

The business-case and environmental impact score for the preliminary structural design of a reclaimed steel low-rise office building.

Developing a tool that generates and evaluates reclaimed steel design alternatives

K. (Koen) Aardoom



Delft University of Technology

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Preface

This thesis is the final step in completing the Master of Civil Engineering at Delft University of Technology. During my masters I followed the track Building Engineering and particularly liked the course parametric design. During my masters I worked as a TA for the python programming course in the Civil Engineering bachelor and I am also inspired to contribute to the task of reducing the environmental impact within the building sector. These interest and skills have resulted in the topic of this Master's Thesis. I write this thesis for actors in the steel industry and building sector. With my research, I hope to increase the use of reclaimed steel elements in the building sector. I want to give insights on costs and environmental impact to reduce one of the barriers which often stand in the way of reusing structural steel elements today.

I would like to thank my committee for the feedback sessions and individual consultation meetings. During these sessions they all provided helpful feedback and suggestions which contributed to the success of this Master's Thesis. I would like to thank Karel Terwel for the help in defining my research topic, bringing me in contact with IMd raadgevende ingenieurs, the company I graduated at, and being the chairman of my thesis committee. Next, I would like to thank Chris Noteboom for his expertise in parametric design and helping me in the process of setting-up my algorithms and models as well as evaluating them. As the last committee member from the university I would like to thank Florentia Kavoura for her help during the structural analysis and verification as well as pointing me to relevant research in the steel branch.

From IMd raadgevende ingenieurs I would like to thank Pim Peters and Geert Hoogerwaard. Their experience in applying reclaimed steel in projects and engineering have helped me in my research. They also helped me get into contact with companies in the building sector which helped me during my research. I would like to thank Vic Obdam, Reijrink, Nebest, BAM, Bnext, IGG, HPstaal, Gemeente Rotterdam and Deltastaal for their collaboration and contribution to this thesis.

Finally, I would like to thank my family, friends and girlfriend, who have supported me during my studies and this graduation work.

*K. (Koen) Aardoom
Delft, September 2023*



Abstract

The goal of this thesis is to determine how to use reclaimed steel elements in a low-rise office design to reduce the environmental impact while ensuring a compelling business-case. The building sector faces the challenge to transition to a circular building economy as stated in European sustainability goals for 2050. Reuse of structural steel sections is part of the solution to close the building materials cycle. To reuse steel on a wide scale, boundaries need to be overcome in designing and building but also information about the costs and environmental impact is required. To give more insights in these figures, the tool Steel-IT is developed in this thesis. A case-study, literature review and interviews with stakeholders in the steel and building sector form the basis of the framework to create and assess reclaimed steel office designs on costs and environmental impact.

Steel-IT uses an office design and database of reclaimed elements which are specified by the user. By performing a structural analysis for two structural configurations and using an algorithm to replace new steel elements with donor elements, two new steel and reclaimed steel designs are generated. Cost figures established by experts and by interviewing steel builders, traders and material test experts are used to estimate the costs. Using Steel-IT, a case is analysed and a potential reclaimed structure is generated. The effects of design parameters, assumptions and future scenarios is analysed. Results from these analyses allow to draw conclusions about how to create an attractive business-case and environmental impact score for low-rise office buildings while utilising reclaimed steel elements.

Most reclaimed steel designs generated in Steel-IT are more expensive than their new steel equivalent. The case that is analysed using Steel-IT shows that the main difference in costs originates from the extra costs for material testing, storage and re-fabrication. New steel is more expensive, €0.90 versus €0.30 per kilogram in the case study, but the above mentioned extra processes involved in reusing steel nullify this advantage. In the most optimal design in the case study, an impact reduction of 25% can be achieved with minimal increase in costs (<15%).

To achieve a donor steel project with a compelling business-case, the user thus needs to find a good match between a design and the database of reclaimed elements. Efficient use of reclaimed elements is important for a good business-case and impact score. Efficient utilisation is controlled by a weight-factor in Steel-IT's algorithm, which is optimally 1.4 to 2.0 for the portal frame. For the braced frame, a trade-off is forced upon the user where a choice between impact reduction and cost increase needs to be made. Furthermore, connections have a high influence on the design and business-case of a reclaimed steel structure. Re-fabrication is costly and reusing connections "as they are" can decrease these costs significantly. In the case study, this can make a 15% difference on the total costs. The choice of a light-weight flooring system result in lighter structures and decrease the impact and costs of the steel structure by 0-30% dependent on the structural configuration.

More gains can be made when sourcing the donor elements from existing buildings instead of stock-piles. This reduces costs for storage and additional handling of the elements. Avoiding elements with toxic conservation systems reduces cleaning costs significantly during re-fabrication. When validating the elements for material properties, elaborate testing allows to use the highest possible yield strength and this is worth while. Especially for the braced frame, a relatively strong correlation (R-squared = 0.11) between an impact reduction and a higher yield strength is present against minimal cost increase.

Future scenarios where emissions taxing is introduced only improves the business-case for reclaimed steel by a small margin. The taxes are low compared to the total costs of the steel structures considered in this thesis. The most promising future scenarios is where reuse of steel becomes normal practice. Higher availability will cause easier implementation of reclaimed steel elements and improves the business-case significantly. Steel produced using green hydrogen can reduce the impact of new steel significantly but won't close the material loop. Donor steel does as reuse is a high mode of circularity. Steel-IT can play an important role in connecting supply and demand and helps closing the research gap on design, costs and environmental impact in donor steel projects.

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1

Introduction

The building sector contributes to around 40 percent of all CO₂ emissions globally and steel and concrete production are the biggest contributing sectors (van Belzen, 2022). Structural steel production is responsible for releasing 3 million metric tons of carbon dioxide each year which amounts to 7-8% of all CO₂ emissions globally (Peplow, 2021). It can be concluded that there is a high need for research and its resulting solutions to reduce these emissions to achieve the environmental goals that are set for the building industry. A transition from a linear to circular building strategy is needed.

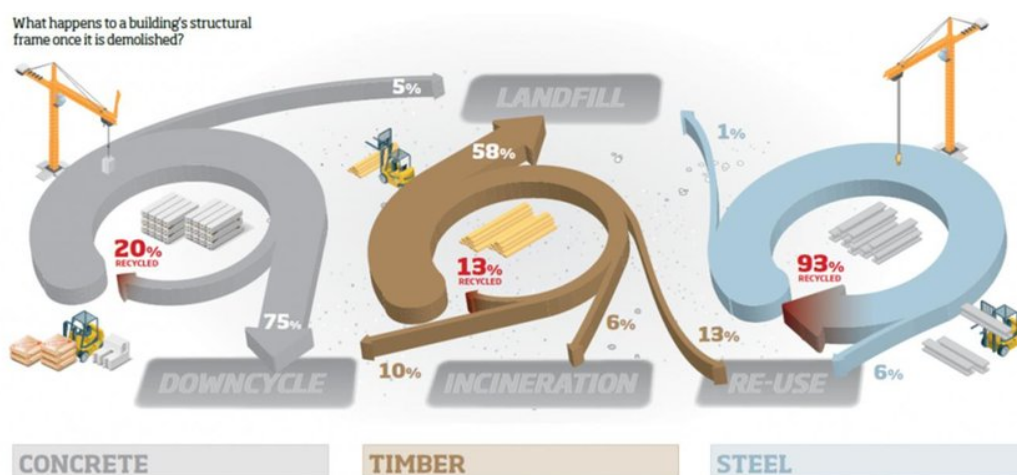


Figure 1.1: end-of-life destinations of materials in the building industry (SteelforLife et al., n.d.-b)

1.1. Transition to a circular building sector

For the transition new design methods and strategies are required. CB'23 is an project with the mission to support the transition to this new way of designing and construction. As of today, a big part of the construction industry is downcycling or landfilling their materials when buildings reach the end-of-life stage (SteelConstruction, n.d.). The steel industry mostly recycles its waste from deconstruction and reuse is not common practice. The recycling of steel scrap and production of new steel requires a lot of heat and results in high carbon emissions. Every ton of steel that is produced emits around 1200 kilograms of carbon dioxide (Kraaijenbrink et al., 2022a). Higher levels of circularity are required to be able to transition to a fully circular building sector. Research from the University of Utrecht has specified a hierarchy on circular strategies. This hierarchy is called the 10R model.

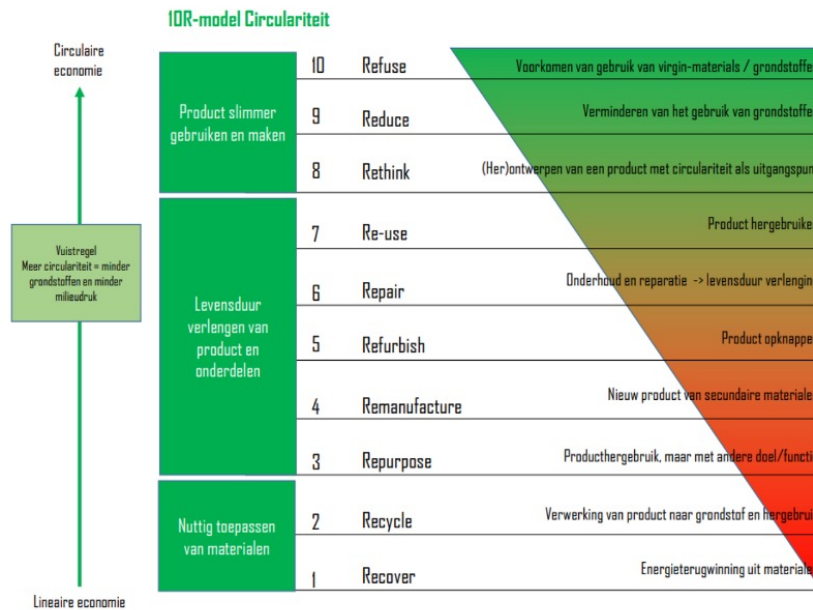


Figure 1.2: 10R model circular strategies (Archipunt, 2021)

As already concluded and seen in the figure 1.2, recycling of materials is not the best way of introducing old steel into a new life cycle. The highest modes of circularity are achieved by using the building in a smarter way and extending the service life of a structure. Recycling and energy recovery are considered as the lowest modes of circularity in this 10R model (Archipunt, 2021). The 10R-model is a result of one of many publications about possibilities to improve circular design of structures. Terwel and Crielaard collected these strategies to create an overview of these options to increase sustainability. Their article (Crielaard & Terwel, 2023) present a flowchart that include the following strategies:

1. Increase the value of current buildings.
2. Increase the value of current elements of an existing structure.
3. Increase the value through long service life and increasing future proofness.
4. Optimize the design in terms of environmental impact.

These strategies can be couple to the 10R model from figure 1.2. The best way to prevent emissions short term, is to not build a new structure at all. Alternative ways to prevent emissions early on in the life-cycle is to reuse elements. This can be achieved by finding suitable used elements for a building design, but adjusting the design to fit available elements can also increase possible reuse. To reuse steel, it needs to be re-certified, cleaned, and modified if it can not be used 'as is'. Flexible design processes are needed to match demand with supply and use reclaimed elements in an efficient way. The reuse of steel can be a big part of the transition to circularity and reduction of carbon emission in the building industry. Steel that is reused is also referred to as 'reclaimed steel' or 'donor steel' in this report.

Steel is a very durable construction material compared to other building materials. It is relatively light, strong, and durable. It is one of the most widely used construction materials in the world. More elaborate and larger designs depend heavily on it for structural integrity. The durability of steel makes it suitable for reuse. Reusing steel is not a new concept. It was more common in the past but because of stricter health and safety requirement for deconstructing buildings and structural safety, the reuse of steel element has decreased over the last few decades (Brown et al., 2019). Several barriers and challenges need to be overcome to start reusing structural steel again.

1.2. Barriers and challenges to using reclaimed steel

An opinion survey among structural engineers in the US, conducted by Rodriguez-Nikl et al. (2015), reveals that the most frequently mentioned barriers to implementing sustainable engineering practices

are actual or perceived costs, code compliance for innovations and the low availability of sustainable materials. The lack of information to specify sustainable material is also a problem. The most common missing information is life-cycle data, information on reuse and a fair comparison between materials. Most of these challenges can be related to lack of experience. The building sector is used to designing in a linear process and providing information and new regulations for circularity are important to make the transition. Similar conclusions are drawn in Europe. The Dutch building sector needs to be informed on what the possibilities and potential is of circular building strategies (Schouten, 2021).

An a conference paper from Densley Tingley and Allwood (2014), opportunities and challenges related to reusing steel are mentioned that were identified during the European Steel Environment and Energy Congress in 2014. The challenges that are associated with using reclaimed steel are in line with the findings of the survey from Rodriguez. The current approach to designing a steel structure assumes high availability of any cross-section type. This allows for a lot of design freedom as cross-sections can be selected that yield a high utilisation factor. In design with reclaimed steel, more flexibility is required. The availability of structural profiles is dependent on the inventory of stockholders and buildings that become available for deconstruction. The market for reused elements is small. With a limited choice of elements compared to the total design freedom of using new steel elements, the design with them seems rather unattractive. Tingley mentions the lack of regulation in quality assurance of reusable elements. Until recently there were no norms for re-certification and quality is now assessed by engineering firms or contractors themselves. This made it quite hard for contractors and engineering firms to come to an agreement on the allocation of the risks that are involved. Advisory and regulatory documents on steel reuse are being published to make this easier. The additional cleaning, re-certification and modification also add extra expenses and thus an extra barrier to reusing steel elements. The mentioned obstacles to making reuse a more common practices are summarised in table 1.1.

Technical	Re-certification regulations
	Efficient/safe deconstruction
Economical	Costs associated with reclaimed steel are unknown/uncertain
	Low availability and unregulated quality control can lead to delays
Availability	Low demand limits the development of the market
	Low availability limits easy implementation in design

Table 1.1: Barriers associated with using reclaimed elements (Densley Tingley & Allwood, 2014).

Reuse of structural steel elements is currently not common practice. Unlike traditional steel structures, information on designing and construction with reclaimed steel is unknown. Regulations on using reclaimed steel in new structures are not widely unrolled and risk allocation is difficult. Because the market for reused steel elements is small, a lot of information on costs, re-certification and design is unknown and/or uncertain. When more design teams choose to use reclaimed steel elements, the market can grow. A bigger market can potentially contribute positively to overcoming the challenges and barriers identified.

1.3. Regulations and research

The reuse of steel elements could be a big part of the solution to the challenge to make the building sector circular. There have been several developments the past years in this research field.

1.3.1. Regulatory recommendations and research

As mentioned before, Platform CB'23 has been publishing documents to guide the Dutch building sector in the transition to circularity. Their different action groups focus on future reuse, circular design, and material passports. Several documents on these subjects have been published in the last years, and in 2023, the final versions of these guideline documents will be presented (CB'23, n.d.).

In 2019 the Steel Construction Institute published a document prescribing assessment, testing and design principles for structural steel reuse. This document has a big potential to help overcome the technical barriers mentioned earlier. It does this by specifying quality assurance procedures and responsibilities to the parties involved in projects that use reclaimed steel (Brown et al., 2019). NEN

published an advisory document (Normcommissie 342086, 2023) for steel reuse in the Netherlands that prescribes a procedure to assess material properties of reclaimed steel. The document is drafted in collaboration with stakeholders in the steel industry and building sector. The documents contains some principles which are also described in the SCI report.

A project funded by the European Union, progress, provides strategies, tools and advice on the reuse of structural steel components. The main target of the project is design for deconstruction and reuse of structural elements and building envelopes. The report (VTT et al., 2020) provides recommendations on standardisation of structural components and suggests a framework to assess the material properties of used steel elements. The new Dutch NTA on reuse of structural steel elements is in-line with the recommendations. Next to the technical view of reuse, economic potential of reuse is also investigated by analysing single-storey, reusable buildings.



Figure 1.3: Advisory reports on regulations for reuse of structural steel.

1.3.2. Previous master thesis research

Multiple master thesis's have investigated the design process which utilises reclaimed steel elements. In research from van Lookeren Campagne (2022), a tool was created using grasshopper that uses a growth algorithm to create a bridge truss out of reclaimed steel elements. This algorithm uses whole length elements to construct the truss geometry. The results were compared to using other design method like optimal dimensions, cross-section design, which can be described as common current methods of designing a truss, and a fitting of the stock to a design. The environmental impact is significantly lower by using the reclaimed steel stock but what can be concluded is that the algorithms using this stock do yield high truss weight and low utilisation factors.

The master thesis from Rademaker (2022) focused on creating a model/tool that fits element from a reclaimed element database to a building design. By manipulating the building geometry, an optimisation could be performed to come to a geometry that fits the maximum number of reclaimed elements. It can be concluded that the stock dictates the design. If there is a more diverse stock, or the design is more uniform it gets easier to design with it as there are more possible use cases for the elements.

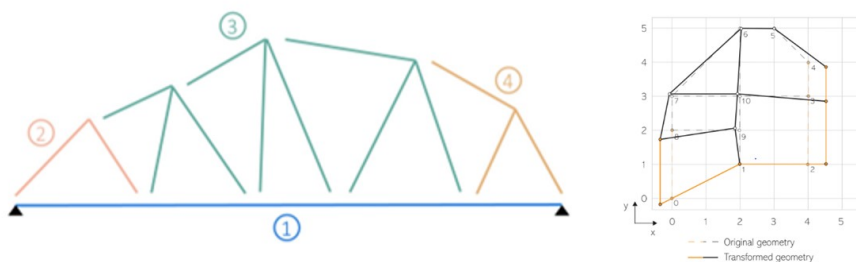


Figure 1.4: Previously conducted master thesis research.

1.4. Conclusions

Change in the building sector is needed to be able to achieve the global and national targets on climate change. Emissions need to be reduced and linear material cycles need to be closed. The structural steel industry already recycles most of its waste but higher reductions of emissions are needed to stay below the 1.5 degree global warming limit. Several studies identify higher modes of recycling and circular strategies. Structural steel has a long technical service life which makes reuse possible. However, several challenges and barriers prevent reuse of materials in current engineering practices. Adversity against new design philosophies, technical re-certification and unknown effects on costs are the main challenges in wide-scale implementation of reclaimed steel elements. Research institutes publish documents to give guidance in the process and regulatory guidelines and norms are starting to be published to overcome the highlighted technical barrier of re-certification.

The unknowns about costs are not overcome yet. Several small projects that utilize reclaimed steel elements have been taking place. Key-figures on the costs are not established yet as most projects are exploratory and unique. Research into the costs of reusing steel can overcome the barrier of perceived and actual costs. Being able to conclude on the financial feasibility of such a project contributes to increasing the likelihood of projects with donor steel being realized.

2

Research Content

This chapter discusses the contents of my research. From the introduction in chapter 1, a problem definition and a main research question is derived and objectives and goals are formulated. The chapter gives an insight about the goal of this thesis and how this goal will be achieved.

2.1. Main research question

The building industry faces the task to make the transition to circularity. This is a big challenge as the sector's material production is responsible for a big part of the carbon emissions in the world. In the structural steel industry, recycling of scrap is the standard, but this still requires a lot of energy and is very carbon intensive. Reusing steel directly without melting it can prevent these emissions and thus reduce the environmental impact of new steel structures. The use of reclaimed steel elements as a construction component is not common practice in the Netherlands. There are innovative projects like Biopartner 5 that implement a so called donor-skeleton, but the wide-scale application of used steel elements stays behind. Research in re-certification and the design process is undertaken to overcome the barriers and challenges to steel reuse. There is, however, still a lot of unknown information about the use of reclaimed elements in building design.

Lack of information in the form of perceived and/or actual costs is one of the biggest barriers to implementing sustainable developments and is also applicable to the reuse of steel. The design and construction process differs from traditional design and it is not known what the effects are on the costs of a project. This is the gap in knowledge that this Master's thesis will address. I consider this the most important gap as in most projects costs play one of the bigger roles in decision-making. In a traditional design process the cost build-up of using structural steel consists of the product price, transport, fabrication and construction on the building site. Using reclaimed elements will have different effects on these cost-components.

This research will focus on developing a tool that can generate a design with reclaimed elements for a low-rise office building and gives insight in the effects on costs and environmental impact compared to a new steel equivalent. The goal of this research is to answer the main research question of this Master's Thesis:

"How to create an attractive business-case and environmental impact score for a low-rise office building with a reclaimed steel structure?"

2.2. Goals

2.2.1. Meta goal

This thesis research contributes to a bigger meta-goal:

"To increase the demand and use of reclaimed steel element in the building sector to transition to a circular economy."

By giving insight into the costs associated with the use of reclaimed steel and where these costs originate from, design teams can prepare for implementing reclaimed elements in their designs. In this way the research contributes to increasing the demand for reclaimed steel elements. If it is possible to create a higher demand, the market will develop further, and the barriers of steel reuse can become smaller. This goal is too big and not achievable by a single Master's Thesis, but it aims at contributing to it.

2.2.2. Research goal

The goal of the proposed research will be to give an insight in the economic and environmental costs that are associated with steel reuse. It will do qualitative research into the build-up of these costs and will quantify them by designing a tool that compares a traditional steel design with a design alternative using reclaimed elements. This research goal can be formulated as:

“To determine the difference in costs and environmental impact between a traditional steel, low rise office building and a design variant that uses reclaimed steel elements.”

2.2.3. Personal goal

With my thesis I aim to finish my master in Civil Engineering by doing a project in a field of my own interest. I like to create a thesis that is relevant for current engineering practices and would like to do this while in contact with an engineering firm. I think sustainability and mainly the transition to circularity in the building sector is a big task that my generation of engineers faces. Contributing to this task in my master thesis is important to me. Furthermore, I have the grades to graduate with a cum laude status depending on the result of my Master's Thesis. I would like to be pushed by my graduation committee members to achieve the full potential of my Master Thesis work.

2.3. Sub-questions

To give an answer to my main research question, several sub-questions are formulated to give insight in specific details that are involved in this Master's Thesis. The first part of my research will focus on the process of designing with reclaimed element in comparison to traditional design and it aims to identify where the changes in costs originate from. The following research questions are formulated to achieve this.

RQ.1 *“How does the process of using reclaimed steel elements differentiate from the traditional design process?”*

RQ.2 *“Where do the differences in costs when designing with reclaimed steel originate from compared to a traditional steel design?”*

To answer these questions a process analysis will be performed on a case study to compare the process of a traditionally designed building and structure designed with reclaimed elements. The process analysis also focuses on identifying where the difference in costs of using reclaimed steel originate from to answer the second sub-question. The knowledge obtained by answering the first set of questions leads to definition of the second set of sub-questions. This set is used to gather information on creating a design and assessing the costs and environmental impact of new and reclaimed steel structures.

RQ.3 *“What are the possible methods of creating a design alternative from an original design using a database of reclaimed steel elements?”*

RQ.4 *“How does utilisation of reclaimed steel influence joinery and member extension and shortening?”*

RQ.5 *“What are the quantitative economic costs of using reclaimed steel or new steel elements in an office-building building design?”*

RQ.6 *“How should the environmental impact of reclaimed steel and regular steel be quantified?”*

The second set of sub questions will be answered by conducting a literature review and interviewing stakeholders in the steel and construction industry. The information that results from answering these sub-questions will be the basis for the tool. The development of the tool asks for an additional set of sub-questions. This set of questions is about how this knowledge should be used in the tool.

RQ.7 *“Which design principles should be fundamental to the design alternative generation in the tool?”*

RQ.8 *“To what extent and in what way should joinery, member elongation and shortening be implemented in the tool?”*

RQ.9 *“Which cost influencing parameters and principles will be used in determining the economic costs and environmental impact in the tool?”*

The answers to these questions are formulated in the algorithms and models that are used in the tool. When the tool is finished it needs to be tested to see if the output of the tool corresponds with expectations. It is difficult to see if the results are correct as there are no case studies available to directly use the tool on. The sensitivity of the assumptions made need to be reviewed. The evaluation of the tool should answer the following sub-question:

RQ.10 *“How does the output of the tool compare to the expectations of professionals?”*

RQ.11 *“How do future scenarios like increased reuse of steel, CO2-tax and green steel production affect the business case and environmental impact score of reclaimed steel?”*

With the evaluation of the tool and the future scenarios, an answer to the main research question can be formulated. A discussion on the results and their sensitivity to the assumptions that were made in this research results in a conclusion and recommendations for future reuse.

2.4. Research scope

The research question immediately describes a big part of the scope of this thesis research. To assure that the ambitions of this research plan can be executed in the time frame available an additional scope is defined that provides the boundaries of the literature review and tool. This research will limit itself to:

- Low-rise office buildings
- The Dutch building sector
- The preliminary structural design stage.

This research is conducted to develop a tool that creates a new and reclaimed steel design and assesses its costs and environmental impact. The tool will be created to be used by engineers that have knowledge on structural design of steel structures. By limiting the research to low-rise office buildings, structural schemes stay relatively simple in terms of stability and lay-out. The analysis of costs and environmental impact is performed based on the Dutch regulations and market. The tool will provide its functionality in a preliminary design stage. Not only because this is when relevant design choices need to be made but also to reduce the amount of detail in consideration of costs and environmental impact.

3

Structural steel in office buildings

Steel is used in structures as it is strong, light and durable. It allows for relatively lightweight and slender structures compared to concrete and wooden structures. This chapter will give an insight into the historical use of structural steel and will then focus on its application in office buildings.

3.1. History of structural steel use

The first use of steel in construction goes back to the end of the 18th century. The first iron bridge was built in 1779 in England. In this early stage they did not make steel yet but made use of cast, pig and wrought iron in structures. Compared to the low carbon steel that we use today, these types of iron had inferior material properties as they were lower strength and brittle. In the middle of the 19th century, the railway industry was only using steel and later buildings would follow. In the 20th century, steel was present in virtually every building that was built. Due to the increase use of steel, cheaper and more efficient production processes were developed which also improved material homogeneity. Technological advances in production of hot-rolled steel sections, boosted the production of structural steel even more and it became the iconic construction material as we know today (Architecture, n.d.).

