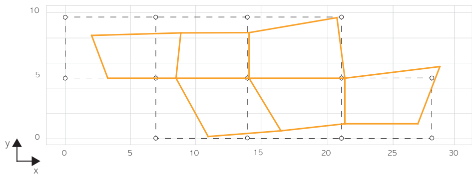


Mean UC columns: 0.64
Mean UC beams: 0.17
Minimum angle: 36.66
Number of changing angles: 22
Number of changing angles more than 10%: 15

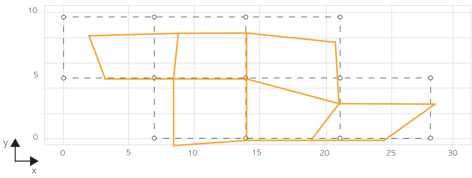
Figure D.5: Overview all possible beam-configurations (1/2)



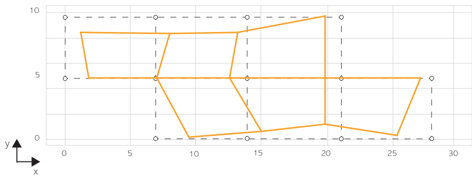
Mean UC columns: 0.69
Mean UC beams: 0.18
Minimum angle: 59.56
Number of changing angles: 20
Number of changing angles more than 10%: 11



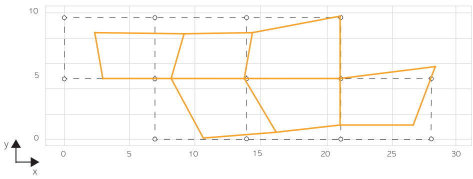
Mean UC columns: 0.68
Mean UC beams: 0.18
Minimum angle: 59.56
Number of changing angles: 20
Number of changing angles more than 10%: 11



Mean UC columns: 0.64
Mean UC beams: 0.17
Minimum angle: 36.48
Number of changing angles: 21
Number of changing angles more than 10%: 12



Mean UC columns: 0.68
Mean UC beams: 0.18
Minimum angle: 59.56
Number of changing angles: 21
Number of changing angles more than 10%: 19

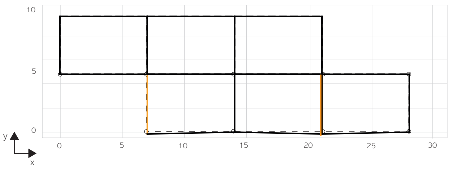


Mean UC columns: 0.68
Mean UC beams: 0.18
Minimum angle: 59.56
Number of changing angles: 21
Number of changing angles more than 10%: 19

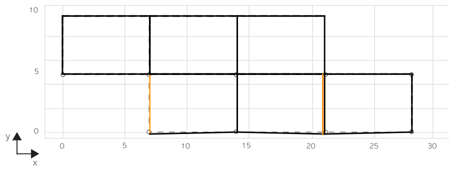
Figure D.6: Overview all possible beam-configurations (2/2)

D.3. Analysis 2.3

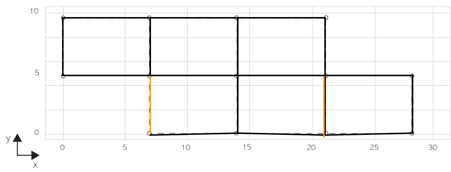
The different results of analysis 2.3 are displayed in Figure D.7 to Figure D.10.



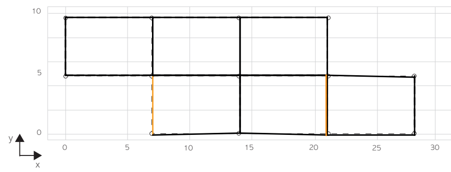
Mean UC columns: 0.37
Mean UC beams: 0.88
Minimum angle: 88.66
Number of changing angles: 10
Number of changing angles more than 10%: 0



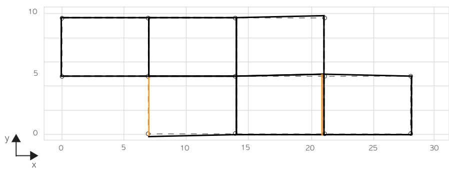
Mean UC columns: 0.37
Mean UC beams: 0.88
Minimum angle: 88.68
Number of changing angles: 10
Number of changing angles more than 10%: 0



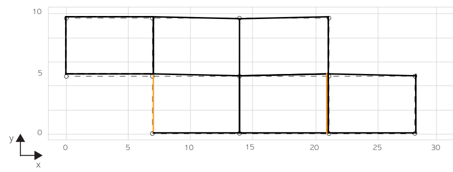
Mean UC columns: 0.37
Mean UC beams: 0.88
Minimum angle: 88.66
Number of changing angles: 11
Number of changing angles more than 10%: 0



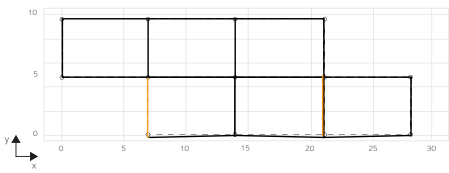
Mean UC columns: 0.37
Mean UC beams: 0.88
Minimum angle: 88.68
Number of changing angles: 10
Number of changing angles more than 10%: 0