3.2. The standard office building

Low-rise office buildings often utilise a steel structure. It is light, cheap and allows for flexibility in the floor plan of the building. An article from Evers et al. (2003), published by *Bouwen met Staal*, describes a standard office building in research about cost effective buildings. This structure, displayed in figure 3.1, has a grid size of 5.4 meters. The grid size is often a multiple of 1.8 meters as this is a measurement that is often used to build the interior with.

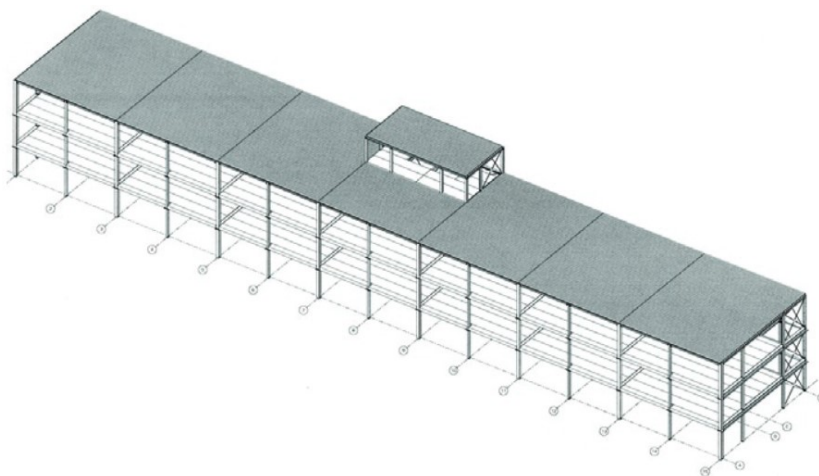


Figure 3.1: Standard 3-layer office building with a steel load-bearing structure (Evers et al., 2003)

This standard office building has floor spans of 10.8 meters to reduce the number of internal columns and the roof, which is lighter, is often not supported with internal columns at all. When internal columns are used, continuous beams reduce stress and deformation. To realise these continuous beams for longer frames, splices using endplates are used to keep element size to a limit to account for maximum transportation sizes.

The storey height of this building is 3.4 meters which allows for 320 millimeters of room for ducting and other utilities. The horizontal members that support the floor are integrated beams to reduce structural height. Concrete hollow-core slabs are a popular choice for this type of building but over the last years, lighter wooden variants like wooden hollow-core slabs are also an option to be considered (P.Peters, personal communication, May 2 2023). In the typical design of Bouwen met Staal, the horizontal stability is guaranteed with wind-braces in the roof of the top floor. When using a slab floor system, horizontal wind-braces are not necessary as the slabs provide diaphragm action. The vertical stability of the low-rise steel structure can be guaranteed by using wind-braces or portal frames as the wind-forces are small for low-rise buildings.

Steel is preferred for office building up to two or three storey's because it is often the most economic option. Costs of materials, fabrication, construction and (fire protective) coating are relatively low. Furthermore, by using a steel skeleton, free floor-plans can be realized (Evers et al., 2003).

3.3. Design regulations for office buildings

Just like any other building type, office buildings should be designed following the rules of the Eurocode. Some starting points from the Eurocode to the design an office building are (Normcommissie 351001, 2019b) (Normcommissie 351001, 2019a):

- Office buildings classify as consequence Class 2 buildings
- The variable floor load is 3.0 kN/m^2
- Minimum fire safety requirement is 60 minutes

In general, structures need to be verified using combinations of different loads prescribed by the Eurocode. The general loadcombinations for ultimate (ULS) and serviceability limit state (SLS) are:

$$ULS : \quad \gamma_G * G_k + \gamma_{Q;1} * Q_{1;k} + \sum (\gamma_{Q;i} * \psi_{0;i} * Q_{i;k}) \quad (3.1)$$

$$SLS : \quad G_k + \gamma * Q_{1;k} + \sum (\psi_{0;i} * Q_{i;k}) \quad (3.2)$$

3.3.1. Ultimate limit state (ULS) design

For ULS combinations for consequence class 2 buildings the following load factors (γ) should be used (Normcommissie 351001, 2019a):

Design situation	Permanent unfavourable	favourable	variable loads leading	other
1	1.35	0.9	-	1.5
2	1,2	0.9	1.5	1.5

Table 3.1: Load factors ultimate limit state design

The ψ factors used are dependent on building type. Table 3.2 summarizes the relevant psi factors office building design (Normcommissie 351001, 2019a).

Building type	ψ_0 (variable action)	ψ_1 (frequent variable action)	ψ_2 (quasi-permanent variable action)
Office ares	0.5	0.5	0.3
Roofs	0	0	0
Snow loads	0	0.2	0
Wind loads	0	0.2	0

Table 3.2: Relevant psi factors for office design

To determine the governing loads on the structure for ULS design, different load-cases are considered. Each element should be strong enough to withstand the forces in both load-cases. The governing load-case can differentiate per element. For a typical frame of an office building, the following load-cases can be considered critical.

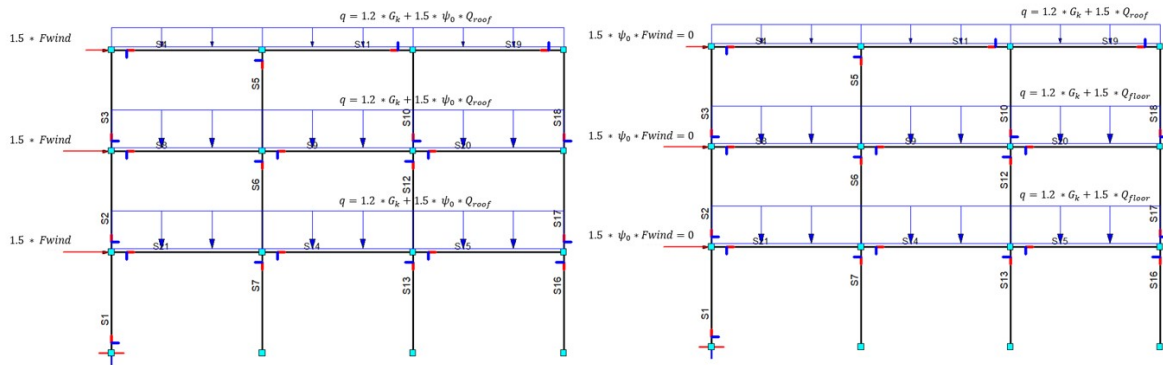


Figure 3.2: Load-cases for dominant wind- and floor-load

In serviceability limit state, all loads factors are 1.0. Global and local displacements need to comply with regulations. For global deformations, the horizontal displacements at the top of a building need to be below $\frac{1}{500}$ times the total building height and displacement per storey should be limited to $\frac{1}{300}$ times the storey height. On local element level, deformations of floors should be lower than 0.003 times the free span (Normcommissie 351001, 2019b). Load-cases can be relevant in different situations. For continuous beams, alternating floor loads can cause bigger sags in loaded floor-spans. There are many load-cases that could be relevant. Software can compute all of them and experienced engineers can recognise critical load-cases.

3.4. Fire safety

Bouwbesluit 2012 (Rijksoverheid, 2023) is a regulatory document for building design in the Netherlands and together with norms, dictates fire safety design. For office buildings the minimal resistance against fire spreading from a one to another compartment is 60 minutes for critical compartments. Critical compartments are identified as compartments that are used as exit-routes or are critical to the overall building integrity. This means that in case of a fire in a critical compartment, the building should stay intact for at least 60 minutes. Any critical structural components need to fulfill this requirement. Figure 3.3 shows the strength of steel plotted against temperature.

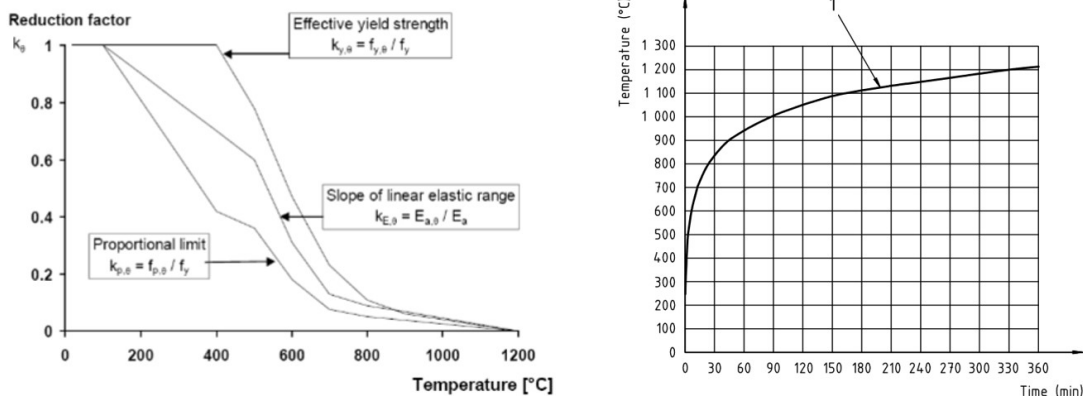


Figure 3.3: Strength of steel versus temperature (Normcommissie 35100102, 2011) and the ISO standard fire curve (Normcommissie 353084, 1999).

After 60 minutes the ISO standard fire curve indicates a temperature of 950°C. In the left graph, the reduction factor for steel at 950°C is lower than 0.1. Even with reduced loads in the fire scenario, most members will not suffice the minimum fire safety requirement of 60 minutes without any measures. There are two main ways to increase the fire safety performance of steel members:

1. Gypsum-board cladding
2. Fire spray

Both measures are effective at increasing the fire resistance of the steel structure. Gypsum board acts as an extra barrier for the heat and fire spray swells up when exposed to high heat. This also acts as insulation to keep the beam at a lower temperature for longer. In terms of this research, fire safety will not be included. It is assumed that fire safety measures are similar for reclaimed steel and new steel. The same will be assumed for costs of the measures taken in fire safety design.

4

Biopartner 5

This chapter will provide information to answer the first set of sub-questions. This will be done by gathering information from the case study: Biopartner 5. The case studies will give insight in the process of building with reclaimed steel and how the costs of such a project differ from traditional steel designs.

4.1. Project description

BioPartner Center Leiden wanted to create an laboratory building and social hub that is an icon of sustainability. Popma ter Steege architects set of with the mission to design a building with a circular interior but during the design process, steel sections from a nearby building became available. The donor building was located on the same campus only 750 meters away from the new building site (Bouwen met Staal, 2022).

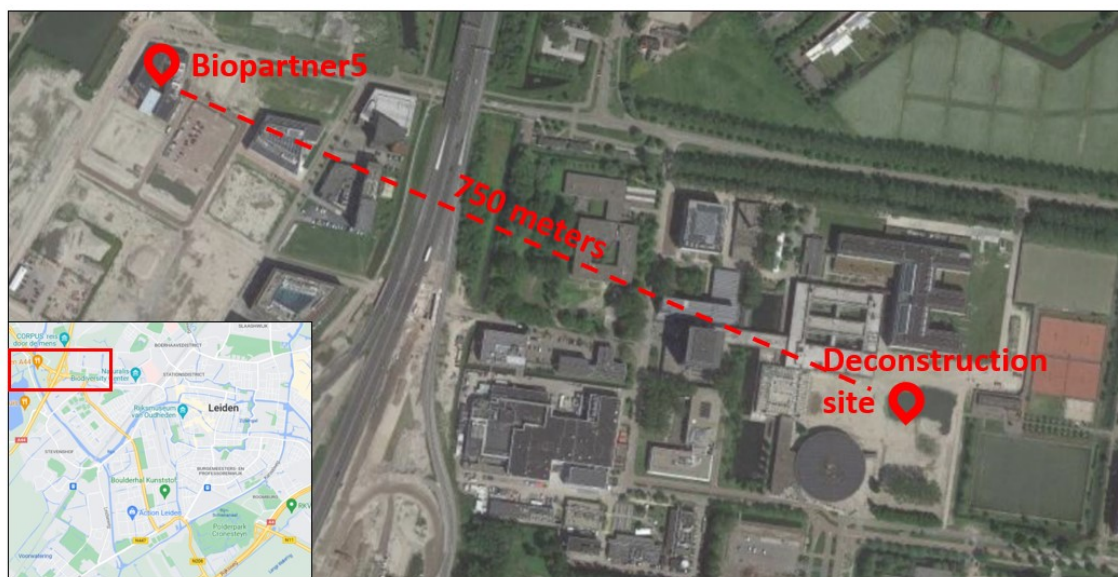


Figure 4.1: The location of the Biopartner 5 and the deconstruction site (Google, n.d.).

Biopartner 5 uses 159 tons of reclaimed steel elements. The project is the first big scale application of the 'donor skeleton' principle and claimed to be the first 'Paris-proof' building in the Netherlands. The project is a good case-study as the original plan was to build a traditional 'new-steel' structure with a circular interior. During the project, when plans for the steel structure were already close to finished, the potential of reusing elements of a building close by came to light. IMd Raadgevende Ingenieurs re-engineered the building to accept the elements that became available. While redesigning, design

for deconstruction principles were applied which makes the structure easier to demount and reuse in the future. In this way, the team created a double sustainable building (Bouwen met Staal, 2022).

Teammember	Role
Popma ter Steege Architects	Architecture
IMd Raadgevende Ingenieurs	Structural engineering
Vic Obdam	Steel structure manufacturer
De Vries en Verburg	Construction

Table 4.1: Involved parties in design and construction of Biopartner 5.

Biopartner was finished in 2021 (LBSPG, n.d.). During the flexible design process, active involvement of all parties was required to complete the project successfully.



Figure 4.2: Biopartner after construction (LBSPG, n.d.)

4.2. Engineering

IMd Raadgevende Ingenieurs played the role of structural engineer for the BioPartner 5 project. The engineered structure consists of concrete hollow-core slabs that rest on a steel structure of columns and beams.

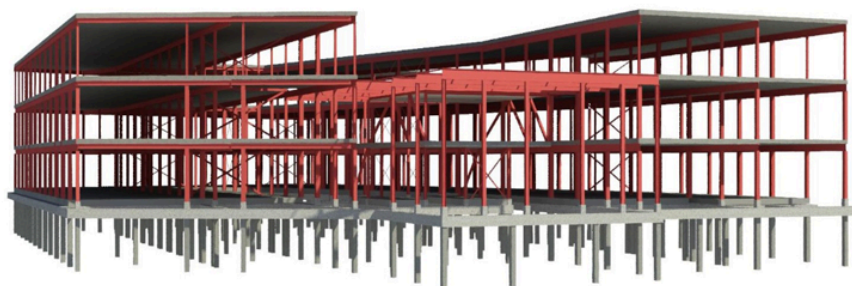


Figure 4.3: Structural system of Biopartner 5 (Bouwen met Staal, 2020).

The horizontal stability is provided by the reused portals from the donor building in one direction and windbraces in the other, as seen in figures 4.3 and 4.4. The figure also suggests that the horizontal stability is provided by diaphragm action of the floorsystem. A big part of this structure is made with donorsteel. Some parts like the windbraces were executed in new steel as this was more cost efficient.

In the design, as many bolted connections were used as possible to improve demountability in the future. This also had a positive influence on the transport costs as the building was assembled on site. The hollow-core slabs are designed to be demountable in the future by using a special detail. The portals that were used have the function to provide stability as they had some overcapacity that could be utilized in the 3.6 meter grid that was adopted in the design (Terwel et al., 2021).



Figure 4.4: Reclaimed steel portals used in the Biopartner 5 steel frame (Beenker, 2021)

4.2.1. Material properties

The steel from the donor building was tested to determine the material properties. Recalculating the current structure gave insight into the stress the structural elements experienced during its life-cycle. The additional testing of samples was performed to validate the results of the recalculation. In the end a strength of 180 MPa was used. (Terwel et al., 2021). When checking the steel quality for welding, it was discovered that the elements were galvanized which makes it harder to weld. This increased the necessity of using bolted connections.

4.2.2. Detailing

The mission to create an easy demountable structure and the complications of welding galvanized steel manifests itself in detailing of the structure. Bolted connections are used throughout the building.

An example of the use of bolted connections and components is seen in the way the column to beam connections are realized in some locations. Instead of regular welded plates, UNP profiles are bolted into the steel beams to make the connection between the top and the lower column. In this way no welding of the beam is required. The UNP-profile is also easily demounted in the future. The connecting column, orange in figure 4.5, does have an endplates. The endplates do require welding.

Another example is the demountable connection between the hollow-core slabs and the steel beams. A threaded rod and steel plates were used to clamp the floor to the edge beams and the seams between the hollow-core slabs were filled with concrete and reinforced with steel to prevent rotation in case of uneven loading of the floor (Terwel et al., 2021).

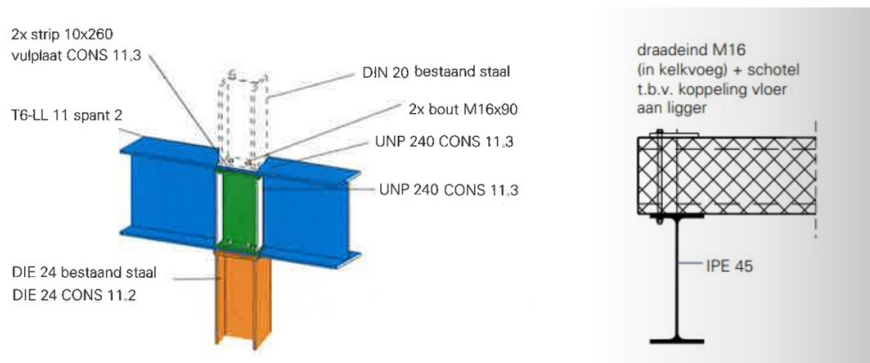


Figure 4.5: Column-beam detail (left) and demountable hollow-core slab to beam connection (right) (Terwel et al., 2021).

Two other connections that facilitate the combination of new and reclaimed steel are the beam splices and finplate connections that were used in Biopartner. The splice uses a new steel plate to connect the beam to the portal frame. It connects using bolts which means that the beam could be modified without welding. On the right, a fin-plate has been welded to a new steel cross-section (in green) and connects to the beams using bolts. This means the reclaimed steel beam did not require any welding in the fabrication process. This saved transportation as all fabrication could be done on-site and prevented extra costs of toxic coating removal. The new new steel section was fabricated in a workshop.

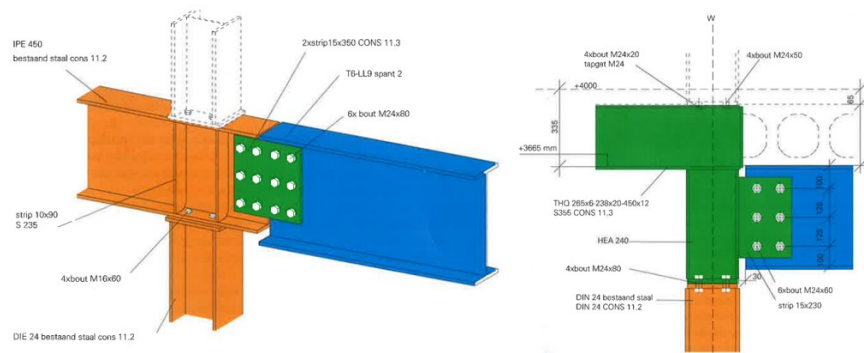


Figure 4.6: Splice and fin-plate connections combining new and reclaimed steel (Redactie Bouwen met Staal, 2021a).

4.3. Execution

The steel structure has been designed and engineered by Imd Raadgevende Ingenieurs. Vic Obdam, a Dutch steel builder performed the detail engineering and fabrication. The steel structure uses 159 tons of reclaimed steel from a laboratory building that was deconstructed only a couple hundred meters away. The frames that were pulled from the existing building were stored directly on the new construction site. Figure 4.3 shows the complete steel structure.

4.3.1. Deconstruction

Before deconstruction could start, a 3D model was created to be able to label the elements. Before the 159 tons of reclaimed steel were harvested a protocol was formulated considering imperfection of the existing building elements. This protocol aimed to quantify acceptable imperfection in size and straightness. The protocol also states acceptable limits of deformation due to deconstruction. The deconstruction itself did not go without problems. Several elements were rejected because they did not pass the limits defined in the protocol. Other damaged elements could be repaired. Aesthetically imperfections were accepted and perceived as marks of the structure's past life.

4.3.2. Steel manufacturing

Vic Obdam set-up a temporary workspace at the project site to modify the donor elements. This did save a lot of transportation. The portal frames are not easy to stack and it would have taken a lot of time and money to get them to the workshop of Vic Obdam and back. Modifying the elements on site is a bit more work than in a specialist's workshop of-course but this out-weighted the advantages. The use of an on-site workshop was new to the team of Vic Obdam but they did find a way to make it work (G.Obdam, personal communication, February 3 2023).



Figure 4.7: On-site workplace for steelwork by Vic Obdam (Beenker, 2021)

In the design, deconstruction was taken into account. As few welds as possible were used in the connections to increase reuse in the future (Beenker, 2021). Pieter Klijn, director at Vic Obdam, states in a article (Redactie Bouwen met Staal, 2021a) that it is not that difficult to execute a project with donor steel. It is not that different from regular steelwork when buying the element. The difference is in the engineering, modifications, fabrication and assembly of the steelwork. There is a lot more collaboration effort needed to make it work. Another challenge is the insecurity about the status and properties of the existing elements.

A challenge identified by an employee at Vic Obdam (J.Mak, personal communication, February 3 2023) has to do with the weld-ability of the steel elements. Toxic conservation systems that include compounds like Chrome-6 or zinc in form of galvanisation can cause the need of sandblasting the elements before welding for health safety reasons. This sandblasting is costly and if a new conservation system is needed, it adds costs and environmental impact to the elements as well. Sawing and pressing holes in the elements can be done without removing these toxic paints. The donor portals used in the Biopartner project were galvanised, which made using bolted connections even more preferable.

4.4. Costs

In the Biopartner project, the IGG-bureau had the role as cost-engineers. Rob Passchier, who was involved with the project at IGG, indicated (personal communication, February 15 2023) that cost estimation in an early design stage often have a low level of detail. A breakdown of the processes involved is done to arrive at a 'price per kilo' using key figures established through experience. Based on a cost comparison between the new and donor steel variant of Biopartner 5, figure 4.8 was created. The table shows a qualitative and quantitative comparison of the new and reclaimed steel design of the Biopartner 5 project. The numbers in this excel are outdated but the build-up is still relevant.

	New steel design	New + reclaimed steel design	
€ 0,70	Steel buy price	Steel buy price	€ 0,45
€ 0,70	Sandblasting + coating		
€ 0,20	Colorcoating		
€ 0,20	Transport to building site	Transport to building site	€ 0,10
		Delivery and mounting	€ 0,29
€ 0,90	Construction	Construction	€ 0,90
€ 0,09	Welder	Welder	€ 0,04
€ 0,14	Engineering	Engineering	€ 0,15
€ 0,28	Extra costs (heavy + availability)	Extra costs (storage)	€ 0,02
		Connection hardware	€ 0,11
5%	Risk	Risk	15%
€ 3,42	Total	Total	€ 2,37

Figure 4.8: Cost comparison between new and reclaimed steel (R.Passchier, personal communication, February 15 2023).

When looking at the comparison, the following things should be mentioned:

- 10% extra risk is allocated for the donor steel alternative.
- The €0.45 donor steel price consists of the costs of demounting the elements from the donor building en the scrap price of the elements (R.Passchier, personal communication, February 15 2023).
- Transport of the donor steel is cheaper as the donor building was closeby and modification were done on-site.
- The estimation indicates a similar amount of engineering for the donor elements. The use of complete frames meant a small amount of engineering in terms of connections, but a bigger engineering fee for research and adjustment of the design makes engineering costs similar.
- The donor steel is not sandblasted and/or coated.
- Construction using donor elements amounts to the same costs as for new steel.
- In the estimation, connection hardware has been included for donor steel and not for new steel.

The extra risk that is accounted for has to do with the unsure material properties of the donor steel, unknown damages and unknown compatibility problems when combining new and donor steel in the same building. In this cost estimation, donor steel costs around €2.40 and new steel about €3.40. This seems to be good for the business case for donor steel. However, it should be noticed that for this first indication, the two design alternatives are very close on costs. The reason that the two design alternatives are so similar in cost is due to the fact that more kilograms of steel are used when designing with donor steel. The donor steel variant uses approximately 240 tons of steel while the new steel alternative uses approximately 170 tons of steel. Together with the extra risks, the two alternatives don't show a direct winner in terms of costs. It is noticeable that the new steel alternative is more expensive in terms of fire protection although there is less mass to protect.

4.5. Environmental impact

In the final design, 159 tons of reclaimed steel and 86 tons of new steel was used. Figure 4.9 shows part of the steel structure and indicates the new steel in green and reclaimed steel in orange and blue.

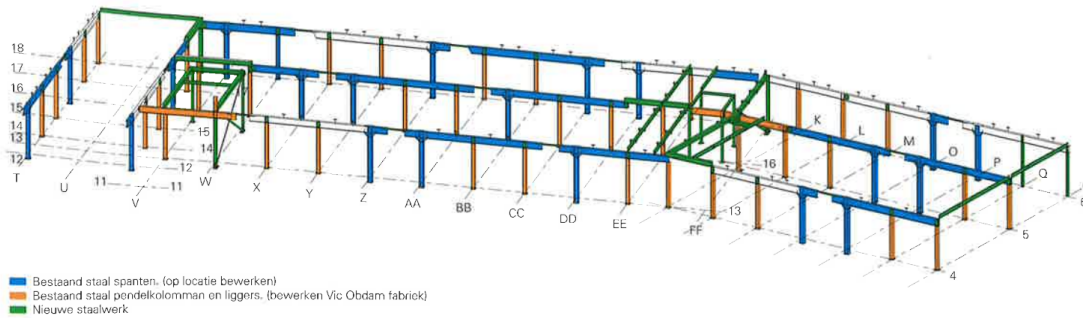


Figure 4.9: Use of new and reclaimed steel in the Biopartner 5 building (Redactie Bouwen met Staal, 2021a)

Around 65% of the steel structure consists of elements from the donor building. Nibe and the Dutch Green Building Council have analysed the material bound emissions which amount to 248 kg CO₂ - eq/m² (Dutch Green Building Council, 2021). This would qualify Biopartner as Paris Proof. This means a maximum carbon emission of 250 kg CO₂ - eq/m² at the time of construction (Spitsbaard & van Leeuwen, 2021b).