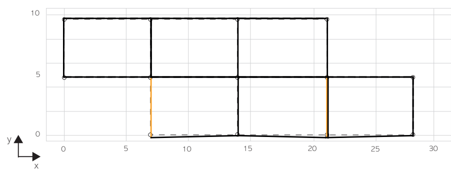
Mean UC columns: 0.37
Mean UC beams: 0.88
Minimum angle: 88.66
Number of changing angles: 14
Number of changing angles more than 10%: 0



Mean UC columns: 0.37
Mean UC beams: 0.88
Minimum angle: 88.64
Number of changing angles: 19
Number of changing angles more than 10%: 0

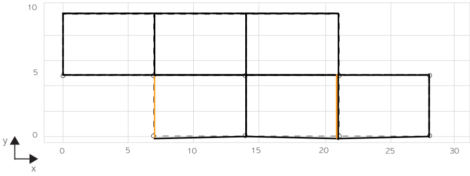


Mean UC columns: 0.37
Mean UC beams: 0.88
Minimum angle: 88.64
Number of changing angles: 11
Number of changing angles more than 10%: 0

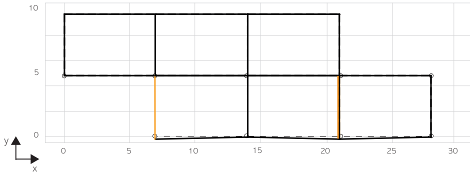


Mean UC columns: 0.37
Mean UC beams: 0.88
Minimum angle: 88.66
Number of changing angles: 10
Number of changing angles more than 10%: 0

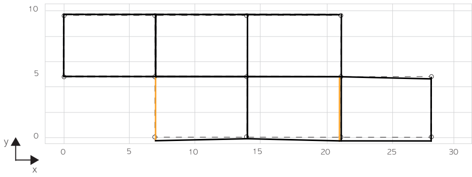
Figure D.7: Overview all possible beam-configurations (1/4)



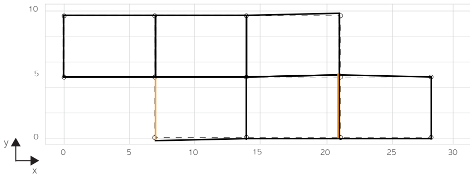
Mean UC columns: 0.37
Mean UC beams: 0.88
Minimum angle: 88.68
Number of changing angles: 10
Number of changing angles more than 10%: 0



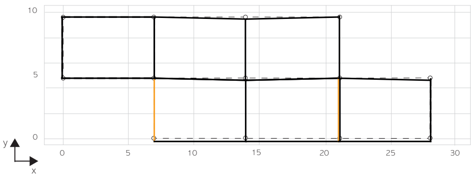
Mean UC columns: 0.37
Mean UC beams: 0.88
Minimum angle: 88.66
Number of changing angles: 11
Number of changing angles more than 10%: 0



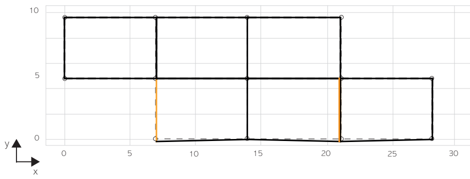
Mean UC columns: 0.37
Mean UC beams: 0.88
Minimum angle: 88.68
Number of changing angles: 10
Number of changing angles more than 10%: 0



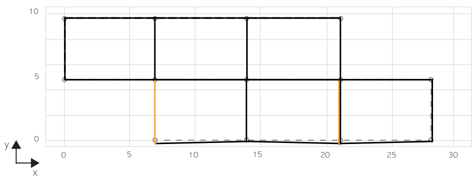
Mean UC columns: 0.37
Mean UC beams: 0.88
Minimum angle: 88.66
Number of changing angles: 14
Number of changing angles more than 10%: 0



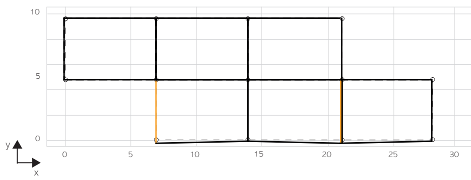
Mean UC columns: 0.37
Mean UC beams: 0.88
Minimum angle: 88.64
Number of changing angles: 19
Number of changing angles more than 10%: 0



Mean UC columns: 0.37
Mean UC beams: 0.88
Minimum angle: 88.64
Number of changing angles: 11
Number of changing angles more than 10%: 0

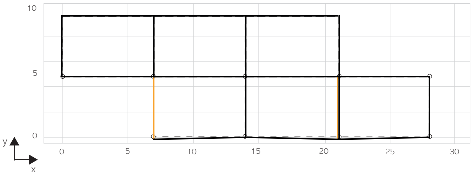


Mean UC columns: 0.37
Mean UC beams: 0.88
Minimum angle: 88.66
Number of changing angles: 10
Number of changing angles more than 10%: 0

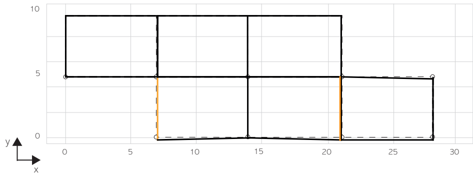


Mean UC columns: 0.37
Mean UC beams: 0.88
Minimum angle: 88.68
Number of changing angles: 10
Number of changing angles more than 10%: 0

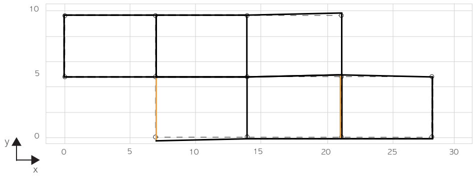
Figure D.8: Overview all possible beam-configurations (2/4)