4.5.1. MPG calculation

The Nibe institute performed a MPG and MCI calculation for the Biopartner project (NIBE, 2020). The MPG is the total environmental impact of the building per square meter of usable surface. This environmental impact is calculated following the standards of the Nationale Milieudatabase. This institutes specifies the life-cycle-assesment calculation procedure and quantifies the factors to monetize the impact across different categories into one monetary value. This value is called the environmental cost indicator, or ECI. Chapter 7 goes into more detail about environmental impact analysis and indicators.

The Nibe report (2020) considers two methods of estimating the ECI value of reclaimed steel. Both assume that the steel harvested from a donor building is 'burden free', meaning that no steel production emissions need to be accounted for. When elaborate modification are required, these processes can be quantified in terms of environmental impact. Quantifying the impact of these modifications can be a lot of work and is different for all elements. Another option is to use the approximation that the impact of these modification is 20% of the equivalent new steel ECI value. In the case of Biopartner, a lot of effort has been done to facilitate reuse of the elements as they were in the previous building. This justifies to not use the 20% approximation, but assume an even lower environmental impact. In the calculation performed by Nibe, the ECI-value of reclaimed steel has been assumed to only contain the transportation from the deconstruction site to the new building's location. In this calculation, sawing of the elements and addition of endplates has been neglected. Transportation between the two sites results in a ECI of only €2.5 as the reclaimed steel was sourced less than 1 kilometer away. The deconstruction of the elements using a crane would add another €11.5 per hour. It was deemed realistic that an ECI value of €100 should be used to quantify the environmental impact of using the reclaimed steel elements.

MPG		MKI	
Berekend per m ² BVO, per jaar		Berekend over de totale BVO en levensduur	
0,539		184.088	
A. Productiefase	0,424	A. Productiefase	144.730
A. Constructiefase	0,021	A. Constructiefase	7.235
B. Gebruiksfase	0,154	B. Gebruiksfase	52.688
C. Afdankfase	-0,001	C. Afdankfase	-396
D. Buiten gebouwlevensloop	-0,059	D. Buiten gebouwlevensloop	-20.170

Figure 4.10: Results of the environmental impact assessment of Biopartner 5 (NIBE, 2020).

The results from the analysis of the whole structure show that most of the environmental impact still comes from the production of materials. Information about the contribution of the steel structure is unknown. An article from Bouwen met Staal (Bouwen met Staal, 2022) claims that the use of the elements from the donor building among other measures resulted in a 40% decrease of environmental impact compared to an equivalent traditional design.

4.6. Conclusions

The Biopartner 5 project has put the donor skeleton principle on the map. The building qualifies as a Paris Proof structure with 248 kg CO₂ per m² of use-able building area. The success of the project comes down to the following main features of the design and building process:

- Local sourcing of reclaimed elements.
- Thorough inspection and guidance of deconstruction.
- Using material tests to validate strength of elements from recalculations of the existing structure.
- Flexibility in the design.
- Reusing reclaimed elements and components 'as is' in the new design.
- Clever detailing to prevent welding to the reclaimed elements.
- On-site fabrication to reduce transportation.

Using the case study of Biopartner, RQ.1 and RQ.2 can be answered.

“How does the process of using reclaimed steel elements differentiate from the traditional design process?”

“Where do the differences in costs of a reclaimed steel structure originate from compared to a traditional steel structure?”

4.6.1. The difference in process

The process of designing and building with reclaimed elements has some big differences compared to a traditional steel building. The process starts with the search for donor elements. Their properties and the possibilities for reuse need to be determined and this already involves more work and parties. Labelling before deconstruction allows to keep track of the elements. The design itself needs to be flexible to change during the process as challenges may arise due deconstruction, material testing and (re-)fabrication. This is quite the difference with a traditional design process where elements are available from the factory on demand.

The aim is to reuse elements as they are to minimise re-fabrication which can cause challenges and costs. The design needs to fit the available elements which is a fundamental difference in design philosophy compared to a new steel design where it generally is the other way around. There is limited experience and toxic conservation systems make it difficult to weld to the reclaimed steel elements. In some cases, this asks for a new approach to detailing where the use of bolted connections can minimise the costs if modifications are necessary.

4.6.2. The difference in costs

The aim in a project that utilises reclaimed steel elements, is to create a cost neutral design alternative compared to the traditional steel variant. The price of the donor steel itself can not be determined from one project but it is likely that the deconstruction contractor will want to make the same amount of profit from one deconstruction contract. This would put the price of reclaimed steel at the scrap price plus some margin. As indicated in the conclusion in the previous paragraph, by reusing elements as much 'as is' high costs for re-fabrication and transport can be minimised. The fabrication costs for reclaimed steel are a lot higher than for new steel as imperfections, existing hardware and (toxic) conservation systems make it hard to process. In terms of assembly costs, building with reclaimed steel is not different from new steel design.

Making a cost estimation on a project is more difficult as there are more unknown factors that play a role. Extra risk needs to be allocated to absorb extra costs due to design changes, connectivity or setbacks as more details about the donor elements are validated. In traditional steel design, the market is aware of the design and construction process, reducing risks of a project.

5

Reclaimed steel elements as a construction material

Reclaimed steel is part of the solution of moving towards a circular building sector. This chapter will go into the implications and challenges that reclaimed steel use has on designing a building. This chapter will go into sourcing the used elements, determining material properties and designing with reclaimed steel in terms of detailing. Last, some computational design methods are discussed that can be used to design with used steel elements.

5.1. Harvesting of reclaimed steel elements

New steel is fabricated using raw resources and steel scrap from demolished buildings. This means that the kind of steel and geometry properties can be specified by the producer and will be connected to the demand on the market. For reclaimed steel elements, this is not the case. These elements are demounted from existing structure to then be used in a new project. The supply depends on the available donor buildings which poses challenges for design and construction. This section focuses on how reclaimed steel is harvested from existing buildings.

5.1.1. Deconstruction

Deconstruction is per definition very different from demolition. Deconstruction focuses on taking a structure apart in a way that the elements are still use-able. The process of harvesting elements from donor building with the aim of reuse is also called 'urban mining'.

There are several companies that specialise in this new way of deconstruction buildings. B-next and new horizon are good examples. They facilitate not only the deconstruction of buildings but also have a web-shop where the harvested elements that are not directly sold of are put up for sale. In this way the elements that get harvested, are more likely to be reused. New Horizon states on their website (Horizon, 2023): "Urban mining can make a big CO_2 reduction possible if all harvested elements are actually reused". These companies make an inventory of reuse-able elements on building scale and collect information about suitable elements before deconstruction. For steel this information would be geometry, type of element and thickness (A.Hendriks, personal communication, February 20 2023).

In the building sector, steps are made in documenting information of a building's components in so called material- and building-passports. These passports are drafted with the aim to minimise environmental impact and increase circularity. By documenting the type, location and quality of materials, reuse can be increased. It is easier to select suitable donor buildings when the inventory of reusable components can be viewed before inspection or deconstruction.

5.1.2. Market exploration

There are several parties that supply reclaimed steel elements. At mentioned, companies like B-next and New Horizon have web-shops where reclaimed products are sold. It is noticeable that these web-

shops do not contain a lot of reclaimed steel elements. Hendriks from B-next mentions (personal communication, February 20 2023) that they have customers that take the steel elements directly when deconstructing a building. The elements do not reach the web-shop. The price point of the harvested elements are established using key-figures for the branch and the (extra) costs of careful deconstruction.

There are several individuals and companies that offer reclaimed steel sections on second-hand trading-platforms. Marktplaats is the biggest platform in the Netherlands and several users have hundreds of meters of reclaimed steel elements for sale. Structural steel supplier de Charro from Deltastaal warns (personal communication, February 8 2023) for this marketplace. The price of the sections are only marginally lower than the price of new steel sections. This price point is not relevant as the elements have lots of unknowns and are qualitatively not as good as new steel. As project developer this marketplace should not be considered when sourcing reclaimed steel sections.

5.2. Designing with reclaimed elements

Designing with reclaimed elements is different from traditional steel design. Sections are not widely available and material properties are sometimes unknown. The article from Crielaard and Terwel (2023), mentioned in the introduction, comes with a flowchart for the reuse of structural steel elements.

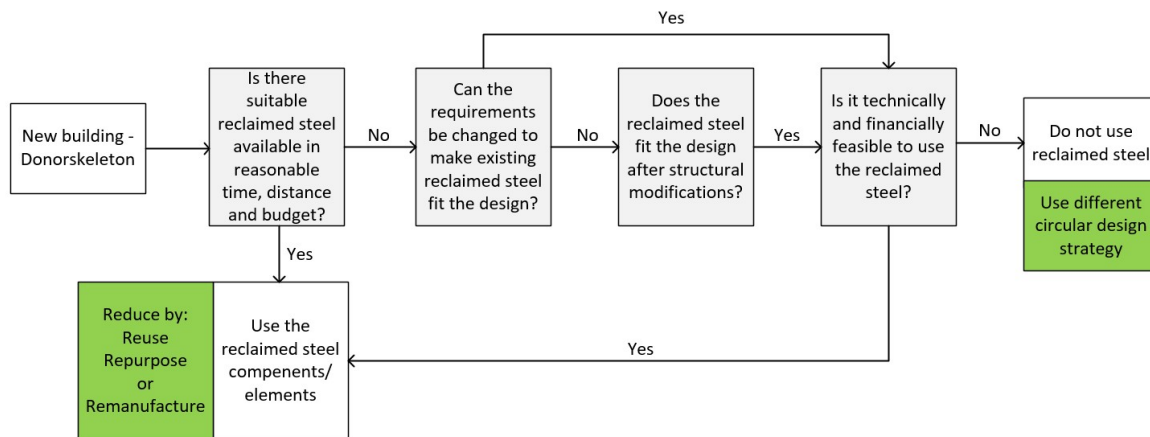


Figure 5.1: Flowchart for reuse of structural elements

There are several options to include reclaimed structural elements. First of all there needs to be established whether there are suitable elements to include in the current design. If there are none, the building design can be altered to match the donor skeleton better or a new donor skeleton can be sourced. Technical and financial feasibility play an important role in the success of a donor steel project. It can be concluded that a new design philosophy is required.

5.2.1. Change in design philosophy

A paper from Gorgolewski (2008) mentions that reuse has different effects on the design process compared to recycling of materials. Recycling gives the opportunity to make a decision on how to recycle the materials. In case of steel, the steel scrap from a building site is fed back into the production process and remelted. Reusing steel requires more flexibility from the designers in terms of design and processes. The paper of Gorgolewski identifies some challenges in the design process.

Firstly, traditional processes are based on cost and time efficiency. Processes associated with reuse of steel, like deconstruction, can be seen as complicated and labour intensive. This attitude results in aversion towards new processes that are key to implementing circular building practices. Secondly, a traditional design depends on matching construction components to the requirements of the structure. Following this approach, it is difficult to coordinate demand and supply. Reclaimed elements will mostly not be available on-time or in the quantity and size that is required. Gorgolewski suggest that the design

process will be turned around. The starting point of a new design will be a list of elements. The section sizes and lengths of these elements will dominate the structural configuration of the design.

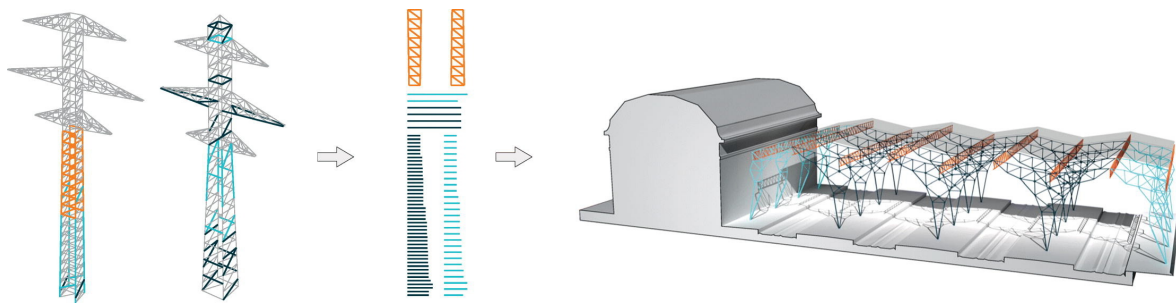


Figure 5.2: The design process where an existing structure is the starting point (Brütting et al., 2019).

A study from Brütting et al. (2019), performs a case-study on the reuse of structural steel elements. Electrical pylons in Switzerland were scheduled for deconstruction. Elements of these towers are installed using bolts. This makes deconstruction easier and reuse possible. By analysing documentation of the pylons, lengths, cross-sections and amounts of steel were identified and used to design a roof for a train station. A structural optimisation method described in section 5.5 optimises the utilisation of the structural elements from the pylons. This workflow is shown in figure 5.2.

In another paper from Brütting, Vandervaeren, et al. (2020), it is mentioned that in structural optimisation for a building with reclaimed elements, limits to the application of donor steel should be implemented. Oversized elements could be reused more efficiently in other structures and the extra weight and structural height has consequences for the rest of the load-bearing structure like the available free storey height. As the reclaimed steel stock is limited, the optimum will often be a hybrid of new and reclaimed steel sections. This analysis is applicable for structure weight, costs and environmental impact.

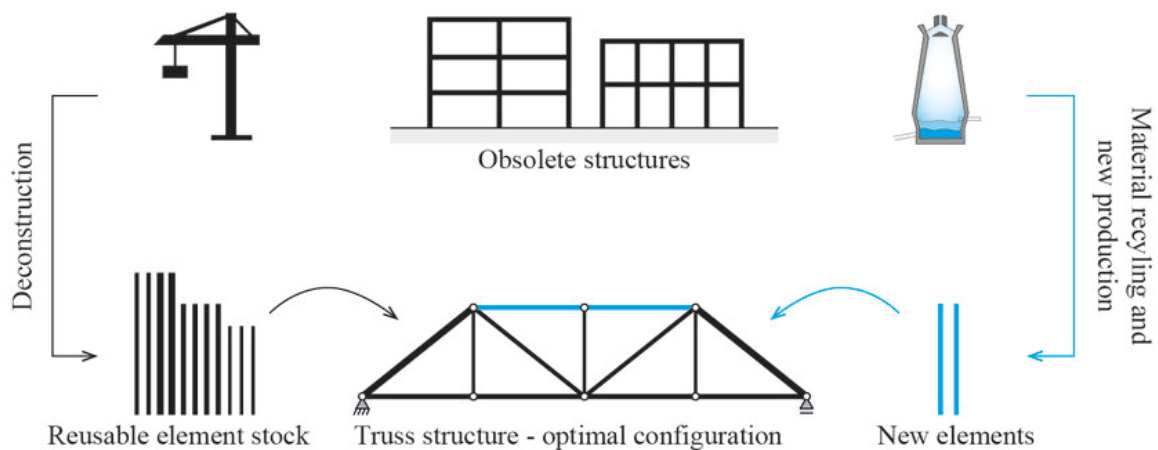


Figure 5.3: Optimal design of a truss with new and reclaimed steel elements (Brütting, Vandervaeren, et al., 2020).

5.2.2. Design for Deconstruction

To make reuse easier in the future, design of new buildings need to consider the deconstruction phase during the building life-cycle. Design for deconstruction focuses on the reuse as the end-of-life scenario. Standardization, connections and detailing are identified as key elements to provide easier deconstruction.

The PROGRESS report (VTT et al., 2020) states that it is important to achieve some form of standardization in building geometry and detailing to increase future reuse. The following key aspects are identified for multi-bay frames:

- Design and detailing of columns should be done to be able to act as internal or edge column.
- Design of connections using bolts, and standardization of these components.
- Use the same structural components for given member lengths and loading.

Universal detailing can increase the possibilities of reusing the structural elements. If more elements are detailed in the same way, transferring parts from one building to the other is less likely to involve extensive modification of the components or elements.

5.3. Material properties

The material properties of steel are important when designing with them. With new steel the steel yield and tensile strength is verified by the manufacturer. The designer knows for sure what material properties to use when performing the structural verification. For used elements, especially elements from older buildings, these material properties are not always known. Three publications that deal with this issue are summarized below.

5.3.1. PROGRESS Report

This project is set-up to formulate methodologies, tools and recommendations on reusing steel. The PROGRESS report (VTT et al., 2020) gives a flowchart to assess elements for reuse. All elements not older than 1970 are eligible for reuse. Steel produced before this time has in-homogeneous material properties which makes material properties validation and thus reuse difficult. Three classes of reclaimed steelwork are formulated in terms of the information on their material properties:

- Class A: Steel materials with original documentation
- Class B: Steel materials that meet performance requirements through testing
- Class C: Steel materials classified as the most conservative grade.

Class A elements have mill certificates and documentation available. This confirms the material properties together with minimal non-destructive testing during preliminary assessment of the reclaimed steel. These elements can be used in the future using the documented material properties for structural verification. Class B elements have no certificates and documentation available. The material properties of class B elements are verified through testing. The results of the tests determine the material properties which will be used for structural verification. Class C elements did not undergo testing and therefore their material properties are based on conservative assumptions. PROGRESS suggests that these elements can only be used in consequence class 1 structures. The flowchart for the proposed assessment system of reclaimed steelwork is shown in figure 5.4.

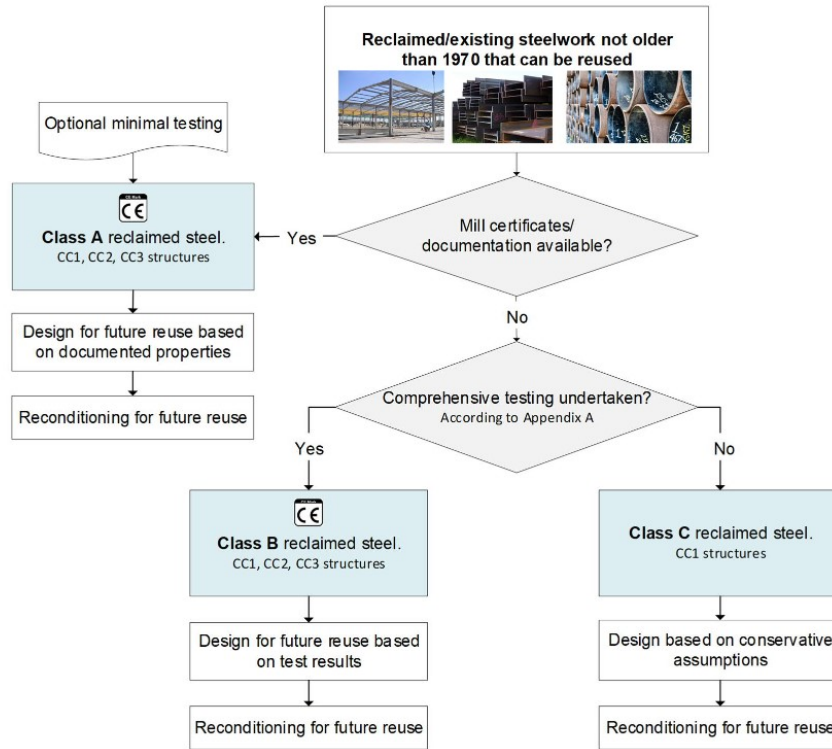


Figure 5.4: Framework to assess steelwork adequacy (VTT et al., 2020)

5.3.2. NTA-8713

NTA-8713 ((Normcommissie 342086, 2023)) about the reuse of structural steel was recently published. The so called technical agreement is created in collaboration with the Dutch steel and construction sector. The document describes how to go about determining the material properties of reclaimed steel elements. To start of there are three classes in terms of material property validation based on the consequence class of the new structure:

Class1: consequence class CC1a and CC1b.

Class2: consequence class CC1a, CC1b and CC2.

Class3: all consequence classes.

There are several methods of determining material properties of the reclaimed steel. These methods use archive information and tests to validate the material properties. The guideline makes a distinction between five levels of archive information.

Status	Document
1	Material certificates, CE-markings or a Declaration of Performance
2	Fabrication drawings
3	Execution drawings
4	Construction drawings and calculations
5	Design drawings and calculations

Table 5.1: The five levels of archive information specified in NTA-8713.

There are two ways of determining the suspected material properties of a structure before material testing. The tests are then used to validate the assumed value for the yield and tensile strength of the donor steel.

1. Archive information The material properties of the steel can be determined by looking at documents from the donor building. The year of steel production and the type of steel are the basis on which the strength properties are determined. The document contains tables with values that can be used.

2. Lower-bound method The lower-bound method uses the year of construction of the donor building to determine the minimum production standard of that time. The lower-bound values are summarised in table 5.2. This method can be used for every class.

Year	f_y [N/mm ²]	f_u [N/mm ²]
1955-1972	235	355
1972-1990	200	300
1990-1997	235	360
1997-2005	235	360
2005-now	235	360

Table 5.2: Lower-bound method yield strength for production periods from 1955 (Normcommissie 342086, 2023).

The guideline describes that the assumed properties, which are determined by using the above methods, will need to be validated by doing material tests. Only when the building is deconstructed and relocated as a whole and documents of status 1,2 and 3 are present, tests can be left out of this procedure.

To start the procedure of testing the reclaimed materials, the elements need to be divided into test units. A test unit consists:

- at maximum of 20 tons of elements with the same cross-section.
- of elements that had a similar application in the donor structure.

For each research class, different requirements are specified for the tests that need to be performed on each test unit.

Class1: Archive information of status 5 and higher are used to determine the steelgrade in combination with three non-destructive hardness-test.

Class2: The steelgrade can be determined using status 4 and higher archive information or by doing hardness tests on each individual element. This result needs to be considered in combination with one tensile test per test unit.

Class3: The steelgrade can be determined using status 2 and higher archive information or by doing hardness tests on each individual element. This result needs to be considered in combination with three tensile tests per test unit.

The steelgrade is determined based on the measured value from the tensile test which should be higher or equal to the value from the archive information or hardness-tests.

If the elements needs to be welded to during re-fabrication, the chemical composition of elements need to be checked by evaluation the CEV-value of the steel. For class 1 and 2, this value can be determined using the lower-bound method or by performing one destructive test per test unit. For class 3, three destructive tests need to be performed per test unit and the use of the lower-bound method is not allowed. A flowchart is presented to indicate the steps in material property validation according to the guideline.

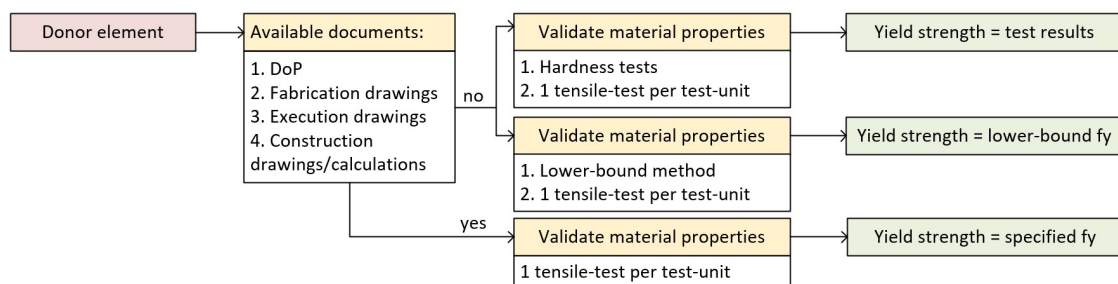


Figure 5.5: Flowchart to determine material properties f_y and f_u for reclaimed steel using tensile tests

5.3.3. IMd - Case study: The Upcycle Mall

IMd raadgevende engineers are part of the Upcycle Mall project in Rotterdam which features a donor skeleton from a laboratory building. The municipality experienced resistance in getting the required permits concerning the quality assurance of the reclaimed steelwork that was going to be used (R. van den Berge, personal communication, January 31 2023). IMd drafted a protocol for this project. Conclusions about the procedure of assuring the steel properties were:

- If material certificates are available, the steel quality can be assured without further tests for verification.
- When there are no certificates available, a test program can verify the properties of the steel.
- If deconstruction is difficult, strive for a reserve on the allowed stresses.
- When welded components are reused, the welds need to be checked visually and for critical welds, more elaborate inspection in microscopic level is needed.

Again, this complies with the flowchart and procedure described in the PROGRESS report and Dutch NTA. In this document, some case studies are highlighted which gives an insight on how the quality assurance was dealt with. In these cases, a reduction of the allowed stress is often used to gain some extra safety margin in case of imperfections. This reduction is often around 15 percent. Older steel is handled even more conservative as their properties are not as consistent. In the BioPartner 5 project, 180 MPa was used after recalculating stresses of the previous building and validating the assumed minimal value of 180 MPa by limited testing. In comparison with the NTA it can be concluded that this is more conservative than the new regulations will prescribe (Terwel et al., 2021). An advantage to this method of material property validation is that less tests are needed as they are just used to validate and not to determine the material properties.

5.4. Connections

The difference in designing with reclaimed steel compared to new steel elements also has its effect on connection detailing. As mentioned earlier, buildings that use reclaimed steel elements often have bolted connections. This can be because the material is difficult to weld to because of preservation systems that were applied in the previous life cycle or because deconstruction in the future is taken into account. In a steel frame, the distinction can be made between primary and secondary connections. Primary connections connect the structural steel elements to each other or the foundation. Secondary connections connect the steel structure to other building components like the facade. In this thesis, only the steel structure is considered. In a typical steel frame, the following primary connection types can be identified:

1. Beam-to-column connections
2. Beam-to-beam connections
3. Column-to-foundation connections
4. Wind-brace connections

5.4.1. Beam-to-column connections

In the Biopartner project, two types of beam to column connections are used. The first one from figure 4.5 connects columns from two storeys to a continuous beam. The continuous beam is a reclaimed steel element that was installed without extensive modifications as an UNP profile was bolted to the element to transfer the normal forces between the two columns. The columns, which were also taken from the donor building, had to be modified in a workshop as this connection requires endplates to bolt to the beam and UNP profile. The big advantage compared to welding in plates to transfer the column forces is that no welds are needed and it is easy to take apart. Especially the first advantage can mean a lot for the feasibility of using reclaimed steel elements as sandblasting and repainting adds a lot of additional labour and costs.