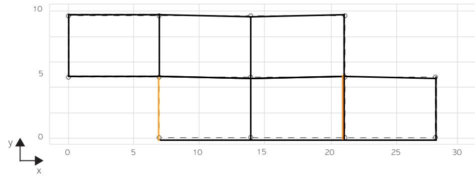
Mean UC columns: 0.37
Mean UC beams: 0.88
Minimum angle: 88.66
Number of changing angles: 11
Number of changing angles more than 10%: 0



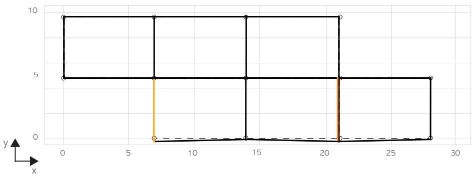
Mean UC columns: 0.37
Mean UC beams: 0.88
Minimum angle: 88.68
Number of changing angles: 10
Number of changing angles more than 10%: 0



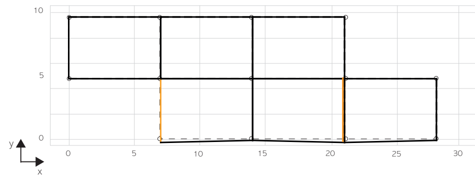
Mean UC columns: 0.37
Mean UC beams: 0.88
Minimum angle: 88.66
Number of changing angles: 14
Number of changing angles more than 10%: 0



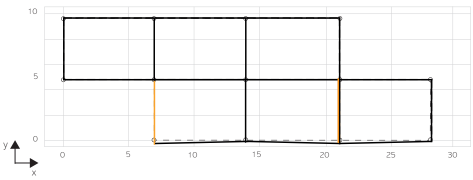
Mean UC columns: 0.37
Mean UC beams: 0.88
Minimum angle: 88.64
Number of changing angles: 19
Number of changing angles more than 10%: 0



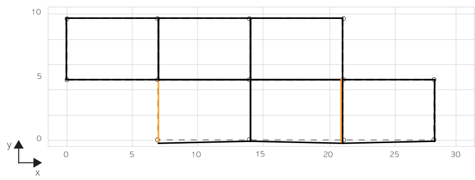
Mean UC columns: 0.37
Mean UC beams: 0.88
Minimum angle: 88.64
Number of changing angles: 11
Number of changing angles more than 10%: 0



Mean UC columns: 0.37
Mean UC beams: 0.88
Minimum angle: 88.66
Number of changing angles: 10
Number of changing angles more than 10%: 0

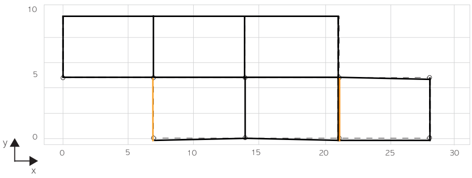


Mean UC columns: 0.37
Mean UC beams: 0.88
Minimum angle: 88.68
Number of changing angles: 10
Number of changing angles more than 10%: 0

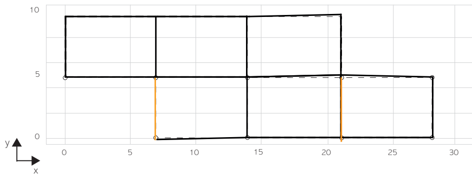


Mean UC columns: 0.37
Mean UC beams: 0.88
Minimum angle: 88.66
Number of changing angles: 11
Number of changing angles more than 10%: 0

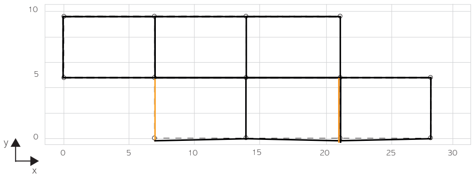
Figure D.9: Overview all possible beam-configurations (3/4)



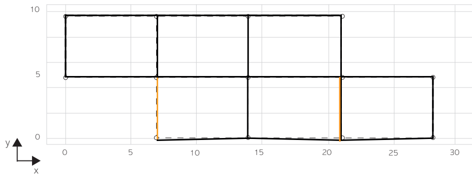
Mean UC columns: 0.37
Mean UC beams: 0.88
Minimum angle: 88.68
Number of changing angles: 10
Number of changing angles more than 10%: 0



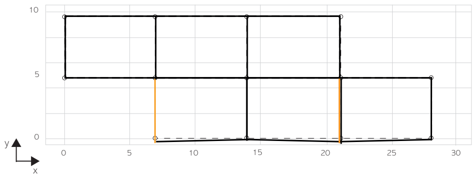
Mean UC columns: 0.37
Mean UC beams: 0.88
Minimum angle: 88.66
Number of changing angles: 14
Number of changing angles more than 10%: 0



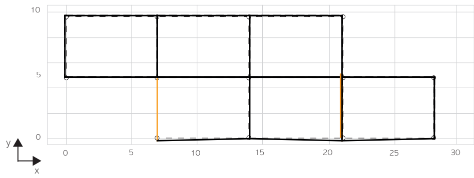
Mean UC columns: 0.37
Mean UC beams: 0.88
Minimum angle: 88.64
Number of changing angles: 11
Number of changing angles more than 10%: 0



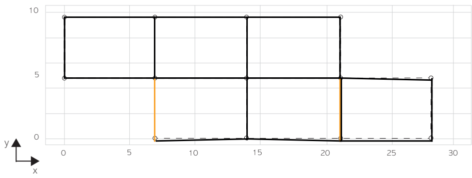
Mean UC columns: 0.37
Mean UC beams: 0.88
Minimum angle: 88.66
Number of changing angles: 10
Number of changing angles more than 10%: 0



Mean UC columns: 0.37
Mean UC beams: 0.88
Minimum angle: 88.68
Number of changing angles: 10
Number of changing angles more than 10%: 0



Mean UC columns: 0.37
Mean UC beams: 0.88
Minimum angle: 88.66
Number of changing angles: 11
Number of changing angles more than 10%: 0

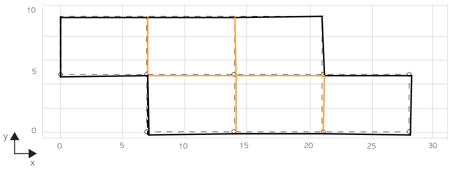


Mean UC columns: 0.37
Mean UC beams: 0.88
Minimum angle: 88.68
Number of changing angles: 10
Number of changing angles more than 10%: 0

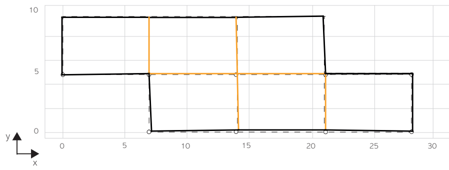
Figure D.10: Overview all possible beam-configurations (4/4)

D.4. Analysis 3.1 and 3.2

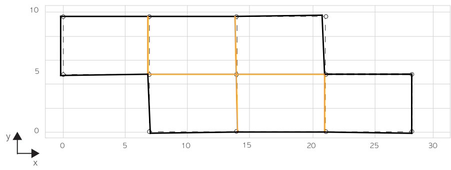
The different results of analysis 3.1 are displayed in Figure D.11 to Figure D.14.



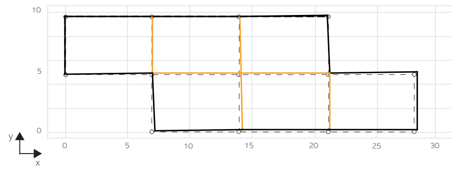
Mean UC columns: 0.94
Mean UC beams: 0.94
Minimum angle: 87.60
Number of changing angles: 20
Number of changing angles more than 10%: 0



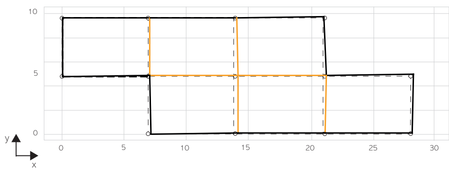
Mean UC columns: 0.94
Mean UC beams: 0.94
Minimum angle: 87.60
Number of changing angles: 20
Number of changing angles more than 10%: 0



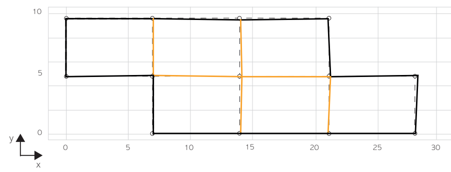
Mean UC columns: 0.94
Mean UC beams: 0.94
Minimum angle: 87.60
Number of changing angles: 21
Number of changing angles more than 10%: 0



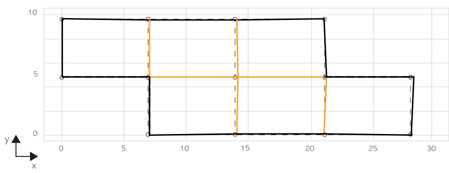
Mean UC columns: 0.94
Mean UC beams: 0.94
Minimum angle: 87.60
Number of changing angles: 20
Number of changing angles more than 10%: 0



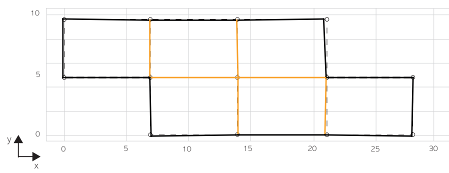
Mean UC columns: 0.94
Mean UC beams: 0.94
Minimum angle: 87.60
Number of changing angles: 20
Number of changing angles more than 10%: 0



Mean UC columns: 0.93
Mean UC beams: 0.94
Minimum angle: 86.81
Number of changing angles: 22
Number of changing angles more than 10%: 0

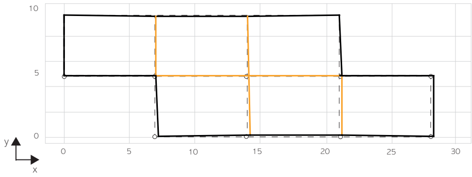


Mean UC columns: 0.94
Mean UC beams: 0.94
Minimum angle: 87.55
Number of changing angles: 22
Number of changing angles more than 10%: 0

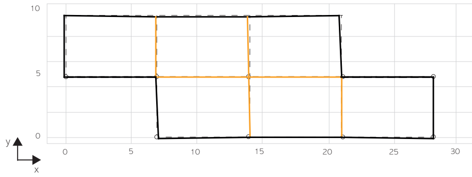


Mean UC columns: 0.94
Mean UC beams: 0.94
Minimum angle: 87.60
Number of changing angles: 21
Number of changing angles more than 10%: 0