The second connection is a fin-plate connection. The fin-plate, for this hinge-type connection, is welded to a new piece of steel (green in figure 4.6). Welding to new steel is easier as it does not imply weld-ability assessment and paint removal like a similar reclaimed steel detail would need. The beam - column connection in figure 4.5 do however suggest that welding is possible, even in the case of

Biopartner where the elements were galvanised. Another good option for the fin-plate would be to bolt to cleats to the beam and column. Both welded and bolted alternative are shown in figure 5.6.

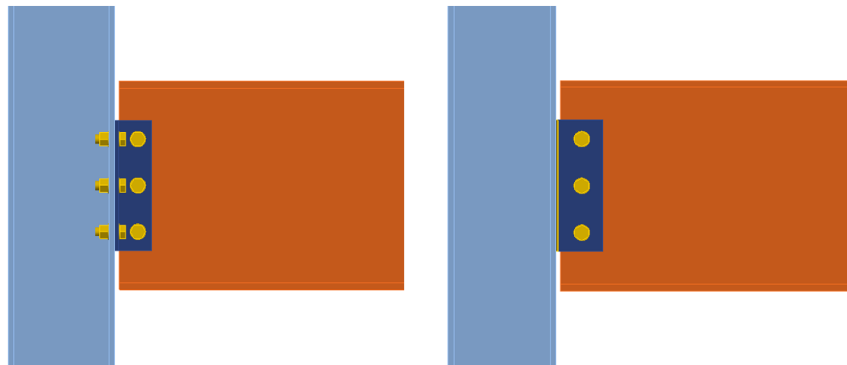


Figure 5.6: Bolted and welded beam to column fin-plate connection (IDEAStatiCa, 2022)

The welded connection only uses one plate. Using two plates would mostly not be possible as it is impossible to weld both sides of the second plate when the first plate is already installed. This does make the bolted connection more expensive as angle cleat needs to be installed on both sides (Moore & Wald, 2003). When using welded fin-plates when designing with reclaimed steel, additional sandblasting and repainting should be considered in the total costs of the connection. This cleaning and repainting is not needed when only using bolts (G.Obdam, personal communication, February 3 2023).

The fin and angle-cleat connections only allow for pinned connections. In steel structures, often, continuous beams are used. When using a beam that spans multiple supports, occurring bending moments and deformations are reduced. There are several ways of making a rigid connection from one span to the other. Two options are shown in figure 5.7.

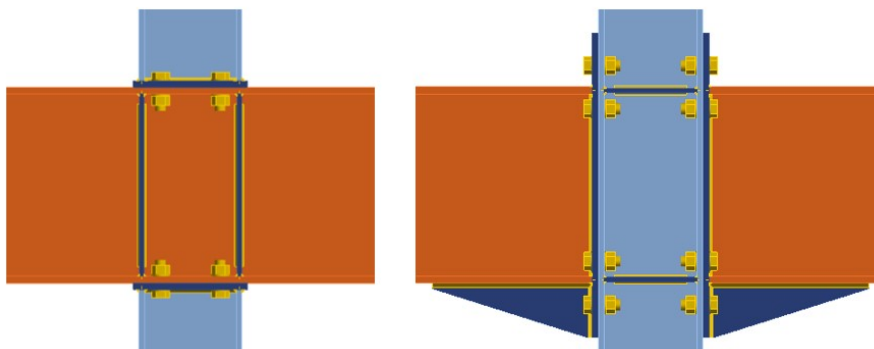


Figure 5.7: Moment resisting beam to column connections to create continuous beams (IDEAStatiCa, 2022).

The left assembly results in a hinge-like connection to the column while the right connection results in a rigid connection. The stiffeners in the web of the beam in the left assembly allow transfer of normal forces between the columns. In the Biopartner project this connection was used. The stiffeners were executed by bolting UNP profiles in the beam, to prevent welding. The columns do need end-plates to connect to the beam. The second option on the right establishes a more rigid connection between beam and column. High bending moments can be transferred between the two beams and column. Both connection types can be used to create rigid portals to provide stability. It can be concluded that right connection is more expensive to fabricate when looking at the amount of welds, bolts and plates that need to be used.

5.4.2. Beam-to-beam connections

As seen at the Biopartner project, there can be cases where the cross-sections of beams that need to be connected through a splice are different. For new steel splices where the cross-sections of the beams are the same there are 3 general types of beam splice. Bolted splices with plates or endplates and welded splices. These types are displayed in figure 5.8.

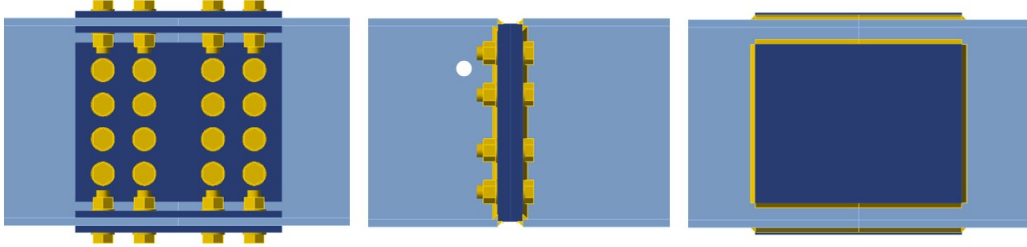


Figure 5.8: Types of splices for beams of equal cross-section.

In chapter 4, a splice with two different cross-sections was shown in figure 4.6. It should be noted that the plates on the flanges are missing as the bottom flanges do not align. This does mean that the connection loses its ability to transfer bending moment. Using this connection type means no welding of the donor elements is required, which is preferred. Another option is to connect the elements using endplates. This connection can transfer more bending moments. Figure 5.9 includes drawings of both alternatives to connect beam sections with a different cross-section.

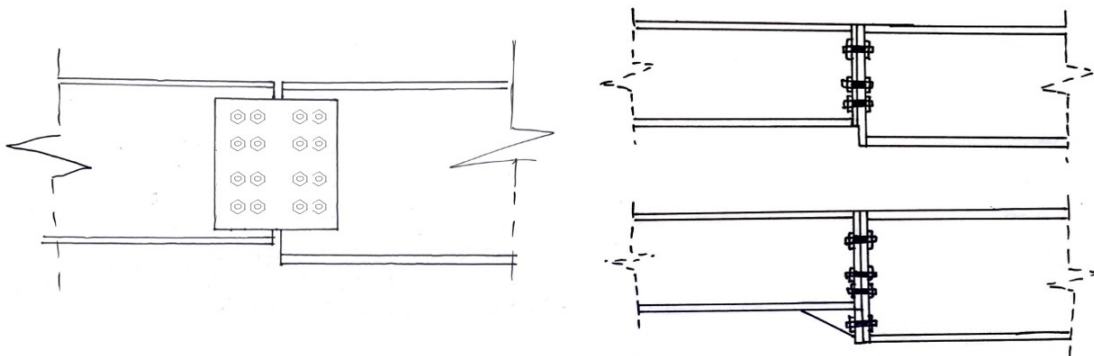


Figure 5.9: Beam splices using web plates only (left) and end-plates (right).

Both connections won't be able to transfer as much bending moment as the first connection in figure 5.8. The web-plate variant in figure 5.9 will behave more like a pinned connection, only transferring the shear and normal forces in the beam. The end-plate connection would be able to transfer more bending moment. When looking at beam splices, next to strength, stiffness should be taken into account as well. When using a pinned connection, like the web-plate connection in figure 5.9, deformations can be large in asymmetric loading conditions as seen in figure 5.10.

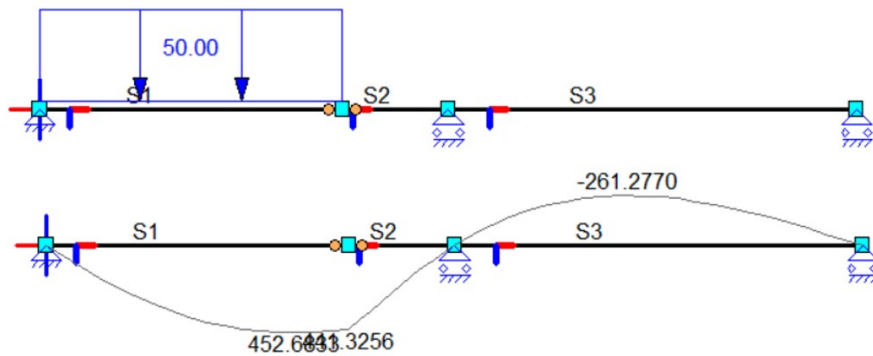


Figure 5.10: Deformation of a hinged splice under asymmetric loading (Matrix Software, 2021).

When using a connection that has a higher bending moment resistance like the end-plate connection in figure 5.9 the spliced beam will deform more monolithic as the bending moments can be transferred through the splice connection. This can be seen in figure 5.11.

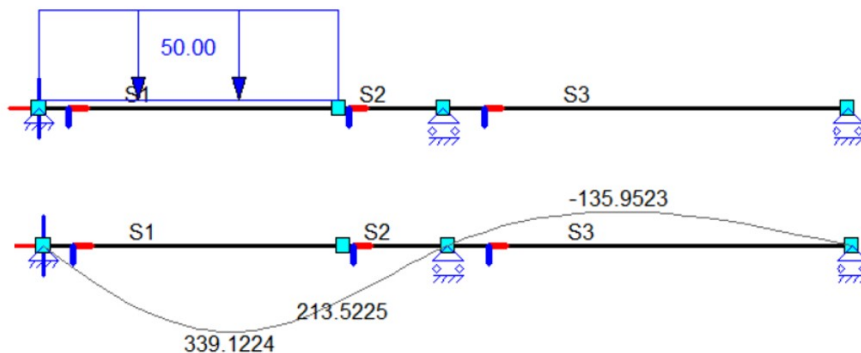


Figure 5.11: Deformation of a splice with higher moment resistance under asymmetric loading (Matrix Software, 2021).

5.4.3. Column-to-foundation connections

A typical detail for this type of connection is an end-plate that is connected to the foundation using bolts that are anchored in the concrete. This connection detail can be executed in a shear and moment connection. The difference between the two is the location of the bolts.

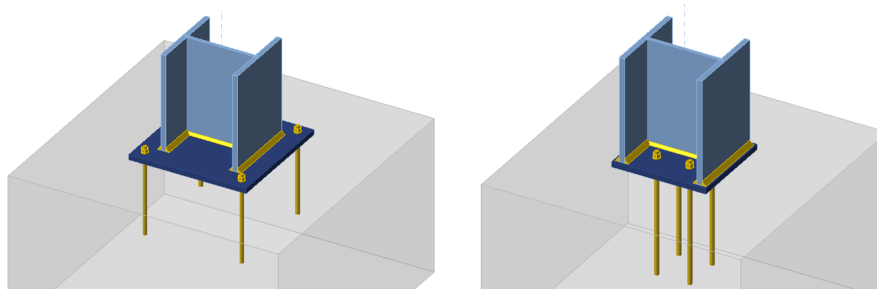


Figure 5.12: Moment resisting and hinged (shear) column-to-foundation connections (IDEA StatiCa, 2022).

5.4.4. Wind-brace connections

The last connection that is applicable to the design of a steel-frame low-rise office building is the connection of the wind-bracing to the frame. Normally plates are welded to the profiles and the wind-bracing is bolted to them. When using reclaimed steel, it is best to omit any welding if possible. The same plates

can be bolted into the beams and columns. Figure 5.13 shows two variants of these bolted wind-brace connections.

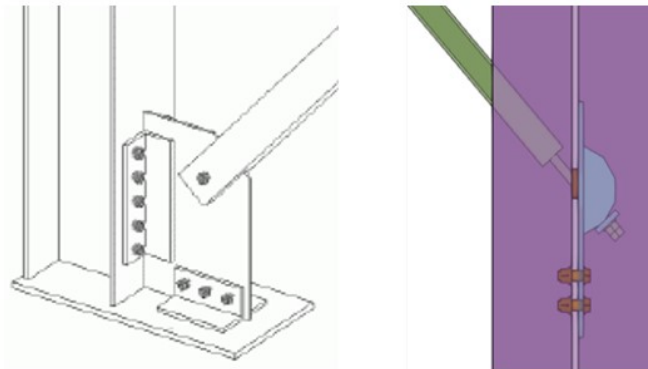


Figure 5.13: Flange-bolted (Trimble, n.d.-b) and web-bolted (Trimble, n.d.-a) wind-brace connection details

5.5. Computational design algorithms

Designing with reclaimed elements asks for a lot of flexibility and introduces some new design strategies. Computational and parametric design could be used to explore the possibilities of using reclaimed steel elements in building design. Using algorithms and computing power provides the tools to explore a broader solution space compared to manual design processes. Different studies and these have been carried out on computational design with reclaimed steel elements. These algorithms look at placing elements from a limited database in a new design. Three algorithms are discussed in this section.

5.5.1. Assignment and cutting-stock optimisation

Research from Brütting, Senatore, et al. (2020) presents optimisation methods to design structures from a stock of reclaimed elements. The assignment of elements in a design is focused on and the optimal way of cutting the elements in the stock which results in the lowest amount of waste is considered. These two methods are visualised in the figure.

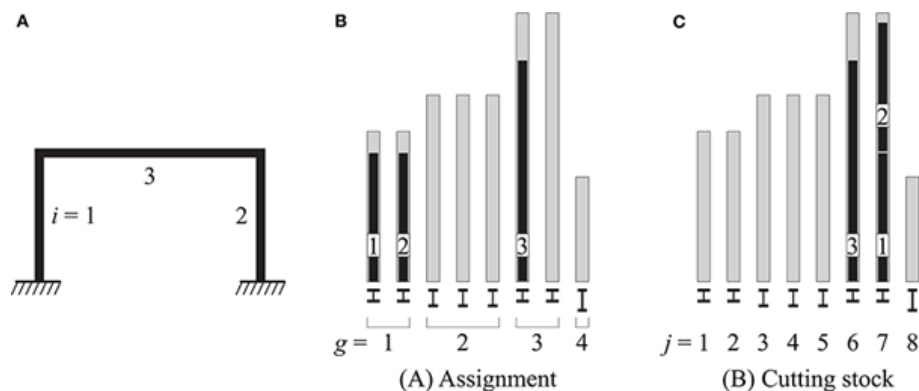


Figure 5.14: Assignment and cutting stock optimisation (Brütting, Senatore, et al., 2020)

The assignment of elements is defined as a combinatorial problem which is described by equations 1 to 4. t_{ig} is a binary design value which describes if a reclaimed element is used at a member position (1 is yes, 0 is no). c_{ig}^A is the costs of assignment t_{ig} . The cost can be the associated carbon or economic costs. Equation 2 ensures that each element from the reclaimed stock is used only once. Equation 3 makes sure the assignment is constrained to the number of available elements per group (n_g). The last equation makes sure the length of the reclaimed elements is equal or bigger than the original element's length.

$$\min_{t,y} \sum_{i=1}^m \sum_{g \in S} t_i g C_i g^A \quad (5.1)$$

$$\sum_{g \in S} t_i g = 1 \forall i = 1 \dots m \quad (5.2)$$

$$\sum_{i=1}^m t_i g \leq n_g \forall g \in S \quad (5.3)$$

$$l_i^- \leq \sum_{g \in S} t_i g l_g \forall i = 1 \dots m \quad (5.4)$$

The element will be assigned to the member position that has the lowest environmental cost in the scope of the research. This cost can be altered to be any objective function like economic costs and efficiency in the form of a unity check or a combination of both. Cutting stock optimization is the second type of optimization that is mentioned in the paper and uses the following objective function 5.5:

$$\min_{t,y} \sum_{j \in S} y_j c_j^B + \sum_{i=1}^m \sum_{j \in S} t_{ij} c_{ij}^B \quad (5.5)$$

It searches for the option where all costs (c_j^B) related to using an element j and all costs (c_{ij}^B) for installing that element at position i in the structure is a minimum. Equation 6 ensures all elements are used and 7 takes care of the element length to be sufficient.

$$\sum_{j \in S} t_{ij} = 1 \forall i = 1 \dots m \quad (5.6)$$

$$\sum_{i=1}^m t_{ij} l_i^- \leq y_j l_j \forall j \in S \quad (5.7)$$

Using these equations, elements from a database can be fitted to an existing geometry. As for each reclaimed elements, multiple 'fits' could be possible, lots of combinations are possible. Minimisation of the total costs results in the best design. This is a form of global optimisation.

5.5.2. Growth-algorithm

In the thesis of van Lookeren Campagne (2022), a tool is developed that uses a growth algorithm to generate a truss structure for a pedestrian bridge. The algorithm first calculates the required capacity of the bottom chord by using a standard warren truss (1). The bottom chord is preferably constructed of the same elements but when these are not available it can also be a mix of different profiles. Using node equilibrium and the method of section the algorithm determines the forces and thus required cross-sectional area of the elements in the top part of the truss. The algorithm creates a list of suitable options to 'grow' the truss and the most efficient option is used. The algorithm starts from one side of the bridge by picking the first two elements that make up the first triangle (2). Then it chooses elements for the intermediate triangles (3) and at the end picks 3 elements to complete the truss(4). The truss generation is a random process. This means that the algorithm will come with a different truss design each time it is evaluated. When the algorithm is finished, a valid truss option is presented and this can be added to the solution cloud. The user can then choose a design from the solution cloud.

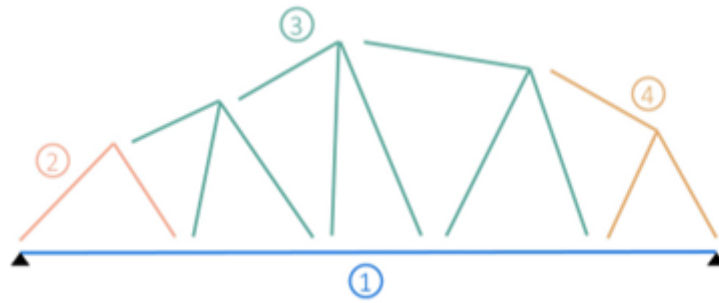


Figure 5.15: bridge truss design evolution using a growth algorithm (van Lookeren Campagne, 2022).

The way the elements for the bottom chord are selected is shown in figure 5.16.

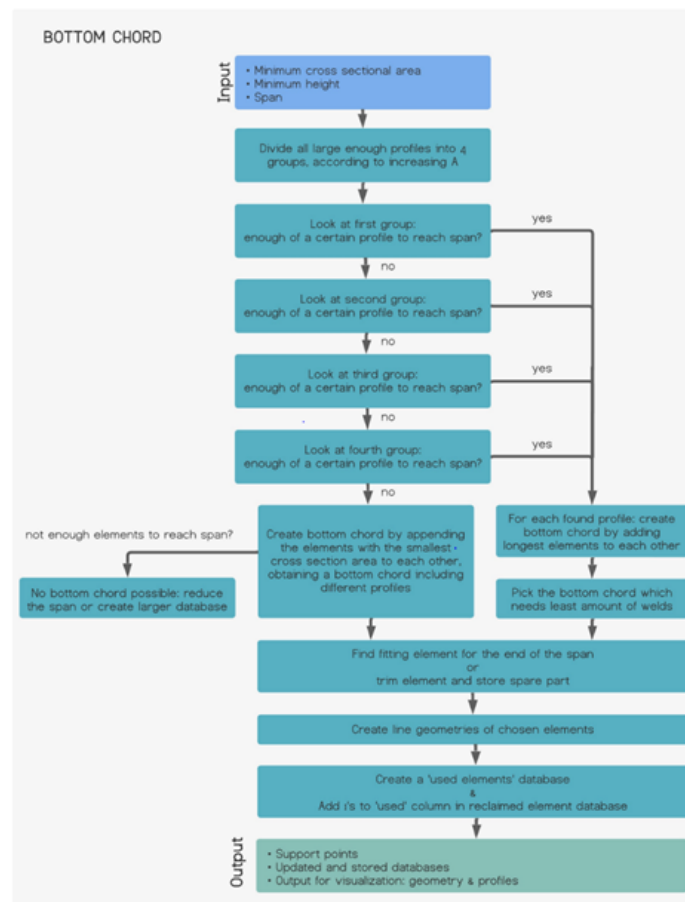


Figure 5.16: flowchart of cross-section selection of the bottom chord (van Lookeren Campagne, 2022).

The algorithm is not suitable for the application within this research as the structural frame of an office building does not have the properties of a truss. The algorithm only considers normal forces in the elements and the resulting geometry has an irregular shape. Constructing a building of multiple layers will become a problem as it is necessary to have horizontal lines in the structure at every floor level to let the floors sit on.

5.5.3. Nodal displacement optimization model

The master thesis from Rademaker (2022), focused on creating a model that fits elements from a reclaimed element database to a building design. By manipulating the building geometry, an optimisation could be performed to come to a geometry that fits the maximum number of reclaimed elements. The

model has the nodal coordinates as a continuous variable. This means that all possible positions are allowed. The cross sectional area is a discrete variable as there is a certain list of reclaimed elements to choose from. The length difference between the original member length in the design and the applied member can be limited to limit the difference in geometry between the original and the generated design alternative that uses reclaimed elements.

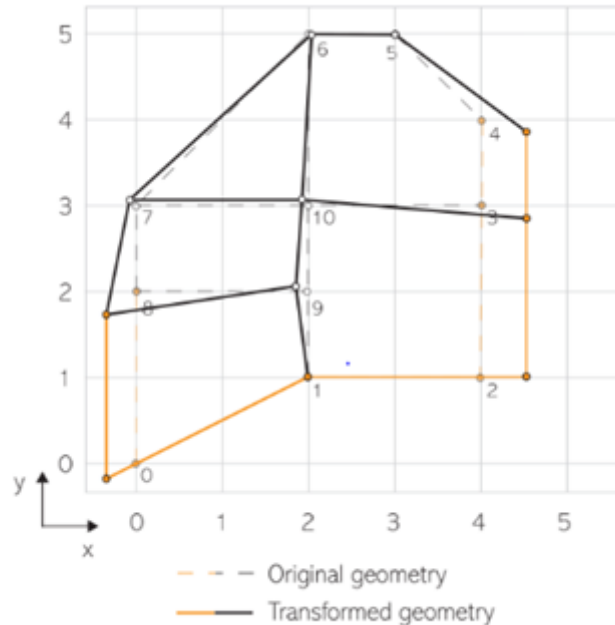


Figure 5.17: Example of a design alternative using the node displacement algorithm (Rademaker, 2022)

It can be concluded that the stock dictates the design. If there is a more diverse stock, or the design is more uniform it gets easier to design with it as there are more possible use cases for the elements. The assignment of reclaimed elements to the columns is done by looking at groups of suitable profiles in the database. All possible combinations are then considered. So if there are 8 available columns of group A and 6 of group B and a total of 10 columns is needed, all compositions of group A and B elements are considered. The algorithm focuses on finding closed loops with elements from the same loop. This can lead to split levels in the generated design. The assignment of the beams includes all suitable options. These options are evaluated by using unity checks to conclude what the most efficient option is. If one element can be used in more than one place it will be placed at the position where it is used more efficiently. This approach shares similarities with the earlier discussed assignment optimisation method.

The algorithm is good at implementing as many reclaimed elements as possible by altering the dimensions of the structure but it is also possible to limit the nodal displacement compared to the original design. By only moving the nodes in the horizontal plane, the story height is preserved throughout the building and the application of split levels is embedded in the algorithm. Adding stories to the building is not included in the algorithm and will probably reduce the freedom of the algorithm as an identical layout between floors is preferred. The irregular geometry that results from the model does have its effects on the design and choice of a floor system. The way that the beam elements are assigned to a spot is interesting as it includes all possible solutions and chooses the most efficient.

5.6. Conclusions

Using reclaimed steel as a construction material poses some challenges and new philosophies in designing compared to traditional steel design. The information in this chapter gives an answer to RQ.3 and RQ.4.

“What are the possible methods of creating a design alternative from an original design using a database of reclaimed steel elements?”

“How does utilisation of reclaimed steel influence joinery and member extension and shortening?”

5.6.1. Acquiring reclaimed elements and the design process

Harvesting of reclaimed elements happens on building level which allows for limited testing to determine the quality of all elements in a building. Deconstruction contractors like New Horizon and B-Next do this and sell reclaimed elements directly from deconstruction or via their online marketplaces. Designing with these elements requires a new design strategy. By changing the design to fit the existing elements, re-fabrication and thus emissions and costs can be minimized. In design, technical and financial feasibility are centered. From these considerations, some elements in a design might not be able to be substituted with a reclaimed element. This creates the necessity of hybrid designs that consist of new and reclaimed steel elements.

5.6.2. Material properties

The yield and tensile strength of steel is critical information for the structural design process. Material tests can be used to determine these material properties of reclaimed steel elements. There are many advisory documents which follow similar principles and categorization. Such a document is drafted in collaboration with stakeholders in the steel and construction sector in the Netherlands. This “NTA” specifies a validation procedure which uses archive information together with limited testing of the reclaimed steel elements. Cases show that recalculation of the existing donor structure can also be used to determine the minimum strength by evaluating the maximum stress that the elements should be able to take. The assumed strength is then validated by performing sample tests.

5.6.3. Connections

Re-fabrication of reclaimed steel can be compromised by toxic paints which makes welding unfavourable. Clever detailing centered around using bolts instead of welds can omit the necessity of welding the reclaimed steel.

Beam-to-Column connections Fin-plate connections are often used to create a pinned connection between beam and column. In case of reclaimed elements, angle cleats could be preferred as no welding will be required during (re-)fabrication. Rigid connections use more plates and bolts and require a lot of welding. A connection detail used in Biopartner seems to limit this. A continuous beam connects to the columns using end-plates. A UNP-profile is added to transfer normal forces between the columns. This configuration reduces the welding and thus costs compared to rigid haunched beam-to-column connections.

Beam-to-Beam connections Splicing elements to create longer members with reclaimed steel can be challenging due to difference in cross-sections between the to-be connected elements. This does not make it possible to connect the top and bottom flanges with plates. A connection that only uses web-plates can make their joinery possible but this type does have a low moment capacity. This results in a pinned connection which can be problematic for deformation criteria. End-plate connections can be used to transfer more bending moment and will deform more monolithic, reducing deformations. The end-plates are often present on used elements but need to be welded if they are not.

Column-to-Foundation and wind-bracing connections These connections are quite standard which makes reuse a bit more straight-forward. Existing endplates can be reused to establish hinged and more moment-resisting connections to foundations and wind braces can be bolted to either the flanges or webs of beams and columns.

5.6.4. Computational design algorithms

The different algorithms that are reviewed in the chapter can be useful in creating new designs of office buildings from a limited stock of elements. The assignment optimization can be used to assign the limited elements to places in the building geometry. The assignment could be based on weight which is directly related to impact and costs. Assignment on these criteria are in-line with the main research question of this thesis work.

6

Economic costs of new and reclaimed steel elements

Economic costs in buildings design is a parameter where a lot of decisions are based on. The tool to be developed in this master thesis project will determine the costs of design alternatives to give a direct comparison between alternatives that do and do not include reclaimed steel. To set up a cost model, the costs of new and reclaimed steel and their differences need to be identified.

6.1. Costs of buildings

Material selection for the design of a structure has a big influence on project costs. Selection is often done in an early stage of the project and is not likely to change during the design and construction process. Estimating the costs of a structural system in a preliminary design stage can be difficult as the information is limited. The following key factors that influence the price of a building structure have been identified (Steel for Life et al., n.d.-a):

- Function, sector and building geometry
- Form, site conditions and complexity
- Location, logistics and access
- Programme, risk and procurement route

The type of building has influence as each type uses the created floor area differently. Adding more complexity to a building, like unconventional sections and connections, adds fabrication and construction time and thus costs. A more detailed estimation can be made when more details of the structures are known. From drawings that indicate frame configuration, element sizes and floortypes, the design can be broken down into four components(Steel for Life et al., n.d.-a):

- Main members like columns, beams and trusses
- Secondary members
- Fittings and connections
- More specific items like stairs, temporary steelwork and (composite) floors

At this stage the quantities in the described categories can be multiplied with key-figures to estimate the costs. These key-figures are established by experience and data from completed projects. In a cost breakdown of a building with a steel load-bearing structure, the structure only accounts for around 15 percent of the costs of a building. The facade, interior and services have a bigger influence on the total building costs (Evers et al., 2003). Bouwen met Staal describes in an online article n.d. that the steel structure itself only comprises 7.5% of the total investment costs. If a steel structure ends up costing 20% extra, the total building costs only rise by 1.5%. It is a lot more effective to save on other cost components in a building project.

6.1.1. Influence of the structural engineer

One of the responsibilities of an structural engineer is to guarantee the safety of the structure and to create a smart design. The design process is steered by regulations and methods to guarantee structural safety. Safety factors on loads and material properties are specified to have enough margin on the capacity of the structural elements. Another factor that has influence on the design of a building structure is costs. To win procurement procedures, costs need to be acceptable and competitive. Cost savings can be established by reducing the material use in a structure. The mission of structural engineer is to design a structure that is both safe and economical.

6.1.2. Factors that influence costs

The table below summarises the most important factors that influence costs in steel structures (Janisch, 2022).

Factor	Influenced by
Material costs	Steel market
Energy costs	Energy market
Labor costs	Wages employees
Indirect costs	Unknowns

Table 6.1: Cost influencing factors for steel structures.

Material costs

Material costs are heavily influenced by demand and supply. Steel prices fluctuate and this has a direct effect on the costs of a structure. Early 2023, the costs of steel is around €1.10 per kg (J.de Charro, personal communication, February 8 2023). The steel price index from 'Brink staalbouw' gives a good indication how unstable the steel prices are. Begin 2023 the index was around 200 compared to 340 half-way 2022 (Brink staalbouw, 2023).

Energy costs

Energy costs are dependent on supply and demand as well. For example, in peak hours of solar and wind production, energy prices drop. Next to the market influencing prices, the war between Ukraine and Russia have shown how conflicts and politics can change energy pricing. Steel construction does not depend heavily on electricity unlike the production of the material. The energy price results in rising manufacturing costs and have a big effect on the cost price of the material.

Labour costs

Labour costs have a big influence on the costs of fabrication and construction. In complex structures more labour is required and fabrication costs can be high. Wages are highly dependent on the country where the activities are carried out. The table below gives examples of the average wage in 2019 for different European countries.

Country	Germany	Slovakia	Poland	Roumania	EU average
€/hour	€41.20	€38.90	€10.50	€6.90	€28.20

Table 6.2: Wages in the steel industry in 2019 across European countries (Janisch, 2022).

The difference in wages is big and has a big influence on the total costs of a steel structure. In the Netherlands, the average wage for a steelworker is around €2500 per month. More experienced specialist employees have higher wages. Welders can earn up to €3800 per month in wage (Werkzoeken.nl, n.d.). Projects where machines play a bigger role in production have lower labour costs. In these project other factors play a bigger role like costs of machinery, energy and transportation.

Indirect costs

Indirect costs are hard to quantify as they are not directly visible. Transportation, import fees, rework and delays add costs to a project. Experience and long-time partnerships with suppliers can make

it easier to estimate these 'hidden' cost components. Often, in a cost estimation, indirect costs are accounted for by including costs for risks. For regular steel a often used percentage is 5% (R.Passchier, personal communication, February 15 2023).

6.2. Cost-models for steel structures

The costs of a traditional steel structure are built up out of material costs, fabrication costs, erection costs and other costs in the percentages shown in the pie chart. The 'other costs' consists of engineering and fire-proofing of the building among other minor expenses (Barg et al., 2018).

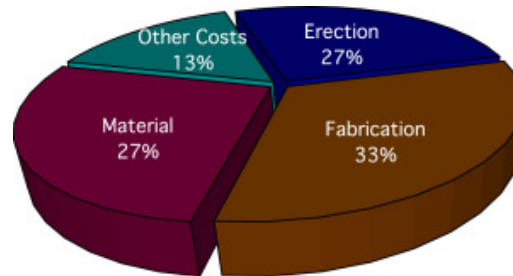


Figure 6.1: Pie Chart of cost components of a steel structure (Barg et al., 2018)

An article from Bouwen met Staal (2013) specifies some costs figures for steel frames in office buildings. These figures include costs for the profiles themselves, fabrication, finishing, construction, and fire proofing. Such figures are often presented in euro's per kilogram of steel structure. This does lead to a misconception. Light steel structures are not always the cheapest. Material price is currently not the most important factor in costs of a steel structure as material costs only cover 27% of the total costs. It is more effective to aim for simple connections and a minimal amount of unique elements. Cross-section selection, the applied steel grade and choice for conservation system are other factors that have a big effect on the costs of a steel structure (Evers et al., 2003). However, in an preliminary design, these details are not always known. There are several methods with different detail levels that are used to estimate costs of a steel structure.

6.2.1. Model 1: Weight method

Early on in a design process, the most used method is using a steel price per kilogram of frame. This method can give an indication of the steel frame costs early on in the design process. In this method, fabrication costs of connections are estimated based on their complexity and a corresponding percentage is added to the total weight of the structure. In this way the weight that is added adds to the total costs as it is multiplied with the costs of the steel. This percentage can range from 10 percent for simple to 50 percent for complex connections (Ajouz, n.d.). This method can be described with the following equation:

$$\text{€} = \text{€}_{kg,steel} * kg_{tot} * (100\% + \%_{connections}) \quad (6.1)$$

This method does imply that it is cost beneficial to create very slender structures. In terms of detailing this estimation method is very global. If there are a lot of complex details or a lot of variations in the design, the cost estimation will not be very accurate. This combination can be misleading and therefore success of this costing method is dependent on the experience of the cost analysts to make a good estimation of the total costs of the connections in the design. This method might not be considering a lot of details of the design but is based on experience. IGG cost-engineer Rob Passchier (personal communication, February 15 2023) argues that adding more detail does not necessarily add more accuracy to the estimation as there are still a lot of unknown factors.

6.2.2. Model 2: Percentage of beams weight based on rational capacity

This costing model uses the rotational capacity of connections to determine additional costs to the steel structure. This approach is mentioned several times in literature. Research from Xu and Grierson (1993) uses the following equation to describe the total costs of a frame including connections:

$$Z(x) = \sum_{i=1}^{nm} W_i A_i + \sum_{j=i}^{nbm} \sum_{j=1}^2 (\beta_{ij} R_{ij} + \beta_{ij}^0) + \sum_{i=1}^{nco} (\beta_i R_i + \beta_i^0) \quad (6.2)$$

nm	total number of members in frame
nbm	total number of beams in frame
nco	total number of columns in frame
W_i	weight coefficient (material density * member length)
A_i	cross-sectional area of member
β_{ij} and β_i	connection rotational stiffness
β_{ij}^o and β_i^o	cost coefficients pinned connections = $\frac{0.225W_i A_i}{S_i}$
R_{ij} and R_i	connection rotational stiffness = $0.125W_i A_i$
S_i	Estimated rotational stiffness [$226kNm/rad < S_i < 565e3kNm/rad$]

Table 6.3: Used symbols in equation 6.2 (Xu & Grierson, 1993).

It can be seen in the table that for pinned connections, 12.5% is added to the members weight. The weight that is added for semi-rigid connection depends on the desired rotational stiffness of the connections. This is in line with research of Simões (1996), which indicates that published data suggests between a 20% and 60% cost increase for a beam with pinned and stiff connections respectively. By including the individual stiffness of connections, more detail is provided in the cost calculations where normally connections are assumed to be either rigid or pinned. In a preliminary design, exact stiffnesses are not always known, which can be a problem for this costing method.

6.2.3. Model 3: Activity based costing

This last method does not only look at material quantities but also at the activities that are involved in fabrication and assembly. This method can be summarised in the following equation (Ajouz, n.d.):

$$\text{€} = \text{€}_{kg,steel} * kg_{tot} + \sum_{activities} Time * Hourlyrate \quad (6.3)$$

This method looks at all processes that lead to the realisation of the civil engineering artefact. A paper on activity based costing by Bel Hadj Ali et al. (2009), categorises these actions in material, fabrication, erection and foundation costs. The material costs are included in the first part of the above equation and the rest in the second part of the equation. Determining the costs for fabrication can be very complex as it depends on a lot of factors as discussed in section 6.1.2. It requires timing of processes and elaborate flowcharts for each type of connection to get a detailed result. An article from Ajouz (n.d.) in *Bouwen met Staal*, mentions that over complicating an activity based costing model makes it difficult to keep in control of the results. He mentions that it should be prevented that every process is included in the analysis. Some might not play a significant role in the total costs of the structure.

6.3. Costs of designing and building with reclaimed steel

The previously described cost-models are not directly applicable when designing with reclaimed elements as the costs for materials and fabrication are not identical. Cost experts IGG, steelbuilders Vic Obdam and Reijerink, steel supplier Deltastaal, participators from project LivingLab, deconstruction contractor Bnext, material experts Nebest and reclaimed steel trader HPStaal were contacted to ask about their view on the costs and processes that are involved with using reclaimed steel elements in a building project.

6.3.1. Cost engineers IGG

The IGG bureau had the role of cost-engineers for the Biopartner 5 project. Rob Passchier gives information (personal communication, February 15 2023) about their cost estimation procedures. They work with a framework that is quite similar to the earlier mentioned activity-based costing-model. In general, they subdivide the costs of a steel structure into three subcategories:

1. Steel material costs
2. Modifications costs
3. Construction costs

In the early stages of design there is a low level of detail. At this moment in the project, the costs are estimated by using a price per kg. approach that includes the three subcategories. A percentage is added on top of this to account for end-plates and connections. This mostly adds up to around 7%. Rob Passchier mentions (personal communication, February 15 2023) that going into more detail is generally not adding to the accuracy of the cost estimation but makes it more complicated. The use of a price per kg. of steel is similar to the first costing method described in the previous section of this report.

The way this price per kilogram is build-up is seen in a cost-breakdown from the Biopartner 5 project for the new steel and donor steel alternative. In this breakdown, material costs for the reclaimed steel are estimated to be €0.45 cents per kilogram. The transport of the reclaimed elements is only half of the transportation costs of the new steel variant. This is probably due to the fact that the reclaimed elements were allocated only 750 meters from the new building site where the elements were modified in a temporary workshop. For construction, both breakdowns show the same price, €0.90 per kilogram of steel.

Passchier also mentions rates for measures to protect steel profiles in a fire scenario. Using paint to protect members costs around €98 per m² and boxing a member in with gypsum is a bit cheaper at €88 per m².

6.3.2. Steelbuilder Vic Obdam

Vic Obdam had the role of steelbuilder in the Biopartner 5 project. The difference between new steel and reclaimed steel originate from the difference in content of three categories mentioned by IGG. For example, deconstruction and quality assurance bring extra costs and this affects the price of (reclaimed) steel. Next to this the fabrication process and transport is different as well.

In the case of Biopartner a lot of double work has been performed. For example, the first design already included engineering of a structure with new-steel. After this was completed, the reclaimed elements were identified and the engineering firm had to redo a lot of work which adds costs to the project. At this point the design was pretty much set so implementation of the reclaimed steel elements did cost a lot of extra time and thus money. Identification of reclaimed elements in an early stage is essential to avoid these extra costs. Table 6.4 shows the different components for new and reclaimed steel identified by Vic Obdam (G.Obdam, personal communication, February 3 2023).

	New Steel	Reclaimed steel
Steel price	raw material Transport raw materials Production TATA	Measuring and labeling Material testing Deconstruction
Fabrication	Transport to steel builder Modification/fabrication Engineering Coating	Transport to steel builder Modification/fabrication Engineering Blasting and coating Transport Storage
Construction	Transport to site Mounting	Transport to site Mounting

Table 6.4: Processes in using new and reclaimed steel in a building project

Obdam thinks that reclaimed steel elements need to be a euro cheaper than their new steel equivalent to make incorporating it in a design financially interesting. With this difference, extra fabrication and material testing costs can be absorbed (J.Mak, personal communication, February 3 2023). In the Biopartner 5 project the steel was sold to the new project at price of steel scrap (Redactie Bouwen met

Staal, 2021b), which was around €0.20 per kilogram at the time (Hollandrecycling, 2023). Mak adds that removal of paint and reapplying it does involve a lot of costs and should be avoided when reusing structural steel. This does mean that it is sometimes not possible to weld to the elements as the paint might contain toxic elements. Obdam and Mak suggest that it is therefore better to use as many bolted connections as possible.

For fabrication of traditional new steel structures, a fabrication cost of €0.70 to €0.75 per kilogram is realistic for the current market. In relatively small projects, like the scope of my thesis, the fabrication work is mostly done manually as automated processes take more time to set-up. For fabrication for reclaimed steel, Obdam argues that the amount of steel and work is not very weight dependent. The amount of material and type of activities is not massively different when fabricating a HEA-240 instead of a HEA-200 section. However, the activities that are performed do take longer or are more difficult in terms of engineering. This makes the fabrication of reclaimed sections expensive (G.Obdam, personal communication, July 6 2023).

6.3.3. Steelbuilder Reijrink

Reijrink is a company near Tilburg that is specialised in the fabrication of steel structures. Their workshop contains automated machines that can saw and weld. In this process, the elements are transported over a multi-directional conveyor-belt system that transports them from machine to machine. They indicate that reclaimed steel elements might not be suitable to be processed in their automated workshop and that they would need to use manual labour to do the modifications to the steel elements. From experience they think that fabrication of reclaimed elements has the following implications on costs compared to new steel (F.Reijrink, personal communication, March 2 2023):

- Transport from deconstruction site +€0.05
- Cleaning of elements in preparation for fabrication +€0.10
- Extra calculations and drawing +€0.05
- Actual fabrication +€0.45
- Element inspection +€0.05
- Sandblasting and painting (if necessary) +€0.20

These extra costs amount to €0.70 per kilogram of reclaimed steel, without sandblasting and reapplying paint. This is thus on top of the costs for new steel fabrication. In terms of the steel price of reclaimed steel, Reijrink thinks that this would be around twice the steel scrap price. With a steel scrap price of €0.20 and a new steel price of €1.10 the extra costs could be covered by the deficit between new and reclaimed steel material prices.

The costs for sandblasting and paint are not included as the elements will have some conservation system applied to them which can be reused. If elements need to be completely stripped, this is quite costly. If toxic conservation systems are present the indicated costs can even be up to 5 times as high as precautionary health measures need to be taken.

6.3.4. Steeltrader Deltastal

The director of steel supplier at Deltastal points to the fact that the price of new steel fluctuates and the margins in the sector are small. Price lists are generally not representative as discounts are given to come to a price that is more competitive on the market. In early 2023, the steel price per kilogram of structural beams is around €1.10 when accounting for these discounts. From a steel trader's perspective, reclaimed steel elements are worth as much as steel scrap as this is the price the deconstruction contractors will get if they sell it as scrap. Only when there is a direct use for the structural element it can be worth a bit more. If there is no direct use and it needs to be stored first it is even more profitable to directly sell it as scrap (J. de Charro, personal communication, February 8 2023).

6.3.5. LivingLab project

It is hard to put a price on the deconstruction of a building to harvest the steel elements. The Living-Lab consortium/project have performed an analysis in the business case of reclaimed steel. They looked at the costs of traditional demolishing and deconstruction for reclaimed elements and calculated the

price per ton by looking at the difference between the two. The cost build-up of the reclaimed steel consists of using different tools for the deconstruction phase, costs of support from IDDS engineering firm, costs of testing and structural engineering by IMd. Multiplication factors are used to determine the amount of units of a certain tool is needed per ton of steel.

Using this information, a break-even point for deconstruction can be calculated. The case analysed by Living Lab, has a break-even point compared to a new steel price of €1800 when 13 tons of steel is harvested from the building. It should be mentioned that buying reclaimed steel at the same price as new steel is financially not attractive as the extra modification costs still have to be accounted for. The cost breakdown mentions the following key figures about circular deconstruction (A. Koot, personal communication, January 29 2023).

Process	Unit and price	key-figure per ton of steel
Boom lift	€200 per day	unknown
Cutter + tools	€75 per hour	1.46 h/ton
Telescopic crane	€200 per day	1.46 h/ton
Transport	€60 per ton	1 unit/ton
Storage	€20 per ton	1 unit/ton

Table 6.5: Key-figures for circular deconstruction Ellermenstreet.

These key-figures are case dependent. If a structure is more difficult to deconstruct, the cost might also be higher but the model does give an insight in key-figures that were applicable in this case. When all these variables are compressed to a single parameter this would mean that a ton of steel could be salvaged for around €454 excluding engineering and testing fees. This comes down to €0.45 per kg, which is more than the scrap price of steel but it is not far off. This figure is important as deconstruction contractors will want their expenses paid to deconstruct and salvage the reclaimed elements.

The analysis also accounts for costs to determine the material properties for groups of similar members. These costs are quite high and amount to a big part of the final price for donor steel costs. On element level, this testing may be too expensive. When a whole building is demolished, a smaller testgroup can give insight in the material properties of all elements in the building.

6.3.6. Circular deconstruction contractor Bnext

Hendricks from Bnext, a circular deconstruction contractor, indicated (personal communication, February 16 2023) that in terms of costs that deconstruction is generally covered by the steel scrap price plus some extra costs for careful deconstruction. In practice this comes down to 1.3 times the steel scrap price. With a steel-scrap-price of around €0.25 this results in a price of €0.33. He also identifies that projects with reclaimed steel aim to cost around the same as their new steel equivalent but that this is not always possible. When building with reclaimed steel is more expensive than new steel, this is mostly due to extra costs for fabrication and material testing.

When Bnext deconstructs a building, they start with listing all reusable elements in the building after which specialist deconstruction teams demount these elements. When registering these elements, important characteristics like dimensions, profile type and thickness are documented. After deconstruction, the elements are stored and/or modified in one of their circular hubs.

6.3.7. IMd Raadgevende Ingenieurs

IMd have been involved in several big projects with reclaimed steel. Examples are Biopartner Leiden and the Upcycle project in Rotterdam. The work that needs to be performed is different compared to a traditional steel building. Extra costs are made because the structural engineering needs to solve the puzzle of where to put reclaimed elements in the building. The use of reclaimed steel needs to be documented and communicated towards all stakeholders extra carefully as their collaboration is of key importance to the success of the project. Guidance of the material properties validation tests also requires extra hours of work. In general these extra elements amount to an increase of 15% of engineering fees. When recalculation of the building is required to determine material properties, like in the case of Biopartner, an extra 10% needs to be added to the fees of the structural engineers (K.C. Terwel, personal communication, April 12 2023).

6.3.8. Material research experts Nebest

Nebest is a company that is specialized in performing material tests. J. Davelaar, employee at Nebest, gives (personal communication, June 12 2023) some quantitative information on testing costs. This indication is based on the guideline from NEN which is described in section 5.3.2.

The procedure of performing material tests starts with grouping the elements into test units. If not enough documentation is present, hardness-tests need to be conducted on site. Furthermore, for each test unit, a sample needs to be taken to conduct the tensile tests if necessary. To do the inventarisation, in-situ tests and sample collection for 20 test units, a full day in the field is needed with two Nebest employees. If additional chemical composition tests need to be performed an extra worker is needed on that day. Davelaar suggests the following costs for this work:

- A two-person day in the field: €2500
- A three-person day in the field: €3200
- Costs of a tensile test: €150

These figures are based on the assumption that the elements will be sorted on the deconstruction site in an orderly manner. If elements are hard to access, the number of days that are needed for the inventarisation, in-situ tests and sample collection can increase.

6.3.9. Reclaimed steel trader HPStaal

HP-Staal buys and sells reclaimed steel elements. Rob Voorbij describes (personal communication, June 22 2023) their way of operations. The reclaimed steel can be purchased from two types of sources, either from deconstruction of buildings outside their organisation or the return of new steel from their own projects in temporary structures. For the first source, no documentation on the material is present. For the second type, certificates and documentation is available. HP-Staal has a big yard where all the elements are stored before they are sold on. The storage is located in the open air. Rob argues that it is unlikely that the market will start to store elements in warehouses. With new steel, the element sizes are uniform and easy to store, this is not the case for reclaimed steel. Sheltered storage of reclaimed steel takes up too much space.

To cover the costs of operations, an additional 35% is added to the purchase price of the steel and an additional €75 per ton is charged for handling and organising the steel elements properly. It is noticeable that the storage costs do not seem to vary over time but are based on yearly revenue or costs. Rob indicates that only if an element is uncommon, they would try to sell it quicker by applying a discount. Research in collaboration with a graduate student at JP van Eesteren shows a difference of €0.25 between donor steel from a building and a steel trader (Molenaar, 2023).

6.4. Circularity and end-of-life impact on costs

To complete the build-up of economical costs of new and reclaimed steel elements, the effect of the end-of-life scenario of these construction materials is considered. In circular building practices, designing for reuse at the end-of-life can bring economic advantages and there are several ways of quantifying these benefits.

6.4.1. PROGRESS - Design for Deconstruction

The economic case for design for deconstruction is interesting and shows potential. Figure 6.2 shows the development of the economic value of a single-storey building or steelwork. It shows that the value goes up during construction and depending on policy of the end of life there is a resulting value of the structure.

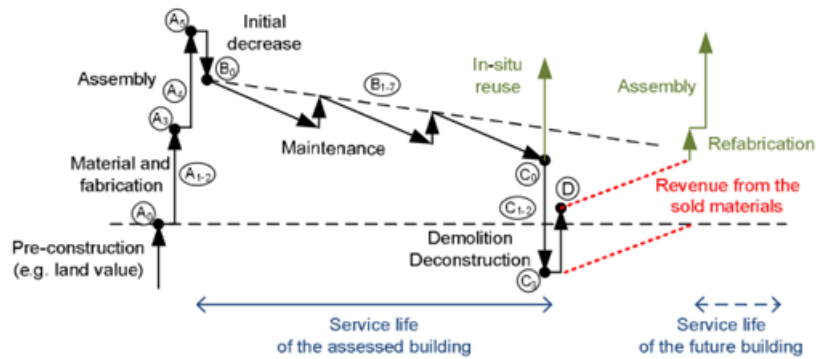


Figure 6.2: economic value of single storey buildings and steelwork (VTT et al., 2020).

The progress report (VTT et al., 2020) proposes a cost model that is used in the analysis of the case studies they mention in the report. A diagram shows the flows at the end-of-life stage. Different types of reuse and recycling processes will result in different residual values of the structure.

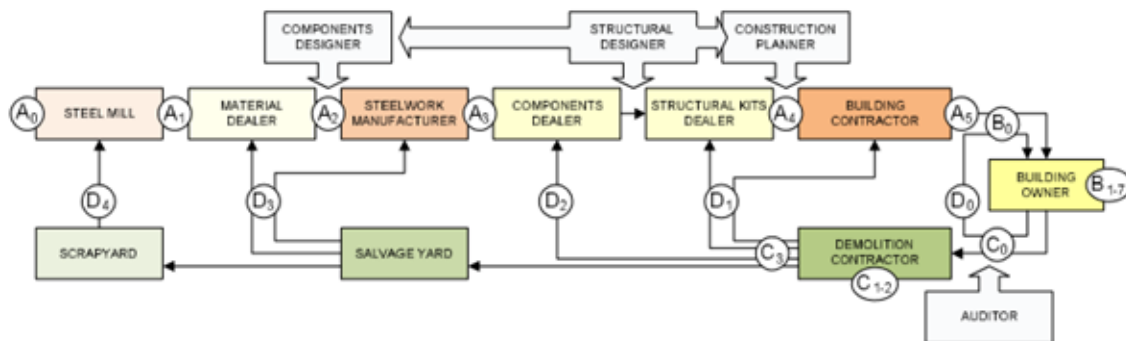


Figure 6.3: End of life processes for residual values (VTT et al., 2020).

The final cost model includes four scenarios at the end of life:

- D4: New steel (44% recycled scrap).
- D3: Reconditioned constituent components.
- D1-2: Relocate and re-assemble steelwork.
- D0: In-situ reuse.