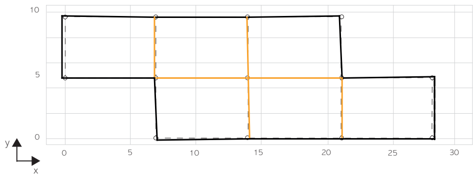
Figure D.11: Overview all possible beam-configurations (1/4)



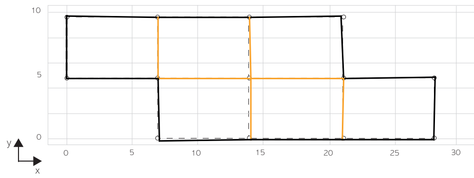
Mean UC columns: 0.94
Mean UC beams: 0.94
Minimum angle: 87.60
Number of changing angles: 21
Number of changing angles more than 10%: 0



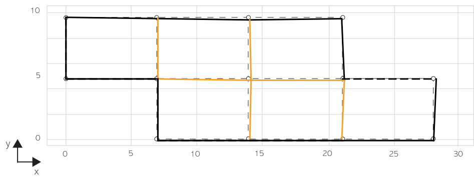
Mean UC columns: 0.94
Mean UC beams: 0.94
Minimum angle: 87.60
Number of changing angles: 22
Number of changing angles more than 10%: 0



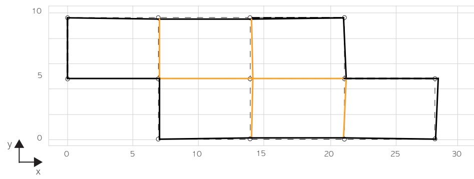
Mean UC columns: 0.94
Mean UC beams: 0.94
Minimum angle: 87.60
Number of changing angles: 21
Number of changing angles more than 10%: 0



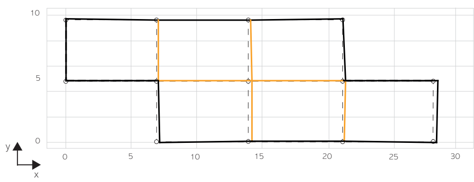
Mean UC columns: 0.94
Mean UC beams: 0.94
Minimum angle: 87.59
Number of changing angles: 21
Number of changing angles more than 10%: 0



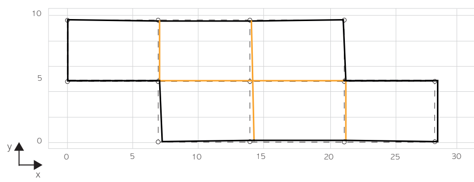
Mean UC columns: 0.94
Mean UC beams: 0.94
Minimum angle: 86,81
Number of changing angles: 22
Number of changing angles more than 10%: 0



Mean UC columns: 0.94
Mean UC beams: 0.94
Minimum angle: 87.55
Number of changing angles: 21
Number of changing angles more than 10%: 0

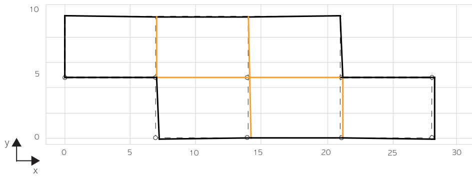


Mean UC columns: 0.94
Mean UC beams: 0.94
Minimum angle: 87.60
Number of changing angles: 20
Number of changing angles more than 10%: 0

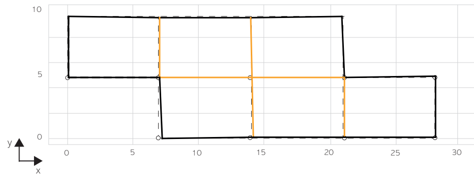


Mean UC columns: 0.94
Mean UC beams: 0.94
Minimum angle: 87.60
Number of changing angles: 20
Number of changing angles more than 10%: 0

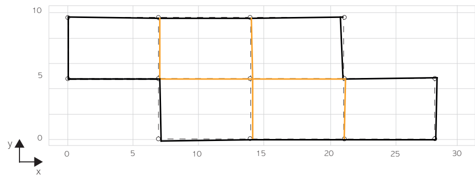
Figure D.12: Overview all possible beam-configurations (2/4)



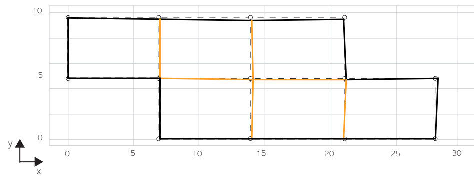
Mean UC columns: 0.94
Mean UC beams: 0.94
Minimum angle: 87.60
Number of changing angles: 21
Number of changing angles more than 10%: 0



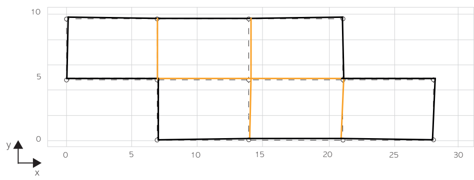
Mean UC columns: 0.94
Mean UC beams: 0.94
Minimum angle: 87.60
Number of changing angles: 20
Number of changing angles more than 10%: 0



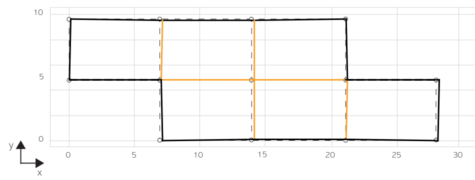
Mean UC columns: 0.94
Mean UC beams: 0.94
Minimum angle: 87.60
Number of changing angles: 20
Number of changing angles more than 10%: 0