The costs in the production stage (A1-A3) are considered in a simplistic way. The new is steel is assumed to contain 44% recycles scrap which is priced €200 per ton and the raw material costs are estimated at €300 per ton. The price of reused steel is considered to be the same price of new steel minus the costs associated with reconditioning, shot-blasting and testing for material quality/steel grade. D1-2 steelwork is assumed to cost €984 per ton. Demolition and deconstruction costs (C) are estimated to be 50% higher for deconstruction for reuse. The end of life components (D) components are based on the potential income due to recycling and reuse. These are summarized in figure 6.4 .

Recycling (D ₄)	Reuse (D ₃ reconditioning)	Reuse (D ₁₋₂ reerection)	Reuse (D ₀ in-situ reuse)
-200 €/t revenue from the sold steel scrap	- 374 €/t 100 €/t additional cost of deconstruction 30 €/t additional cost for design for deconstruction 20 €/t profit - 524 €/t revenue from the sold recovered material	- 834 €/t 100 €/t additional cost of deconstruction 30 €/t additional cost for design for deconstruction 20 €/t profit - 984 €/t revenue from the sold recovered structure	- 1742 €/t 30 €/t redesign for reuse 5 €/t profit -276 €/t savings from demolition (including profit, transport) - 1501 €/t revenue from the sold structure before refurbishment

Figure 6.4: End of life income for recycling and reuse practices (VTT et al., 2020).

It can be concluded that, with these numbers, all included types of reuse strategies show a potential in generating more income at the end-of-life stage. A breakdown of the full life cycle costs is shown in figure 6.5. In this breakdown, they analyse the effect of two different material sources and two different end of life scenarios.

Material source	New steel		Reused steel	
	Recycling ¹ (D ₄)	Reuse (D ₁₋₂ re-erection)	Recycling (D ₄)	Reuse (D ₁₋₂ re-erection)
Production (A ₁₋₃)	108 191 €	108 397 €	102 670 €	103 876 €
Construction (A ₄₋₅)	22 378 €			
Use ² (B ₆)	205 000 €			
Demolition (C ₁₋₂)	12 569 €	17 144 €	12 569 €	17 144 €
Total costs (A-C)	348 138 €	352 919 €	343 617 €	348 398 €
Pot. savings (D)	-2 740 €	-11 549 €	-2 740 €	-11 549 €
Residual value	-9 829 €	-3 664 €	-9 829 €	-3 664 €

¹ Not designed for reuse

² 27 years service life

Figure 6.5: LCC including different end-of-life strategies (VTT et al., 2020).

By using the model on a case study, it is concluded that the residual value of steel structures is better when the DfD strategy is implemented. The production costs when using reclaimed steel as material source is lower than when new steel is used in this case study. The total costs of modules A to C are higher when using the D1-D2 end of life scenario. The difference in this research can be explained by the difference in demolition costs. The potential saving from reuse is relatively high compared to the recycling scenario which makes the business case for the reuse scenario better in buildings with reclaimed and new steel as their material source. The real economic potential seems to be in the potential savings that can be made in module D in terms of income that follows from the implemented end-of-life scenario. These profits come after a long time when the service life of a building is over. This makes it an unattractive investment as there is a clear imbalance in costs and profits from an investor's perspective (VTT et al., 2020).

When making a comparison with interviews summarised in section 6.3 and the results in figure 6.5 some similarities can be found. First of all, construction costs are in both cases similar for new and reclaimed steel. Also for production costs, the differences between new and reclaimed steel are small. Similar results are concluded in analyses by Vic Obdam and Reijrink despite indicating that fabrication is more complex for reclaimed steel.

6.4.2. Building Circularity Index - BCI

Alba Concepts and the Technische Universiteit Eindhoven have developed a method to assess the circularity of structures in an early design stage (bcigebouw, n.d.). The BCI gives an indication of

material use and demountability in a single number and also integrates the environmental performance of building structures from the 'Nationale MilieuDatabase'.

In the BCI-analysis, the circularity of each building component is quantified. This is achieved by including the origin of materials, the end-of-life scenario and the technical service life of the materials. The origin, end-of-life scenario and utility factor amount to the Material Circularity Index. The formula to calculate the MCI for a single product is denoted in an explanatory white-paper (bcigebouw, 2022) as:

$$MCI = \max(0, (1 - \frac{n_p + s_p + v_p}{2} * \frac{0.9}{\frac{l_t}{l_w}})) \quad (6.4)$$

Where the n_p is the percentage new material as origin, s_p the percentage of materials that will be land-filled and v_p the percentage that will be incinerated at the end-of-life. l_t and l_w are the technical and actual service life of the material. Secondly, the demountability index, LI, is calculated by looking at the connection properties of the product. Bolted connections increase the possibility of reuse at the end-of-life. The product circularity index is determined by taking the square root of the product of the MCI and LI. The analysis also includes monetised environmental impact in the Element Circularity index. All these indexes range from 0 to 1, linear to fully circular. The building circularity index is the summation of the indexes per element of the building. The BCI is also normalised to range from 0 to 1. The complete documentation on calculating the BCI is found in the white-paper on the building circularity index (bcigebouw, 2022)

6.5. Conclusions

Contacting different parties that are involved in the process of designing with reclaimed steel has resulted in quantitative information about costs. Using this information, an answer to RQ.5 can be concluded upon.

"What are the quantitative economic costs of reclaimed steel or new steel elements in an office building design?"

The steel structure of a building structure amount to around 15 percent of the total costs of a building and the steel structure comprises an even smaller portion. The effects of small increases in costs of the steel structure do not have a big effect on the total building costs. The costs of a steel frame are influenced by multiple factors that change through time. Material costs and energy costs have a big influence on the steel prices and labour wages is the most important factor concerning fabrication and assembly costs. Transportation, delays, rework and delays are scaled under indirect costs. This component is hard to determine, but long-term partnerships with suppliers can make this component easier to predict. In general all these costs are time dependent. It is important to have up-to-date figures to make an accurate cost estimation of a steel structure. There are several models to make a cost estimation of a steel structure. The weight method and percentage based on rotational capacity model, estimates costs based on the steel weight and complexity of joints on structure or element level. An alternative to using weight is using activity based costing which involves a lot of detail of the processes involved to create the steel structure. In making a costing model, it is important to include important aspects that determine costs but not over-complicate the model as it makes it harder to be used. The elements that seem to be important factors in the final costs are the price of steel itself, modification costs, construction costs, engineering fees and risk.

6.5.1. Cost-price of steel and reclaimed steel

The price of new steel is dependent on the market. The market fluctuates over time and up-to-date pricing is required to get an accurate cost estimation at that time. Contacting a steel supplier is the best way of determining the steel price at any moment. The price of reclaimed steel is dependent on the price of salvaging and validation of material properties. The deconstruction contractor wants to make a profit on its demolition contract. To do this, the scrap price and additional costs of careful deconstruction need to be paid by the party that wants to use the reclaimed steel. The interviewed companies all give figures which are concluded in figure 6.6.

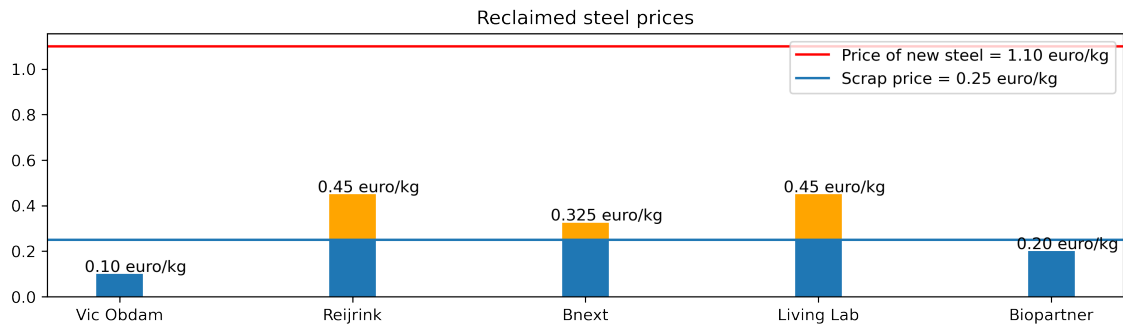


Figure 6.6: Reclaimed steel prices identified through interviews with stakeholders.

Vic Obdam argues that a delta of €1 is needed to make reclaimed steel attractable. The other companies provide estimates of what it would cost to harvest the elements. The logic of scrap price plus a percentage is clearly visible. In the Biopartner case, the steel was donated at steel scrap price. This will not be the case in every project making the indications of Reijrink, Bnext and Living Lab more likely. The costs of testing to validate material properties is dependent on the tests required and scale of the deconstruction project.

6.5.2. Material properties validation

Assuming a well organised deconstruction process, material research costs can be determined by looking at the amount of groups with a similar cross-section. Each test unit needs to be tested with one tensile test. A material research expert company like Nebest can set up test for 20 groups per day. One day of work costs around €2500 to €3200 depending on the desire for CEV-value tests. Each tensile test costs an additional €150.

6.5.3. Storage costs

Traders that buy reclaimed steel stock and sell it on do add extra costs for a client. Their expenses need to be covered and by relocating the steel, an extra stage of handling the elements is necessary. HP-Staal needs and extra 35% on top of the price they buy there steel for to have a sustainable business-model as well as €0.075/kg for the handling. The elements are stored outside as it would not be financially and technically feasible to store the elements indoors. The material properties are often determined by looking at the year of production and in uncertain situations, oversized cross-sections are provided to the customer.

6.5.4. Fabrication

Costs for (re)fabrication depends on the amount of modifications needed. For new steel, automated processes can reduce labour costs but for reclaimed steel, manual labor is required. Workers need to work around existing plates and local cleaning to modify used sections add to the costs. The difference in costs between automated processes and manual labor can be a factor 2 according to Reijrink. This amounts to €0.90 per kg for refabrication and an additional €0.25 for transportation, inspection, cleaning and extra CAD work. Vic Obdam indicates that €1 is needed to modify the sections for its new application. These two figures are relatively similar.

Next to fabrication, conservation systems also have a big impact on costs, especially when old coatings need to be removed. New steel for dry application can be coated for €0.25. In case of reclaimed steel, the already existing systems should be reused.

6.5.5. Construction

The differences between assembling a building with reclaimed steel and new steel are small. Some elements might be heavier due to the fact that the desired cross-sections are not available. IGG uses key-figures of €0.90 per kg of new steel. The assembly costs for a reclaimed steel equivalent are similar.

6.5.6. Engineering fees

In engineering, extra work has to be done to design a building with reclaimed elements. Finding the best place for the elements, communicating these plans with all stakeholders and guidance in the material properties validation procedure add extra costs to the standard engineering costs. Depending on whether the old building needs to be recalculated in the validation process, the extra engineering costs can range from 15% - 25% extra compared to engineering a traditional steel structure.

6.5.7. Risk

A project with reclaimed steel elements needs to be flexible as many things are unknown. Quality of elements, timing and connectivity with new steel can cause unforeseen problems and thus costs. Cost-estimations are based on assumptions made in the model which might not be completely true or accurate. Introducing a risk component in the cost-estimation can quantify this uncertainty. IGG normally uses a 5% risk factor for new steel projects and deems it realistic to use a 15% risk factor for using reclaimed steel.

6.5.8. End-of-life costs and benefits

At the end-of-life of a structure demolition or deconstruction will occur. Components and elements can also be reused. There are several ways of quantifying potential end-of-life profits and costs but the future is hard to predict. It is unknown who will bear the costs and who will reap the benefits from the end-of-life scenario and how much this will be. It will therefore not further be included in this study.

7

Environmental impact of new and reclaimed steel elements

To be able to reduce the environmental impact, it should be measured. European regulations provide a framework to evaluate the effects of a building on the environment. Impact does not only consist of CO_2 -emissions but also includes other negative and positive effects on the environment.

7.1. Environmental impact regulations

As indicated in the introduction, sustainability and circularity is getting more attention in national and international politics. On global level, a recent COP27 meeting has intensified global collaboration in the climate crisis. A damage and loss fund to help countries affected by the climate crisis was agreed upon. In Europe, the Paris Agreement states commitment to keeping global warming below the 1.5 °C limit. This has led to local developments in regulations and the Dutch building sector. Tenders reward sustainability more often and regulations on emissions are increased.

7.1.1. European Union - Paris Agreement

In the Paris agreement, global warming is considered a global challenge. Reducing emissions in the building sector, responsible for 38% of global CO_2 emissions, is an important factor to delivering the Paris agreements. The Dutch Green Building Council has published a proposition paper. In this paper a budget approach to embodied carbon is specified. If the goal is to stay below the 1.5 °C global warming target, the Netherlands has a budget of 909 Mtons of CO_2 for building construction until 2050. Noting that material bound emissions of the building sector in 2018 amount to 188 Mtons, this would mean that the budget will be depleted by 2030 (Dutch Green Building Council, 2021). This analysis results in the following budget per building type (Spitsbaard & van Leeuwen, 2021b).

Paris Proof grenswaarden	materiaalgebonden kg CO_2 -eq. per m^2			
	2021	2030	2040	2050
Woning (eengezinswoning)	200	126	75	45
Woning (meergezinswoning)	220	139	83	50
Kantoor	250	158	94	56
Retail vastgoed	260	164	98	59
Industrie ⁵	240	151	91	54

Figure 7.1: Budgets per building project type to keep to the Paris Agreement.

A recent letter from the ministry of the build environment in Dutch politics has featured this way of quantifying the impact of new buildings to reduce emissions on the short term. The proposition of the Dutch Green Building council has been copied and the ambition to stick to the defined budgets has been formulated and presented to the government (de Jonge, 2022).

7.1.2. Dutch Regulations - MPG

Current Dutch regulations focus on the complete life-cycle of a new building. This includes demolition and also burdens and benefits of the materials after deconstruction. In 2018, the maximum MPG-score was set to 1.0 €/m² per year for offices bigger than 100 m². The ambition is to lower this number over the years to reduce the impact by 50% by 2030. The MPG-score requirements for housing have been lowered to 0.8 €/m² per year in 2021, while office buildings requirements remained at the original value. When determining the MPG score, the life-cycle analysis needs to be performed using a national database with figures for construction materials and processes (Rijksoverheid, 2021).

The MPG value is hard to relate to the embodied carbon figures mentioned in figure 7.1. The indicators are calculated with a different scope. In the case of Biopartner 5, a carbon footprint of 248 kg CO₂ per m² translated to a MPG of €0.539 /m² per year. It can be concluded that it is a lot harder to stay within the boundaries of the Paris agreement as displayed in figure 7.1 than it is to get the required MPG score of €0.8 or even €1.0 /m² per year. In this way the Paris agreement is a bit stricter on the global warming targets than the current MPG regulations.

7.2. Life-cycle assessment

NEN developed regulatory documents (Normcommissie 351281, 2011) (Normcommissie 351281, 2019) that provide a systematic approach for assessing environmental impact. This method involves conducting a life-cycle assessment to quantify both negative and positive effects of the functional unit under evaluation. The life-cycle analysis is categorised into models A to D. Figure 7.2 provides an overview of the various modules and their stages that should be included in the life-cycle analysis.

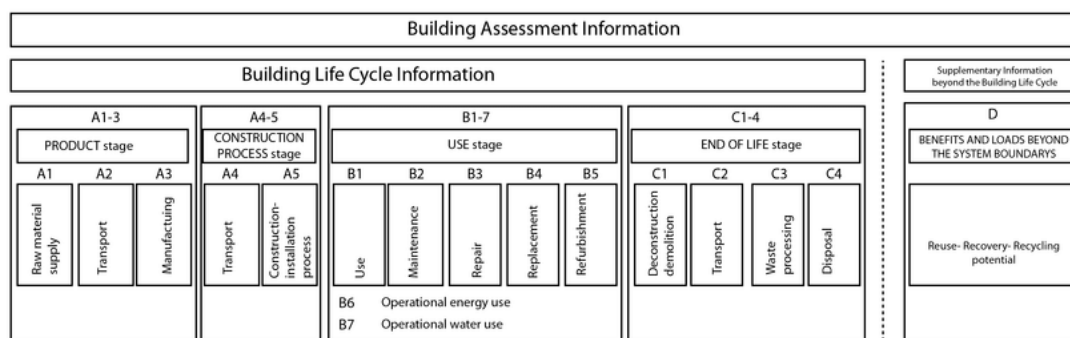


Figure 7.2: Modules in the life-cycle assessment method of NEN (Normcommissie 351281, 2019).

Module A represents the production and construction stage, the modules stages include raw material sourcing, transportation, production, and construction. In the case of steel, the production stage accounts for a significant portion of the total life-cycle emissions (Kraaijenbrink et al., 2022a). Module B includes the impact that is caused during the use-phase. In the context of steel, this module is regarded to be negligible as steel elements have low maintenance requirements. Module C refers to the end-of-life stage. It includes processes like deconstruction, waste processing, and land-filling, all of which contribute to the environmental impact in a different amount. The last module, D, is indicated separately in figure 7.2. This last module quantifies positive and negative effects on the environment. An example of this could be the increase in biodiversity in a city or village because a building has a green roof.

7.2.1. Functional Unit

There are certain rules to performing a life-cycle assessment. Before quantifying the impact in the different life-cycle modules, a functional unit should be defined that clearly states the performance, service life and system boundaries that the LCA is based on (Normcommissie 351281, 2019). A good functional unit makes it easier to compare the results of the LCA for a product with other alternatives. It is, for example, not fair to directly compare two product that did not consider the same modules in their LCA.

In case of reusing elements, it is important to include the end-of-life stage as this is where reuse can be accounted for. The emissions that are prevented compared to traditional land-filling and recycling give an edge to materials that are intended to be reused at the end-of-life.

7.2.2. Module D inclusion

Module D includes benefits and loads beyond the systems boundary. Benefits include reuse and re-cycle potentials that reduce the environmental impact of the structure. It should be noted that these benefits are based on possible scenario's. A current regulation from NEN (Normcommissie 351281, 2011) does allow inclusion of module D into aggregation of the environmental impact. There is an ongoing discussion whether the benefits of module D should be included in the environmental impact of a product or not.

A report from Wastiels et al. (2013) identifies several difficulties to calculating the impact or benefits of module D. Firstly, system boundaries can change over time. Whether there is a market for recycled or reclaimed elements is dependent on demand. Secondly, it is hard to determine to what extent emissions are prevented. Will steel be used to construct new buildings or is it recycled and is turned into soda cans? It is hard to predict via what route materials will be recycled in the future. At last, the processes have influences on the module D benefits. One unit of used material might not result into one unit of new material and the impact might reduce with newly developed processes in the future. It can be concluded that it is hard to quantify impact of a life-cycle of which the scenario is not necessarily known yet. In the Netherlands, it is allowed to include module D in LCA to calculate the MPG score for buildings. A recent report from TNO (Fraanje et al., 2021) recommends to clearly specify the module D impact to the MPG score. EN-15804 already specifies that module D should be reported separately. It is also stated that frequent reviews of the end-of-life stages should be performed to make them suit reality better.

7.3. Environmental impact indicators

There are different ways to quantify environmental impact. This thesis will consider relevant indicators for the Netherlands. Dutch policy and the Nationale Milieu Database specify a single monetized impact indicator, the environmental cost indicator. This "ECI-value" takes all life cycle modules into account. The letter from Dutch minister Hugo de Jonge insists to also use a indicator that provides more short term information on emissions to keep within the limits of the Paris Agreement. Both indicators are discussed in this section.

7.3.1. Environmental cost indicator

Databases like the Nationale Milieu Database contain Environmental Product Declarations (EPD's) that give information about the emissions in all life-cycle stages of that product. The emission that are included can range per life cycle analysis and should be defined in the system boundaries of the LCA. The following impact categories must be taken into account in the Netherlands according to the Dutch 'bouwbesluit 2012':

	Impact category	Abbreviation	Unit	Monetization value
1	Global warming potential	GWP-total	kg CO2 eq.	€ 0,16
2	Abiotic depletion potential for non-fossil resources	ADP-nonfuel	kg Sb eq.	€ 0,16
3	Abiotic depletion potential for fossil fuel resources	ADP-fuel	kg Sb eq.	€ 0,05
4	Ozone layer depletion potential	ODP	kg CFC 11 eq.	€ 30
5	Photochemical ozone formation	POCP	C2H4 eq.	€ 2
6	Acidification	AP	kg SO2	€ 4
7	Eutrophication	EP	kg PO4 3-	€ 9
8	Human toxicity	HTP	1,4-DCB eq.	€ 0,09
9	Fresh water aquatic ecotoxicity	FAETP	1,4-DCB eq.	€ 0,03
10	Marine aquatic ecotoxicity	MAETP	1,4-DCB eq.	€ 0,0001
11	terrestrial ecotoxicity	TAETP	1,4-DCB eq.	€ 0,06

Figure 7.3: mandatory environmental impact categories and their monetization values (nationale milieudatabase, 2022).

NMD is developing a new set of 19 impact categories. Their monetization values are not concluded on yet but by including the quantities in EPD's already they can be implemented as the regulations are updated in the future. For soil, infrastructure and water related projects (GWW sector) the ECI value is an important indicator of the environmental impact. For public buildings, offices and housing (B&U sector), the ECI value has to be converted to the MPG indicator. This indicator reduces the ECI value to a functional unit of cost per m² per year (nationale milieudatabase, 2022). The goal is to bring the maximum MPG-value for new residential buildings and offices larger than 100 m² down to €0.5 / m² / year (de Jonge, 2022).

There is criticism on which elements should be considered in the life cycle assessment. Around 15 to 20 years ago, the inclusion of module D in the life cycle assessment procedure seemed like a good idea to stimulate recycling and reuse. The ambition is to have a circular building sector in 2050 to try and keep global warming to a minimum. A valid point is whether we should long term gains influence decision making if emissions need to be reduced right now. The benefits and burdens in module D only manifest in the end-of-life scenario. Predicting the precise end-of-life scenario for a building is challenging, and even if it were known, its future impact remains uncertain. It is unlikely that the processes emit the same emissions as new technology and processes are developed.

Recycling and reuse should be guiding principles in the transition to a circular building sector, and perhaps they do not necessarily need to be incentivized or rewarded (van Leeuwen, 2022).

7.3.2. Embodied Carbon

Embodied carbon includes all carbon emissions that are associated with materials and the construction process throughout the whole life cycle of a structure. This means it includes modules A to C and module D should be addressed separately. Upfront carbon only includes the production, A1-A3, and construction stages, A4 and A5 in the calculation (Adams et al., 2019). Figure 7.4 shows the terminology the world green building council adopts and this terminology will be used in this thesis as well.

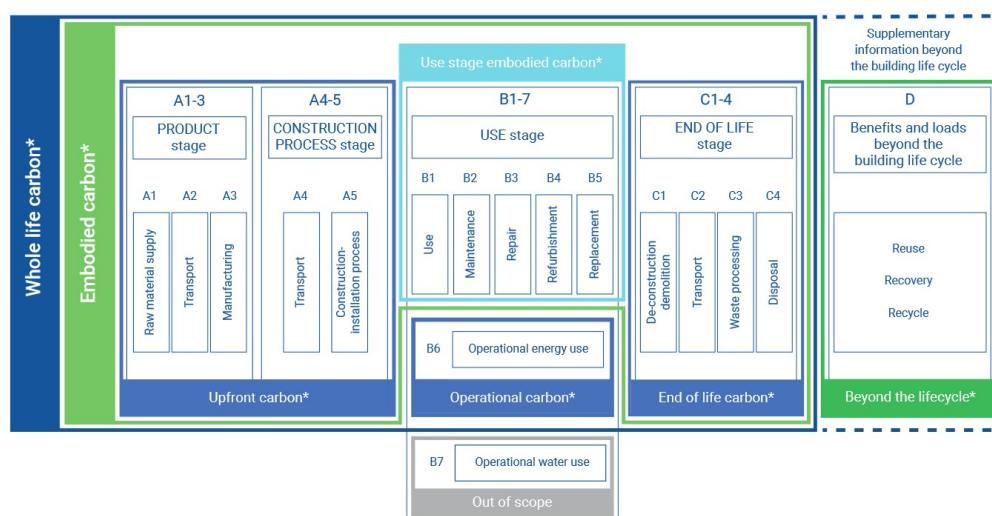


Figure 7.4: Embodied carbon definition and life-cycle boundaries used in this report (Adams et al., 2019)

As mentioned earlier, report from the Dutch Green building Council states that if the goal is to keep global warming to a maximum of 1.5 degrees, the Netherlands has a construction budget of 100 Megatons of CO₂ until 2050. ECI and MPG calculations are not suitable to assess how much of the budget a building takes up as future benefits are also included in the calculations. There is need to reduce carbon now so it is possible to keep within the 1.5 degrees of global warming. DGBC suggests to use an upfront carbon approach to incentivise to reduce carbon emissions (Spitsbaard & van Leeuwen, 2021a). They describe carbon emission limits per m² for different types of buildings to assure that emissions are kept within the budget mentioned earlier. These budgets reduce over the

years. A calculation protocol released by the same organisation states that the embodied carbon should be calculated by summing the GWP 100 year value from all module A life cycle stages. To ensure the quality of these calculations, EPD's from the NMD should be used (Spitsbaard & van Leeuwen, 2021b).

7.3.3. Energy consumption

Another way of expressing environmental impact is energy consumption. The big advantage of this indicator is that it is easier to interpreted than the ECI monitized value or the kg CO_2 equivalent for embodied carbon. Also this value can be directly taken from the EPD's in the 'Nationale Milieu Database'.

7.4. The environmental impact of new steel

In the latest EPD (Kraaijenbrink et al., 2022a) for heavy construction steel, it is assumed that 16% of the materials will be reused in the end-of-life scenario. This conclusion is drafted in collaboration with the dutch steel and construction sector. Of the remaining materials, 99 percent is recycled and 1 percent is sent to landfills. Table 7.1 gives and summary of the environmental impact from values in this EPD for de impact indicators from section 7.3.

Indicator	A1-A3	A4-A5	C1-C4	D	Total
ECI [euro]	0.12	0.01	0.02	-0.02	0.12
Embodied carbon [kg CO_2 -eq]	1.12	0.068	0.081	-0.22	1.05
Non-renewable energy consumption [kWh]	4.36	0.28	0.33	-0.76	4.21

Table 7.1: Environmental Product Declaration for one kilogram of new construction steel (Kraaijenbrink et al., 2022a)

7.4.1. Functional unit

This EPD makes some assumptions for the calculation of its impact. To start, the functional unit contains one kilogram of heavy structural steel. The steel is produced in the Netherlands and applied in the Netherlands. At the end-of-life, a scenario with 16% reuse is assumed. All life-stages have been included in the calculation.

7.4.2. Modules A-C

In the production stages A1-A3, product declarations from the NMD are used for production and applied conservation systems. For transport stage A4, a distance of 150km to the construction site is accounted for. 0.66 hours of crane-use is allocated during the assembly of one ton of steel in life-cycle stage A5. The crane uses electricity for 50% of the time. An electric crane produces an ECI of €4.50 and a diesel fueled crane €11.50 per hour. During construction, a 3% installation hardware loss is taken into account. It is assumed that steel sections are not damaged during construction.

It is assumed that during module B, the use-stage, no emissions result from the use of the structural components. There is no need for maintenance or repairs throughout the life-cycle. At the end-of-life stage, it is assumed that deconstruction results in the same emissions as construction, 0.66 hours of crane usage per ton. After deconstruction, in module D, the following distribution of end-of-life applications is assumed: 16% will be reused, 83% will be recycled, and 1% will be land-filled. For both reuse and recycling the processes for recycling are used to quantify the impact. The EPD for this process includes sorting and compressing the steel scrap. For reuse, compressing will not be necessary. The use of this EPD is therefor considered conservative.

7.4.3. Module D

The EPD assumes that the 16% that will be reused will prevent future production emissions for the next building they end up in. The new element, will not receive a new conservation system which also reduces impact in the future. During fabrication of the new steel element, less energy and material is needed as a part of the existing connections can be reused. The 83% that gets recycles, prevents raw resource use. These prevented impacts are credited to the beyond life impacts in the new steel EPD.

7.5. The environmental impact of reclaimed steel

The EPD for reclaimed steel also used 16 percent of steel reuse at the end-of-life stage just like the new steel EPD. It does also account for 10 percent new steel for the material that is added during fabrication. Just like the last EPD, 16 percent of the steel get reused and the rest gets recycled and landfilled at the end-of-life (Kraaijenbrink et al., 2022b). Table 7.2 below shows the environmental impact per life-cycle stage. The reclaimed steel in this EPD is 'free of burden'. Meaning that the environmental impact of the production stage A1 is zero. Compared to new steel, half of the reclaimed steel won't have to be modified to fit the new structure which also saves emissions.

Indicator	A1-A3	A4-A5	C1-C4	D	Total
ECI	0.02	0.01	0.02	0.00	0.04
Embodied carbon [kg CO ₂ -eq]	0.198	0.068	0.081	-0.017	0.33
Non-renewable energy consumption [kWh]	0.76	0.28	0.33	-0.07	1.34

Table 7.2: Environmental Product Declaration for a kilogram of reclaimed construction steel (Kraaijenbrink et al., 2022b)

7.5.1. Functional unit

The functional unit is one kilogram of heavy structural steel from reuse. Produced in the Netherlands and used in the Netherlands. At the end-of-life 16% of the steel will be reused. A maximum of 10% new steel is added during fabrication. All life-cycles modules are included in the analysis.

7.5.2. Module A - 'burden free' steel

For the production stage, it is assumed that reclaimed steel element consist for 90% out of reclaimed steel as 10% new steel is required for (re-fabrication). This is under the assumption that 50% of the existing connections are reused. This saves 50% of the fabrication work compared to a new steel elements and thus a reduction in emissions for stage A3. The 90% reclaimed steel is brought into the life-cycle 'burden' free. This means that stage A1 has an emissions reduction of 90% compared to the new steel EPD. For the transportation and assembly to the building site, the same assumptions and impact are used as the EPD described in section 7.4.

Module A alternative - discount method A different approach to attributing the impact of stage A1 is to spread the environmental impact of the steel production over the complete life of the steel element. This life spans multiple buildings if the elements is reused. If a product was used for 30 years in its previous life and will be used for another 50 years in the future, the bigger part of the emissions for production would be allocated to the new life cycle. In this case a discount of the new steel production impact of 37.5% would be used instead of the 90% mentioned in the EPD. The difference in impact between new and reclaimed steel would be far less significant. Combining this with the fact that donor steel designs are often heavier than new steel designs, reclaimed steel seems to be less interesting in terms of environmental impact. This method would imply better environmental impact if the service life of a building is shorter.

7.5.3. Module B-D

Just like for new steel, the steel does not require maintenance during the use-phase. The impact in module B is therefore negligible. The benefits in module C and D are quantified in the same way as for new steel assuming 16% reuse, 83% recycling and 1% land-filling. The benefits in module D are, however, lower than for new steel. The difference can be found in the avoided impact in A1-A3. The impact on these categories is lower for reclaimed steel than new steel. The prevented emissions are related to the emissions during stages A1-A3 of the same EPD, which are lower than for new steel.

7.5.4. Cut-off waste

The reclaimed elements that are used in a building are not likely to all be the exact length that is needed. Some cut-off waste will be generated when the reclaimed elements are sawed to fit the building design. This material does not go through the same life-cycle modules as regular or reclaimed steel that is going into the building. In the production module, A, no impact is generated. No material is added and no fabrication is needed. The transportation to the fabrication process is already accounted for in the

previous life-cycle of the reclaimed element and transport to the building site is not needed as the cut off section will not be used in the building. Module C will however happen immediately as the material will reach its end-of-life during the production process. As the material can not be reused, total recycling of the cut off section can be assumed.

7.6. Influence of transportation

In the product declarations of new and reclaimed steel, the environmental impact of transportation in stages A4 and C2 are neglected. Most EPD's suggest transport distances of 150 kilometers for the Netherlands. When assuming that the transport will happen with trucks with a capacity of 60 tons, an ECI value of €0.02 per ton per kilometer needs to be accounted for. When converting this to the functional unit in the EPD's from the NMD using these values, the ECI of the products should be enlarged by €0.003 per transport stage. This is an addition of 5% over new steel, 15% over reclaimed steel and 86% over cut-off waste. This is significant and can not be neglected.

7.7. Conclusions

A literature review in life cycle analysis and the Biopartner case study provides information about the quantification of the environmental impact of new and reclaimed steel. This information can be used to provided an answer to RQ.6.

"How should the environmental impact of reclaimed steel and regular steel be quantified?"

There are several indicators to indicate the environmental impact of a product. These indicators are all different ways of aggregating the impact in different categories. The life-cycle assessment itself is regulated but allows for varying interpretations regarding analysis scope, assumptions, and end-of-life scenarios. The ECI-value includes all emissions in a products life-cycle and beyond. This indicator is used in Dutch regulations and thus a good option to express the impact of new and reclaimed steel. A more tangible indicator is the upfront carbon that is emitted in production and construction of a steel structure. By not including end-of-life benefits, this indicator aims to reduce impact now. All indicators should use data approved by the national database of environmental product declarations.

7.7.1. Assessing the environmental impact of a reclaimed steel building design

To give a quantitative answer to RQ.6, the composition of a reclaimed steel structure needs to be assessed. A steel structure can consist either completely of new steel or can be a new and reclaimed steel hybrid. New steel profiles are needed if the reclaimed elements don't suffice. To calculate the environmental impact of any of these two steel structures, three impact declarations are needed: new steel, reclaimed steel and cut-off waste. The new and reclaimed steel in the design have a different impact, as the production stage is omitted when using reclaimed steel. As the reclaimed elements can be oversized, cutting them will produce unusable rest pieces which need to be disposed off and thus accounted for in environmental impact assessment. The life-cycle modules that are accounted for in each declaration are summarised in figure 7.5.

Accounted life-cycle modules	A1-3			A4-5		B1-7					C1-4				D
	PRODUCT stage			CONSTRUCTION PROCESS stage		USE stage					END OF LIFE stage				BENEFITS AND LOADS BEYOND THE SYSTEM BOUNDARYS
	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	Reuse-Recovery-Recycling potential
New steel	x	x	x	x	x			x			x	x	x	x	x
Reclaimed steel				x	x			x			x	x	x	x	x
Cut-off waste												x	x	x	x

Figure 7.5: Included life cycle stages per material profile

For new steel, the data from the EPD in the national database is used. This data is accepted branch wide and in environmental impact assessment regulations. For reclaimed steel, a 'free of burden'

philosophy to the production stage is adopted. This assumption can be substantiated by the fact that the emissions for production are made in the past and not during the production stage. It is not fair to spread out the impact of the production process over multiple life-cycles. This would mean that the shortest life cycle gets the least material bound impact credited to its life-cycle. This is in contradiction with the claim that extending the service life of a building is a good way to reduce environmental impact. Also, by allocating more ECI to the production of reclaimed steel, the design with the material is not rewarded as much anymore. To quantify the impact, the EPD's from the national database can be used as starting point.

MKI	120,447	MKI	38,306
Berekend over de totale BVO en levensduur		Berekend over de totale BVO en levensduur	
A. Productiefase	124,309	A. Productiefase	21,503
A. Constructiefase	7,711	A. Constructiefase	7,711
B. Gebruiksfase	0,000	B. Gebruiksfase	0,000
C. Afdankfase	11,300	C. Afdankfase	11,300
D. Buiten gebouwlevensloop	-22,872	D. Buiten gebouwlevensloop	-2,208

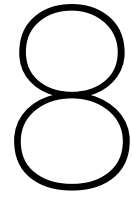
Figure 7.6: ECI values for the life-cycle modules for 1000 kg of new and reclaimed steel (Adviseurs, 2023).

In these environmental product declarations, transport in stage A4 and C2 is regarded as 0. When using the accepted product declarations for new steel and reclaimed steel in combination with a realistic 150 kilometers of transport distance for stages A4 and C2, the ECI for each of these declarations can be determined. The transport amounts to €0.0035 per kg per included stage. For modification, it is assumed that 10% new material is added and only half the amount of fabrication is needed compared to new steel due to reuse. For cut-off waste, module C should be reduced with the impact of deconstruction (C1). It is assumed that deconstruction has the same impact as construction (C5). The following figures should be used to express the environmental impact of new steel, reclaimed steel and cut-off waste.

- New steel: €0.149 /kg, module D -€0.02
- Reclaimed steel: €0.044 /kg, module D -€0.00
- Cut-off waste reclaimed steel: €0.007 /kg, module D -€0.00

For the Paris proof indicator that focuses on upfront carbon, stimulating reduction of emissions in the present, the inclusion of life-cycle stages is different. In general, only modules A1 to A5 are taken into account. This makes the difference between new and reclaimed steel even bigger. For cut-off waste, module C should be taken into account similarly to the ECI determination above as the disposal and recycling of the material occurs in the production stage of the new buildings life-cycle. This results in the following numbers:

- New steel: 1.227 kg. CO₂-equivalent
- Reclaimed steel: 0.305 kg. CO₂-equivalent
- Cut-off waste reclaimed steel: 0.10 kg. CO₂-equivalent



Steel-IT: framework

To be able to make a tool that can assess the economic and environmental impact of an office steel design and its reclaimed steel design alternatives, a framework needs to be established. This framework needs to provide the steps that are needed to generate and evaluate the design. To do this, the desired workflow of Steel-IT is specified. Using this workflow, the framework that provides necessary computation and analysis can be defined and developed. The resulting algorithms and models give an answer to research questions 7, 8 and 9.

8.1. Steel-IT workflow and methods

As described in the introduction, this research focuses on assessing the costs and environmental impact of structures that include reclaimed steel elements. Steel-IT needs to be able to receive the design created by the user as well as an algorithm to evaluate the design and implement the use of reclaimed steel section. The new design will be generated using a database of elements from several sources and Steel-IT will thus give the insight whether the design and donor elements from the database suit each other. By allowing the user to change the design in an iterative process, decisions can be made to match the demand with the supply.

The iterative process supports the needed change in design philosophy characteristic for reclaimed steel design. The available elements from a donor building influence the design choices made by the user of Steel-IT. The intended workflow for the user is shown in figure 8.1 To start, the user needs to get an idea of the stock that is available to create a first design. This design from the user will be fed into the framework which will analyse the design and create one new steel and two reclaimed steel variants. These two alternatives are analysed on costs and environmental impact to assess costs and quantify the environmental impact reduction of the reclaimed steel designs. The results from the designs are stored in a solution cloud. By giving insight in use of reclaimed elements, conclusion on how to improve the design can be made.

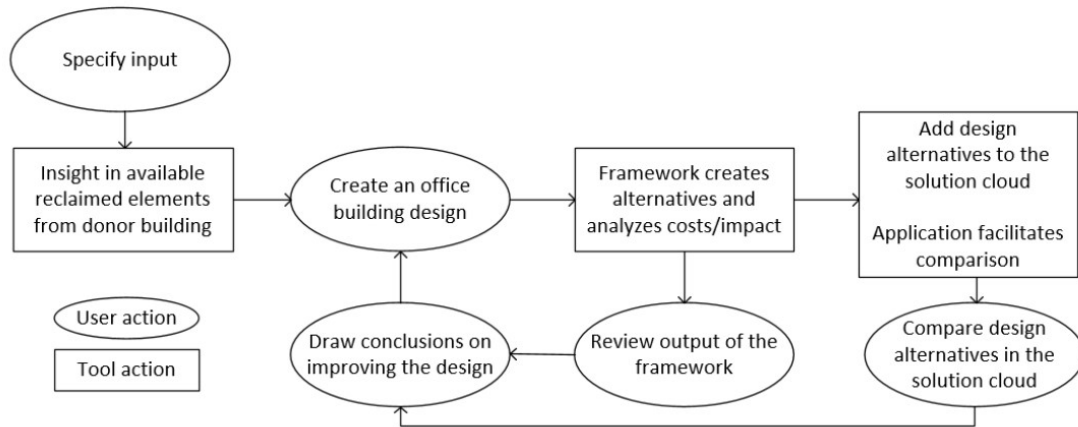


Figure 8.1: Intended workflow when using Steel-IT

By keeping the input design parametric it can be altered in future iterations. The design alternatives, new steel and donor steel, are then compared in terms of costs and environmental impact. One can imagine that the amount of donor steel that can be fitted depends on the design that is created in the first step of the workflow. By giving insight in which elements are used in the design and which are available, the user can go through the process again by adjusting the input to generate a model that is more likely to incorporate more reclaimed elements. By keeping track of the different designs that the user creates, the different design options can be reviewed until the user finds a design that meets their demands and wishes. By calculating the environmental impact and economic costs, Steel-IT can steer to implement reuse of steel to reduce environmental impact while considering costs. In this way the main goal of this research can be achieved.

The choice to leave the iterative process to be conducted by the user's increases the ability of the user to modify the input design so it can be used in more cases. It also gives the user more insight in what materials are available and through the iterative process. By redesigning manually, the user has a better idea of why certain designs work better than others. This high level of engagement in the design is important in designing with reclaimed steel.

8.2. User input

The basis of the analysis performed in a single iteration in Steel-IT is the design of the desired office building by the user. The structural configuration will be based on the typical office building from chapter 3. The office building will consist of a number of frames. The user is able to adjust the dimensions of the building but the configuration is predetermined to limit the scope of this research. The user will be able to change the amount of frames and distance between them, the number and length of spans within the frames, the floor height and the amount of storeys. In this first step of the workflow, the generated geometry will be visualised using lines and nodes.

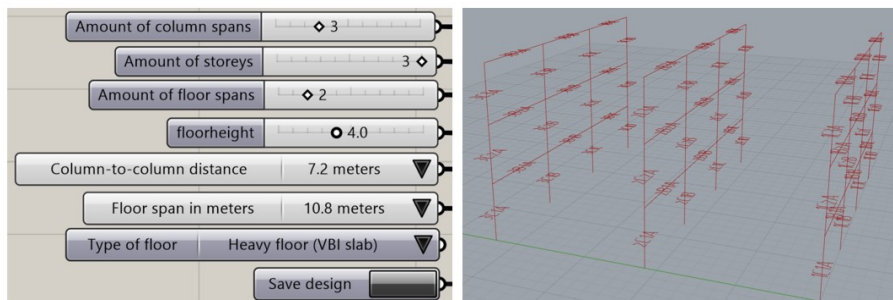


Figure 8.2: Line model of the geometry for the office building specified by the user.

The grid-sizes are limited to be 3.6, 5.4, 7.2 and 10.8 meters as these are common grid-sizes for office buildings. Working with common grid-sizes does improve utilization of available reclaimed elements as it is more likely that donor buildings have the same grid. Secondly, at the end-of-life of the new building, standardization improves re-usability for the same reason (VTT et al., 2020).

Furthermore, the user has to specify a database. This database can consist of multiple sources of reclaimed elements. Information about these sources are relevant for determining the material properties and cost parameters for storage and cleaning. For each source an excel-file with the reclaimed elements needs to be specified. Each file needs to contain element lengths and cross-section types. Each element has its own row. With this information, the database that will be used in Steel-IT is generated. The required lay-out of the excel-files and resulting database is shown in figure 8.3.

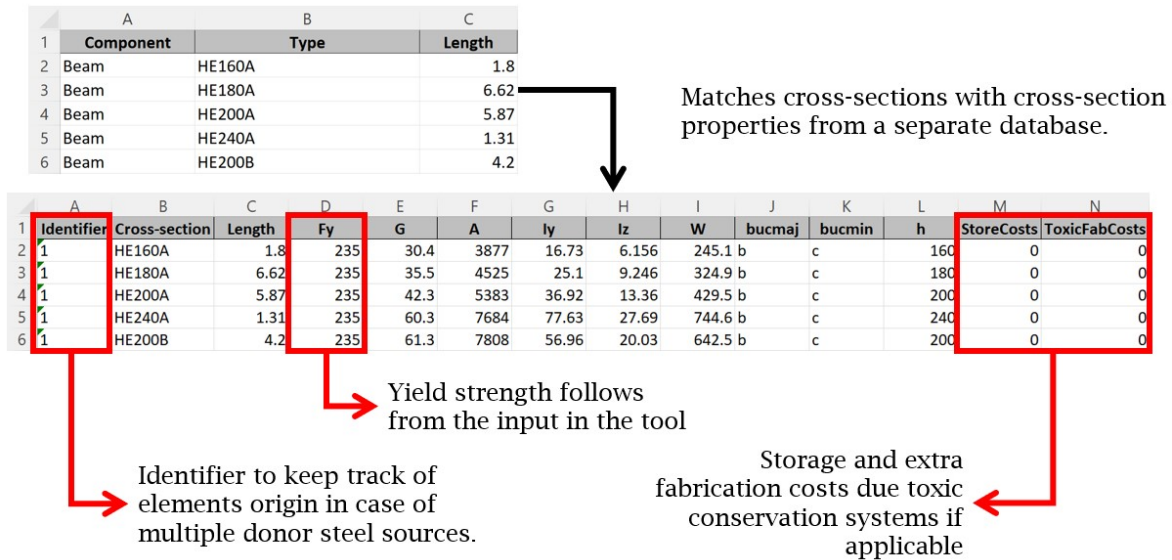


Figure 8.3: From excel-file to database used in the algorithm.

Further explanation on the determination of the yield strength of the donor steel can be found in chapter 8, figure 8.25. To give the user of Steel-IT an indication of the elements in the database, a visualisation is created.

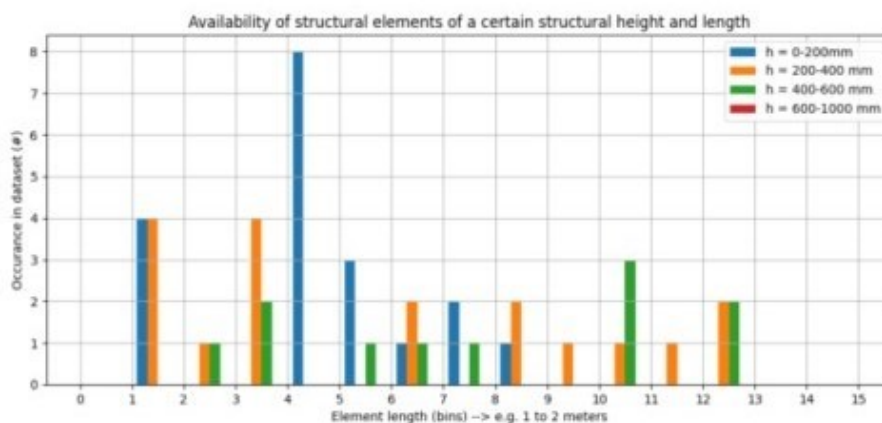


Figure 8.4: Visualisation of the data-base with donor elements.

The element are divided into both length and cross-section height. The length can be used to make a choice on which structural grids could be feasible in the design to implement reclaimed elements. The structural height has correlation with the capacity of reclaimed steel elements.

8.3. The framework

The framework within Steel-IT needs to be able to take the input design, create a new steel design and reclaimed steel design alternatives. It should also quantify costs and environmental impact of these design variants as well as other information to facilitate comparison of different designs. Figure 8.5 shows the framework that will be implemented in Steel-IT which will provide the analysis of the design variants and their cost and impact.

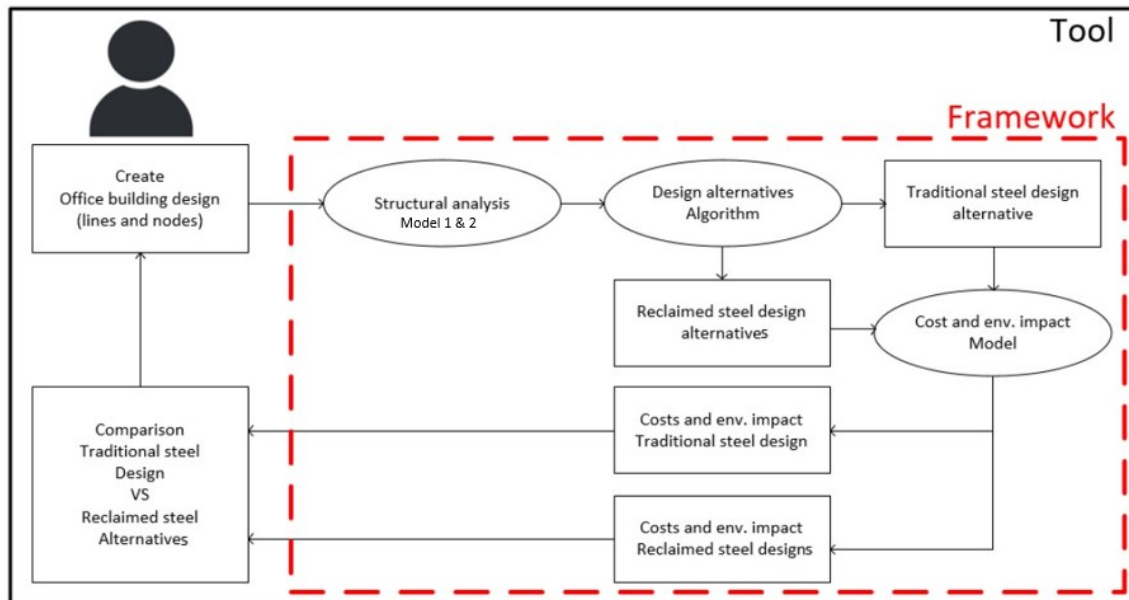


Figure 8.5: Position of the framework that will provide design alternative generation and cost/environmental impact estimations.

Optimally, it would be best to let an algorithm figure out what the optimal structural grid dimensions are to accommodate the most reclaimed elements in a cost-effective way. For the time span and scope of this project, this process will be left with the user as mentioned earlier. The framework will be used to evaluate and compare the design iterations that the user will perform in the described process. This chapter focuses on these foundations of the algorithm to create the design alternatives and models to determine the costs and environmental impact. Therefore the goal of the framework is firstly to generate the traditional steel design and reclaimed steel design alternatives using the users input geometry. Secondly, the framework should return estimates of the costs and environmental impact of both designs as well as other information to facilitate comparison of designs in the iterative process facilitated by Steel-IT.

8.4. Structural design

The first element in the framework of Steel-IT is to perform a structural analysis on the office design that is specified by the user. The assumptions in the structural model have an influence on the implementation of donor steel. Certain configurations might result in better use of the data-set of reclaimed elements as required cross-section properties depend on force distribution. In this research, two structural configurations for the frames will be included.

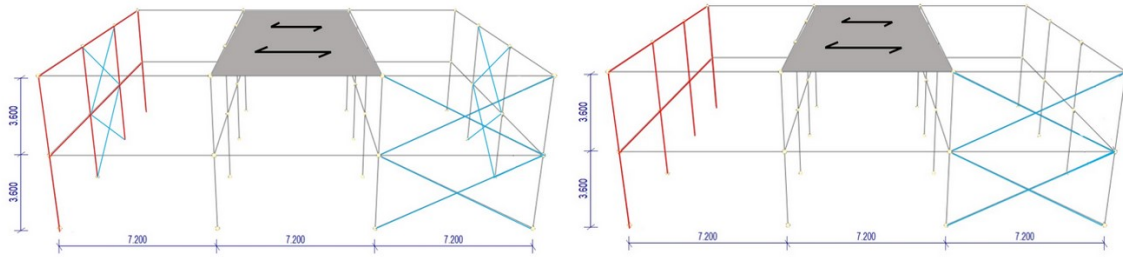


Figure 8.6: Structural model 1 (left) and model 2 (right) that are considered in the framework.

Model one consists of braced frames. This structural configuration:

- has continuous columns.
- has simply supported beams.
- gets its horizontal stability via diaphragm actions in the floors.
- gets its vertical stability via wind-braces.

The second model consists of portal frames. The structural configuration:

- has continuous beams.
- has storey-height columns, rigidly connected at the top, hinged at the bottom.
- gets its horizontal stability via diaphragm actions in the floors.
- gets its vertical stability via portals in the frames and wind-braces between the frames.

The structural analysis will be performed using the geometry created by the user. The grid sizes, floor height and amount of storeys are used to determine the internal forces and minimum stiffness requirements for both models.