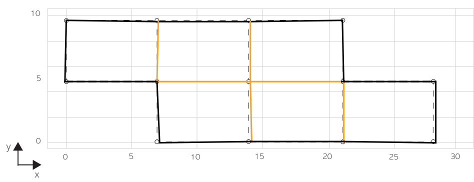
Mean UC columns: 0.94
Mean UC beams: 0.94
Minimum angle: 86.81
Number of changing angles: 22
Number of changing angles more than 10%: 0



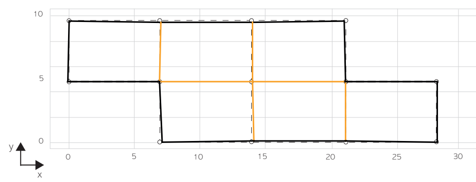
Mean UC columns: 0.94
Mean UC beams: 0.94
Minimum angle: 87.55
Number of changing angles: 21
Number of changing angles more than 10%: 0



Mean UC columns: 0.94
Mean UC beams: 0.94
Minimum angle: 88.78
Number of changing angles: 20
Number of changing angles more than 10%: 0

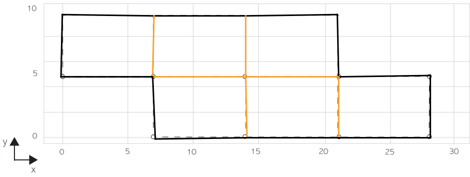


Mean UC columns: 0.94
Mean UC beams: 0.94
Minimum angle: 87.60
Number of changing angles: 20
Number of changing angles more than 10%: 0

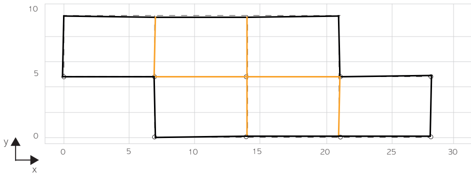


Mean UC columns: 0.94
Mean UC beams: 0.94
Minimum angle: 87.60
Number of changing angles: 21
Number of changing angles more than 10%: 0

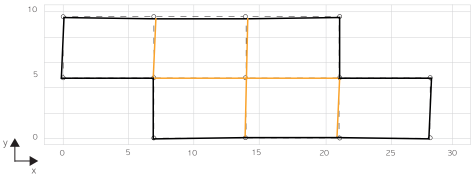
Figure D.13: Overview all possible beam-configurations (3/4)



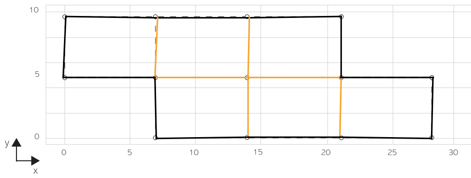
Mean UC columns: 0.94
Mean UC beams: 0.94
Minimum angle: 87.60
Number of changing angles: 20
Number of changing angles more than 10%: 0



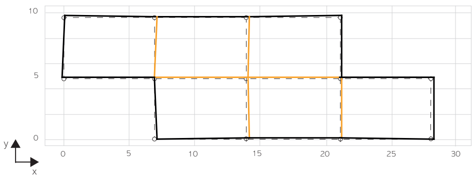
Mean UC columns: 0.94
Mean UC beams: 0.94
Minimum angle: 88.00
Number of changing angles: 21
Number of changing angles more than 10%: 0



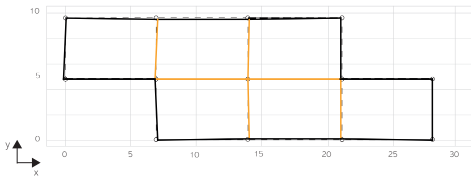
Mean UC columns: 0.93
Mean UC beams: 0.94
Minimum angle: 87.55
Number of changing angles: 22
Number of changing angles more than 10%: 0



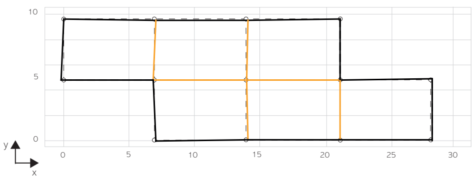
Mean UC columns: 0.93
Mean UC beams: 0.94
Minimum angle: 87.55
Number of changing angles: 21
Number of changing angles more than 10%: 0



Mean UC columns: 0.94
Mean UC beams: 0.94
Minimum angle: 87.55
Number of changing angles: 21
Number of changing angles more than 10%: 0



Mean UC columns: 0.94
Mean UC beams: 0.94
Minimum angle: 87.55
Number of changing angles: 22
Number of changing angles more than 10%: 0



Mean UC columns: 0.93
Mean UC beams: 0.94
Minimum angle: 87.55
Number of changing angles: 21
Number of changing angles more than 10%: 0

Figure D.14: Overview all possible beam-configurations (4/4)

E

Code

The script described in Chapter 5 is accessible via a GitHub repository. To request access, send an email to *gekerademaker@msn.com*.

Bibliography

[1] *Eurocode 3: Ontwerp en berekening van staalconstructies - Deel 1-1: Algemene regels en regels voor gebouwen*, 2016.

[2] *Nationale bijlage bij NEN-EN 1990+A1:2006+A1:2006/C2:2019 Eurocode: Grondslagen van het constructief ontwerp*, 2019.

[3] Standaardformules: Vergeet-mij-nietjes, 2020. URL https://www.studocu.com/nl/document/universiteit-hasselt/draagstructuur-2/vergeet-mij-nietjes/8204652.

[4] Redactie Bouwwereld. Donorskelet voor laboratorium biopartner 5, Jul 2020. URL https://www.bouwwereld.nl/bouwkennis/duurzaamheid/donorskelet-voor-laboratorium-biopartner-5/.

[5] Jan Brütting, Gennaro Senatore, and Corentin Fivet. Optimization formulations for the design of low embodied energy structures made from reused elements. In Ian F. C. Smith and Bernd Domer, editors, *Advanced Computing Strategies for Engineering*, pages 139–163, Cham, 2018. Springer International Publishing. ISBN 978-3-319-91635-4.

[6] Jan Brütting, Catherine De Wolf, and Corentin Fivet. The reuse of load-bearing components. *IOP Conference Series: Earth and Environmental Science*, 225:012025, 02 2019. doi: 10.1088/1755-1315/225/1/012025.

[7] Jan Brütting, Joseph Desruelle, Gennaro Senatore, and Corentin Fivet. Design of truss structures through reuse. *Structures*, 18:128–137, 2019. ISSN 2352-0124. doi: https://doi.org/10.1016/j.istruc.2018.11.006. URL https://www.sciencedirect.com/science/article/pii/S2352012418301322. Advanced Manufacturing and Materials for Innovative Structural Design.

[8] Jan Brütting, Gennaro Senatore, Mattias Schevenels, and Corentin Fivet. Optimum design of frame structures from a stock of reclaimed elements. *Frontiers in Built Environment*, 6:57, 2020. ISSN 2297-3362. doi: 10.3389/fbuil.2020.00057. URL https://www.frontiersin.org/article/10.3389/fbuil.2020.00057.

[9] Jan Brütting, Camille Vandervaeren, Gennaro Senatore, Niels De Temmerman, and Corentin Fivet. Environmental impact minimization of reticular structures made of reused and new elements through life cycle assessment and mixed-integer linear programming. *Energy and Buildings*, 215:109827, 2020. ISSN 0378-7788. doi: https://doi.org/10.1016/j.enbuild.2020.109827. URL https://www.sciencedirect.com/science/article/pii/S0378778819330439.

[10] Massimiliano Condotta and Elisa Zatta. Reuse of building elements in the architectural practice and the european regulatory context: Inconsistencies and possible improvements. *Journal of Cleaner Production*, 318:128413, 2021. ISSN 0959-6526. doi: https://doi.org/10.1016/j.jclepro.2021.128413. URL https://www.sciencedirect.com/science/article/pii/S0959652621026263.

[11] World Green Building Council. Embodied carbon call to action report. URL https://www.worldgbc.org/embodied-carbon.

[12] Catherine De Wolf, Endrit Hoxha, and Corentin Fivet. Comparison of environmental assessment methods when reusing building components: A case study. *Sustainable Cities and Society*, 61:102322, 2020. ISSN 2210-6707. doi: https://doi.org/10.1016/j.scs.2020.102322. URL https://www.sciencedirect.com/science/article/pii/S2210670720305436.

[13] CO2 Emissiefactoren. Lijst emissiefactoren, Jan 2022. URL https://www.co2emissiefactoren.nl/lijst-emissiefactoren/.

[14] Martin Geissdoerfer, Paulo Savaget, Nancy M.P. Bocken, and Erik Jan Hultink. The circular economy – a new sustainability paradigm? *Journal of Cleaner Production*, 143:757–768, 2017. ISSN 0959-6526. doi: https://doi.org/10.1016/j.jclepro.2016.12.048. URL https://www.sciencedirect.com/science/article/pii/S0959652616321023.

[15] Mark Gorgolewski and Lawrence Morrettin. The process of designing with reused building components. *CMS2009: Conference on Construction Material Stewardship - LIFECYCLE DESIGN OF BUILDINGS, SYSTEMS AND MATERIALS. Conference Proceedings*, pages 105–109, 2009.

[16] Jan Haertel. *Design of Thermal Systems Using Topology Optimization*. PhD thesis, 12 2017.

[17] Ali Hasanbeigi, Marlene Arens, Jose Carlos Rojas Cardenas, Lynn Price, and Ryan Triolo. Comparison of carbon dioxide emissions intensity of steel production in china, germany, mexico, and the united states. *Resources, Conservation and Recycling*, 113:127–139, 2016. ISSN 0921-3449. doi: https://doi.org/10.1016/j.resconrec.2016.06.008. URL https://www.sciencedirect.com/science/article/pii/S0921344916301458.

[18] Linwei He, Matthew Gilbert, and Xingyi Song. A python script for adaptive layout optimization of trusses. *Structural and Multidisciplinary Optimization*, 60, 01 2019. doi: 10.1007/s00158-019-02226-6.

[19] Sharon Hercules. Een gloednieuw gebouw, met een donorskelet als basis, Jun 2020. URL https://www.duravermeer.nl/nieuws/een-gloednieuw-gebouw-met-een-donorskelet-als-basis/.

[20] Seongjun Kim and Sung-Ah Kim. Design optimization of noise barrier tunnels through component reuse: Minimization of costs and co2 emissions using multi-objective genetic algorithm. *Journal of Cleaner Production*, 298:126697, 2021. ISSN 0959-6526. doi: https://doi.org/10.1016/j.jclepro.2021.126697. URL https://www.sciencedirect.com/science/article/pii/S0959652621009173.

[21] Julian Kirchherr, Denise Reike, and Marko Hekkert. Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, 127:221–232, 2017. ISSN 0921-3449. doi: https://doi.org/10.1016/j.resconrec.2017.09.005. URL https://www.sciencedirect.com/science/article/pii/S0921344917302835.

[22] J. Van Maastrigt. Quantifying life cycle environmental benefits of circular steel building designs: development of an environmental assessment tool for reuse of steel members in building designs for the netherlands. Master's thesis, TU Delft, 2019.

[23] V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield. IPCC, 2018: Summary for Policymakers. Technical report, World Meteorological Organization, Geneva, Switzerland, 2018.

[24] Linfeng Mei and Qian Wang. Structural optimization in civil engineering: A literature review. *Buildings*, 11:66, 02 2021. doi: 10.3390/buildings11020066.

[25] Bouwen met Staal. BB16, Jun 2012. URL https://issuu.com/bouwenmetstaal/docs/bb16_woningbouw.

[26] Iyyanki V. Muralikrishna and Valli Manickam. Chapter five - life cycle assessment. In Iyyanki V. Muralikrishna and Valli Manickam, editors, *Environmental Management*, pages 57–75. Butterworth-Heinemann, 2017. ISBN 978-0-12-811989-1. doi: https://doi.org/10.1016/B978-0-12-811989-1.00005-1. URL https://www.sciencedirect.com/science/article/pii/B9780128119891000051.

[27] M. Pongiglione and C. Calderini. Material savings through structural steel reuse: A case study in genoa. *Resources, Conservation and Recycling*, 86:87–92, 2014. ISSN 0921-3449. doi: https://doi.org/10.1016/j.resconrec.2014.02.011. URL https://www.sciencedirect.com/science/article/pii/S0921344914000561.

[28] José Potting, M.P. Hekkert, Ernst Worrell, and Aldert Hanemaaijer. *Circular Economy: Measuring innovation in the product chain*. 01 2017.

[29] Vanessa Prieto-Sandoval, Carmen Jaca, and Marta Ormazabal. Towards a consensus on the circular economy. *Journal of Cleaner Production*, 179:605–615, 2018. ISSN 0959-6526. doi: https://doi.org/10.1016/j.jclepro.2017.12.224. URL `https://www.sciencedirect.com/science/article/pii/S0959652617332146`.

[30] Kambiz Rakhshan, Jean-Claude Morel, and Alireza Daneshkhah. Predicting the technical reusability of load-bearing building components: A probabilistic approach towards developing a circular economy framework. *Journal of Building Engineering*, 42:102791, 2021. ISSN 2352-7102. doi: https://doi.org/10.1016/j.jobe.2021.102791. URL `https://www.sciencedirect.com/science/article/pii/S2352710221006495`.

[31] Rijnboutt. Donorskelet Hoogstraat in Rotterdam zichtbaar, Feb 2017. URL `https://rijnboutt.nl/actueel/nieuws/donorskelet-hoogstraat-in-rotterdam-zichtbaar/`.

[32] Yihui Tian, Qinghua Zhu, and Yong Geng. An analysis of energy-related greenhouse gas emissions in the chinese iron and steel industry. *Energy Policy*, 56:352–361, 2013. ISSN 0301-4215. doi: https://doi.org/10.1016/j.enpol.2012.12.068. URL `https://www.sciencedirect.com/science/article/pii/S0301421512011354`.

[33] Nicole Van Buren, Marjolein Demmers, Rob Van der Heijden, and Frank Witlox. Towards a circular economy: The role of dutch logistics industries and governments. *Sustainability*, 8(7), 2016. ISSN 2071-1050. doi: 10.3390/su8070647. URL `https://www.mdpi.com/2071-1050/8/7/647`.

[34] Ministerie van Economische Zaken en Klimaat. Klimaatakkoord, Jun 2019. URL `https://www.klimaatakkoord.nl/documenten/publicaties/2019/06/28/klimaatakkoord`.

[35] Thijs van Gelderen. Truss topology optimization with reused steel elements. Master's thesis, TU Delft, jun 2021.

[36] Ministerie van Infrastructuur en Waterstaat. Nederland circulair in 2050. URL `https://www.rijksoverheid.nl/onderwerpen/circulaire-economie/nederland-circulair-in-2050`.

[37] Roxane Van Mellaert, Kristo Mela, T. Tiainen, M. Heinisuo, Geert Lombaert, and Mattias Schevenels. Mixed-integer linear programming approach for global discrete sizing optimization of frame structures. *Structural and Multidisciplinary Optimization*, 57, 02 2018. doi: 10.1007/s00158-017-1770-9.

[38] Rijksinsituut voor Volksgezondheid en Milieu. Uitstoot broeikasgassen in 2019 opnieuw iets lager, May 2020. URL `https://www.rivm.nl/nieuws/uitstoot-broeikasgassen-in-2019-opnieuw-iets-lager`.

[39] J Yeung, S Walbridge, C Haas, and R Saari. Understanding the total life cycle cost implications of reusing structural steel. *Environment Systems and Decisions*, 37:101–120, 2017. URL `https://link.springer.com/article/10.1007%2Fs10669-016-9621-6`.