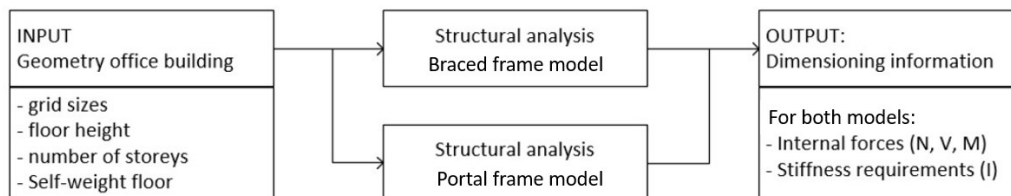


Figure 8.7: Input and output of the structural analysis for both structural configurations.

The structural analysis will be performed in python and uses different methods for each structural configuration. The python code is included in appendix A and the code has been verified using a worked example. This validation is included in appendix B.

8.4.1. Structural model 1: Braced frames

The figure below shows the structural configuration of the frame that is used.

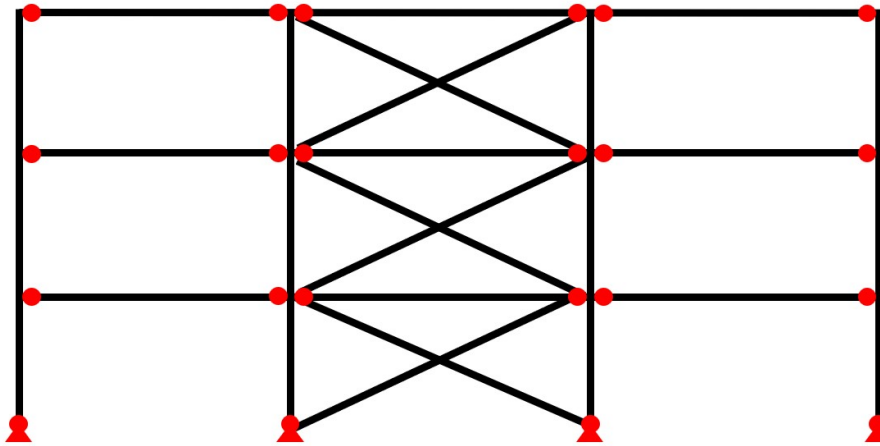


Figure 8.8: Structural model of a single frame for model 1: braced frame.

The following assumptions are made in this structural model:

- The vertical stability is provided by wind-braces.
- Columns are continuous from the foundation up to the roof.
- The beams are simply supported and span between the columns.

The simply supported beams allow for simple connections. Because of this, high costs for modification of donor elements can be prevented. The connections to create a moment resistant joint between column and beam can be quite bulky and require welding of plates, haunches and gussets to the donor elements. The complete building consists of multiple frames. The floors distribute applied loads in one direction, from beam to beam and provide horizontal stability by diaphragm action. The vertical stability between frames is also provided by wind-braces. A 3D visualisation of the braced frame model is shown in the figure below.

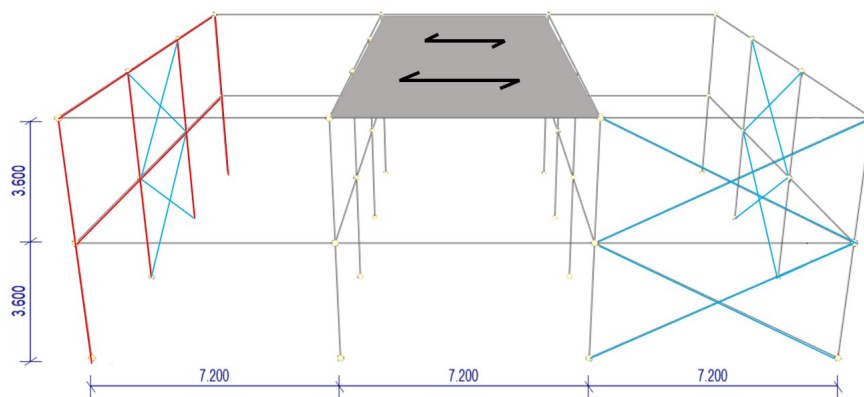


Figure 8.9: Typical wire-frame model for the structural configuration of model 1: braced frame.

The model in figure 8.9 has two storeys with a height of 3.6 meters and four frames spaced apart by 7.2 meters and is one of the many possible configurations that the user can specify. As mentioned the column to beam connections are quite simple. To minimise welding of these connections, bolted angle cleats are used with donor steel compared to the welded fin-plates for new steel. To create the column-splices for the continuous beams, end-plates are used in combination with a plate to spread the normal forces to the flanges of the column if needed. Figure 8.10 shows a sketch of both connections respectively.

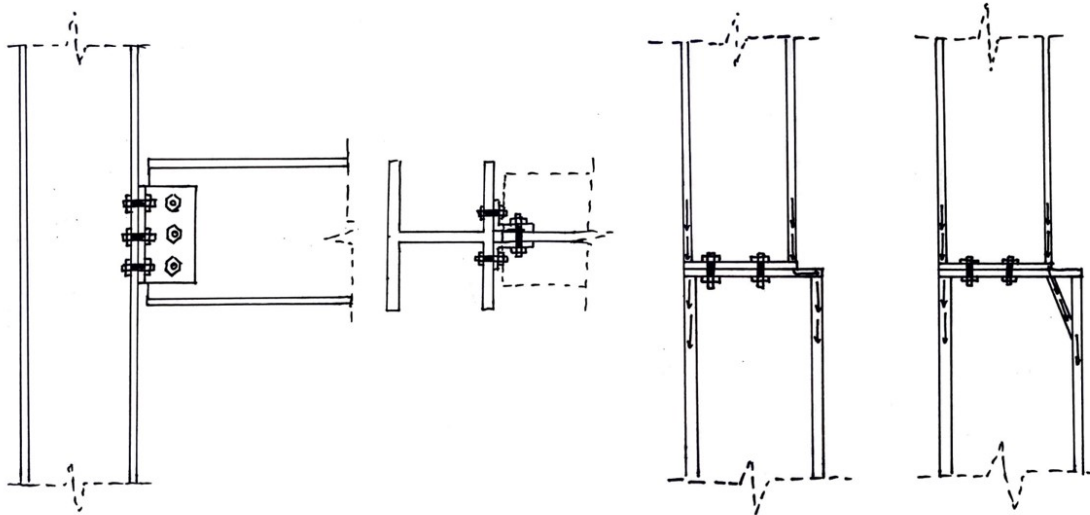


Figure 8.10: Connections used in the braced frame model.

8.4.2. Structural model 2: Portal frames

The figure below shows the structural configuration of the second frame type.

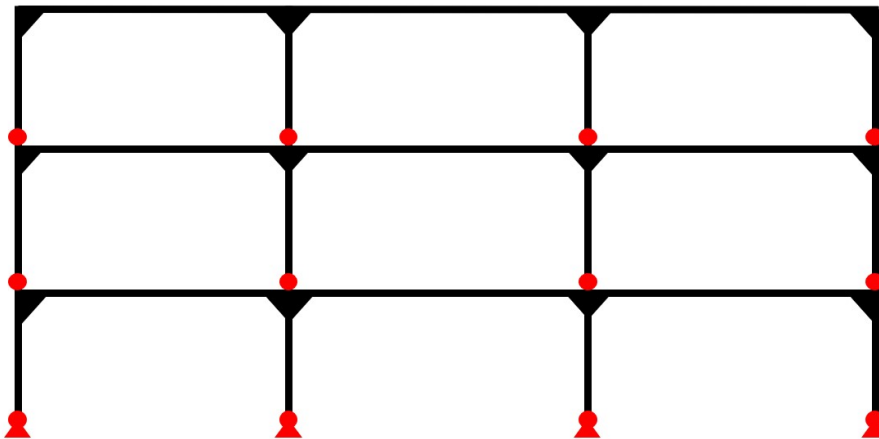


Figure 8.11: Structural model of a single frame for model 2: portal frame.

The following assumptions are made in this structural model:

- The vertical stability is provided by portals in the direction of the frames.
- The beams are continuous and span the complete frame.
- The columns span between floors and are connected with a hinge at the bottom and a rigid connection at the top.

The moment resisting connection between the continuous beam and columns is less complex and this makes that the stability of this frame can be provided by the portals. This model is more common for newly build office buildings. By using the portals for stability, the floor plan can remain open. Just like the braced frame model, the complete structure consists of multiple frames. The vertical stability between frames is again provided by wind-braces. The floors also carry loads in one direction and provide diaphragm action for horizontal stability. The portals that provide stability in the in-frame direction make for a more open floor plan than the braced frame alternative. A 3D visualisation of a possible building configuration is shown in figure 8.11

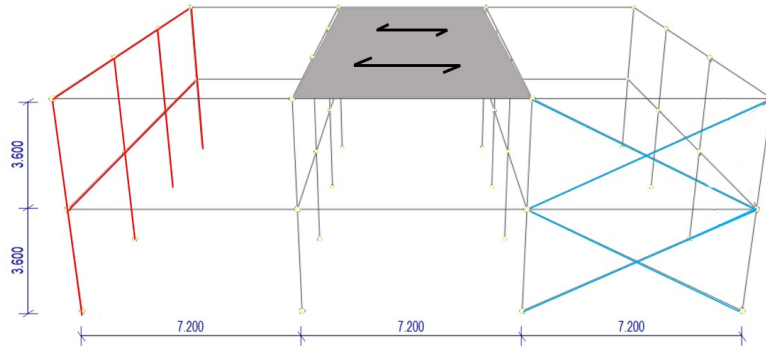


Figure 8.12: Typical wire-frame model for the structural configuration of model 2: portal frame.

The rigid connections in the portal frames require some welding. Because the column is connected to the bottom of the beam, simple end-plates suffice. For the beam to beam connection, the difference in size plays a role again. Also here, endplates can be used. Figure 8.13 shows a sketch of both assumed connections for the portal frame respectively.

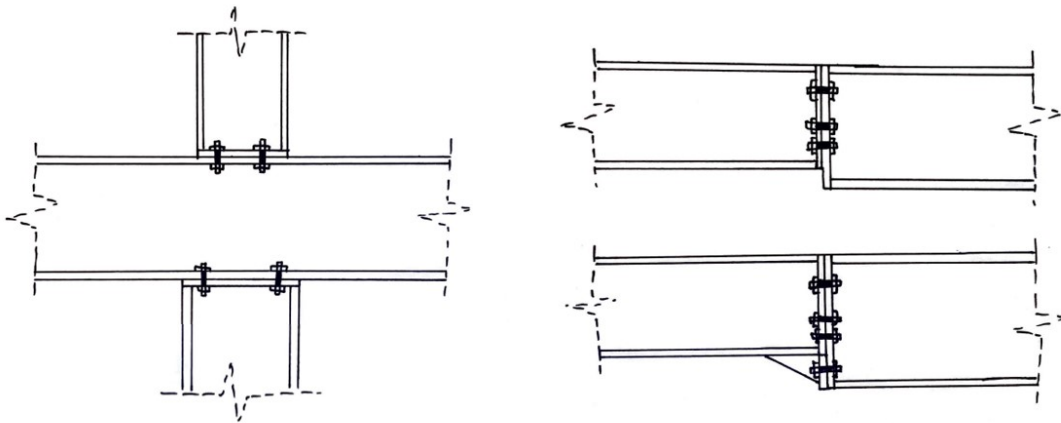


Figure 8.13: Connections used in the portal frame model.

8.4.3. Structural analysis braced frame

To determine the internal forces and bending-moments due to the loading on the first model a method for both vertical and horizontal loading is formulated. If there are load combinations with both vertical and horizontal loading, the results of the two methods can be added up and the minimal required moment and normal-force capacity for design can be determined. To keep to deformation limits, an additional model to determine the minimal required second moment of inertia is formulated.

In appendix B, a worked example of the two models is given to verify the used methods with results of a similar frame analysis using the software package MatrixFrame. Screenshots from this worked example are included in this chapter.

Vertical loading For vertical loading, distributed forces on the beams are considered. The starting point for the structural analysis are the simply supported beams. The moments in the beams and reaction forces can be determined from a basic forget-me-knot.

$$M_{midbeam} = \frac{1}{8}ql^2 \qquad F_{support} = \frac{1}{2}ql \qquad (8.1)$$

The reaction forces will result in compression forces in the adjacent columns. The results of this vertical loading model can be seen in figure 8.14.

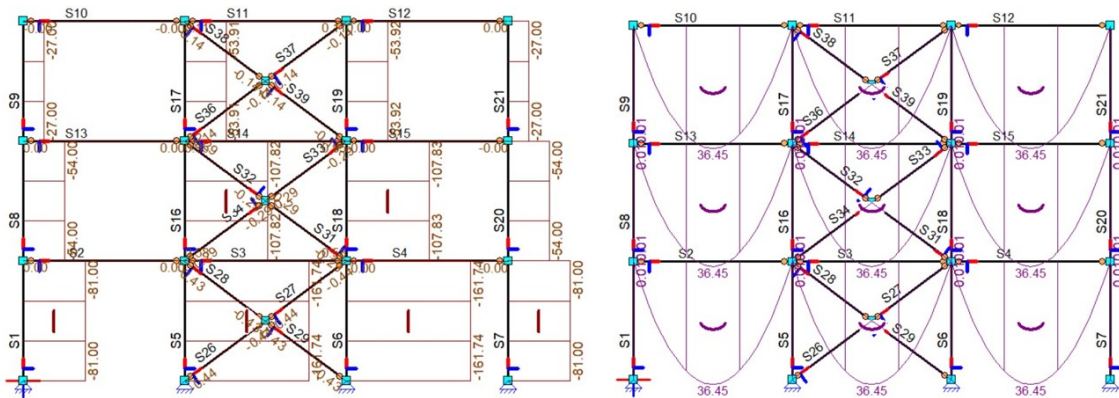


Figure 8.14: Forces and bending moments from MatrixFrame software (Matrix Software, 2021).

Horizontal loading The wind-force on the building results in forces in the stabilising elements. The frames with wind-braces provide this stability. The wind-braces themselves are not considered in this analysis but the resulting normal forces in the adjacent columns is of importance in determining the design normal force. To determine these forces, a simple model is used. First the bending moments created at the bottom of the storey needs to be calculated. This is done by summing the wind-forces times their distance to the base of the floor. Then the normal force can be calculated by dividing this number by the distance between the columns adjacent to the wind-braces. An example is given below.

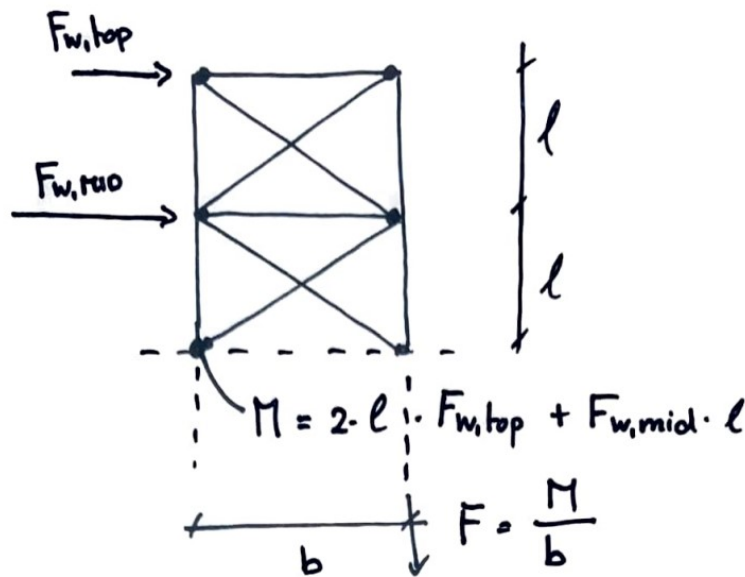


Figure 8.15: Analytical approach to determining the extra normal forces due to wind-loading.

The horizontal loading results in both tension and compression in the columns adjacent to the wind-braces. The internal columns are subjected to higher compressive forces from the floors compared to the edge columns. To prevent tension in the foundation, the preferred place for the wind-braces is in-between internal columns. For both columns in the stabilising 'wind-brace portal' the compressive force is considered as the wind can also come from the other side.

Minimal second moment of inertia A forget-me-knot is used to determine the minimal required second moment of inertia for the simply supported beams under a uniformly distributed load.

$$w = \frac{5ql^4}{384EI} \quad - > \quad I_{min} = \frac{5ql^4}{384Ew} \quad (8.2)$$

The global deformation of the structure is dependent on the cross-sections used for the wind-braces, which are not considered in this research.

Second-order effects It is assumed that the cross-sections of the wind-braces are selected to provide enough resistance to displacement to make the braced structure a non-sway frame. First-order analysis will suffice in this case. For column buckling, the non-sway buckling lengths can be used.

8.4.4. Structural analysis portal frame model

A method for vertical and horizontal loading is formulated to determine the internal forces and moments. In appendix B, a worked example of the models is given to verify the used methods with results of a similar frame analysis using the software package MatrixFrame. Screenshots from this worked example are included in this chapter.

Vertical loading Distributed loads are also considered for vertical loading in this model. A simplification is used to be able to determine the internal forces and moments due to this loading. The assumption is done that the inflection points in the beam is at $0.1 \cdot$ beam-length from the supports.

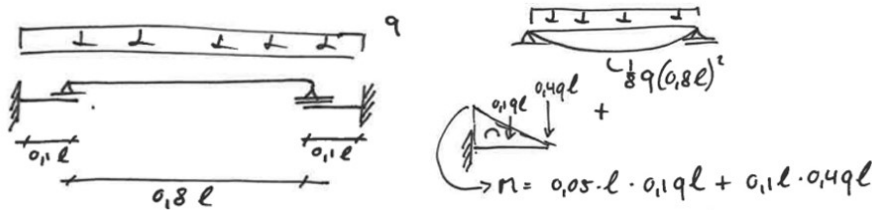


Figure 8.16: Beam model used in the vertical loading model

At the edges of the beams, the moments can be determined using the above formulation, at internal columns the moments are twice as high. The bending-moment diagram in-between the support is parabolic and the support reactions can be calculated by determining the slope of the bending-moment line at these points. These support reactions can be directly translated to normal forces in the columns.

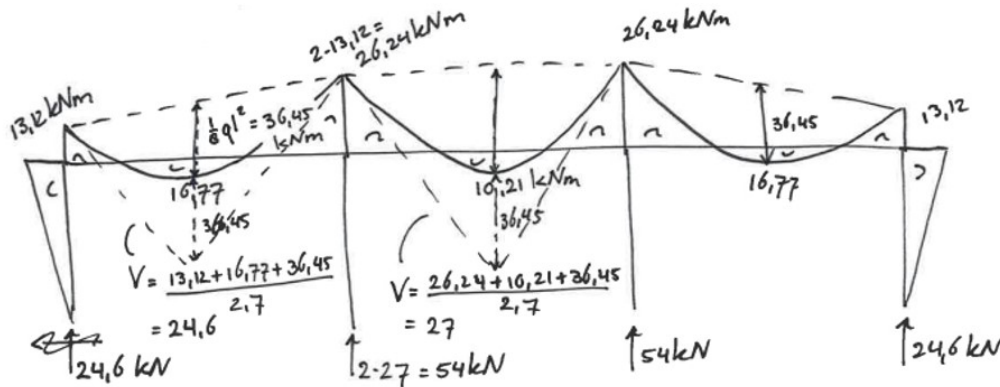


Figure 8.17: Determining the bending moments and normal forces in the columns

Horizontal loading For horizontal loading, the portal method is used to determine internal forces and bending moments. Steps in this method are:

1. Introduce hinges at mid-span of each beam.
2. Distribute the shear-force due to horizontal loading over the columns.

Then divide the model up into sections as illustrated in the figure below and perform the following steps:

3. Determine the normal-forces in the beams using horizontal force equilibrium.
4. Determine the shear-force in the beams using moment equilibrium around the base.
5. Determine the normal-forces in the columns using vertical force equilibrium.
6. Construct the bending-moment diagram by using the above calculated internal forces.

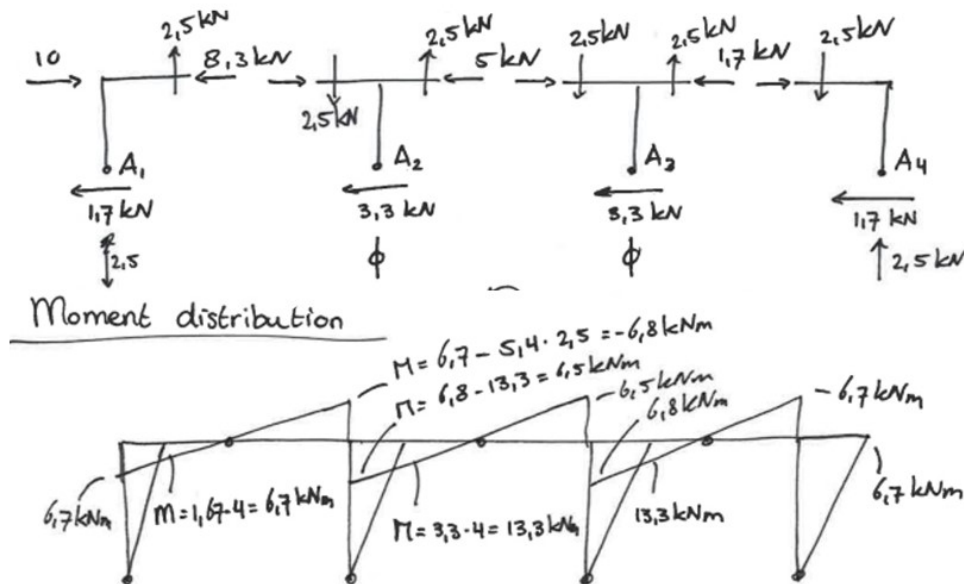


Figure 8.18: Determining internal forces and bending-moments due to horizontal loading of the portal frame model.

Minimal second moment of inertia For local deformation limits of the beams, forget-me-knots are used again. The beams are continuous and alternating loading patterns need to be considered as they can be governing. The geometry provided by the user influences which forget-me-knot should be used.

Q-last met schaakbord belasting

Belasting	Reactiekracht Dwarskracht			Moment				Door- buiging Y_{max}	
	A	B	C	M_{r1}	M_{r2}	M_{r3}	M_{r4}		
	R =	$0,45 q \ell$	$1,2 q \ell$	$0,085 q \ell^2$	$0,125 q \ell^2$			$\frac{q \ell^4}{110 EI}$	
	V =	$0,45 q \ell$	$0,65 q \ell$ $0,65 q \ell$						
	R =	$0,45 q \ell$	$1,2 q \ell$	$0,095 q \ell^2$	$0,115 q \ell^2$	$0,065 q \ell^2$		$\frac{q \ell^4}{101 EI}$	
	V =	$0,45 q \ell$	$0,65 q \ell$ $0,60 q \ell$						
	R =	$0,45 q \ell$	$1,2 q \ell$	$1,1 q \ell$	$0,090 q \ell^2$	$0,115 q \ell^2$	$0,065 q \ell^2$	$0,100 q \ell^2$	$\frac{q \ell^4}{102 EI}$
	V =	$0,45 q \ell$	$0,65 q \ell$ $0,60 q \ell$	$0,55 q \ell$					

Figure 8.19: Forget-me-knots for alternating load patterns on continuous beams.

The supports are considered to be pinned, which is not the case in the actual structure. The actual connection to the columns in frame will be a bit stiffer which results in smaller angular rotations and beam deflections. The choice to use the forget-me-knots reduces the complexity of the structural analysis.

The portals do play a role in global deformation and the selected cross-sections need to have sufficient stiffness to keep within the global deformation limits. The portal method is used to determine this minimal second moment of inertia in combination with two forget-me-knots. This analysis consists of the following steps.

1. Determine the internal forces and bending-moments using the horizontal model described above.
2. Select the section of the frame with the highest bending-moments (internal columns).
3. Determine the angular rotation of the nodes due to the moments in the beam.
4. Determine the displacement due to the shear-force in the column.
5. Calculate the minimal I to limit the deflection per storey and for the total structure.

The principles used are elaborated further in the figure below.

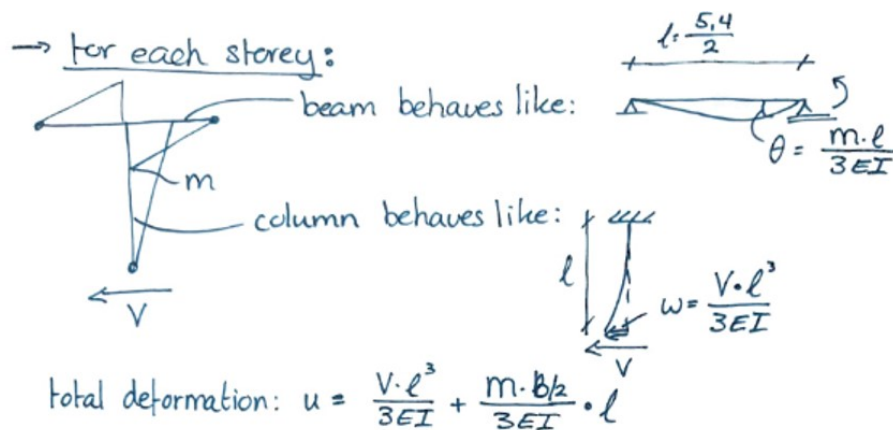


Figure 8.20: Using the portal method to determine the displacement per storey and the total structure.

By specifying limits to the maximum deflection per storey and the complete structure, a minimal required second moment of area can be calculated to make sure the final structure keeps within these maximum displacement limits.

- Per storey: $u_{max} = \frac{1}{300} \cdot \text{storey height}$
- Total building: $u_{max} = \frac{1}{500} \cdot \text{building height}$

MatrixFrame is used to compare the deflection of a frame with sections applied to it with the minimal required second moment of inertia to check the method used. The difference between the MatrixFrame deflection of the portal frame and the simplified analytical model was found to be 5% on the conservative side. This validation is included in appendix B.

Initial imperfections and second-order effects Initial sway imperfections cause extra horizontal forces that contribute to the bending moments in a portal frame. The determination of these forces following the Eurocode is summarised in figure 8.21.

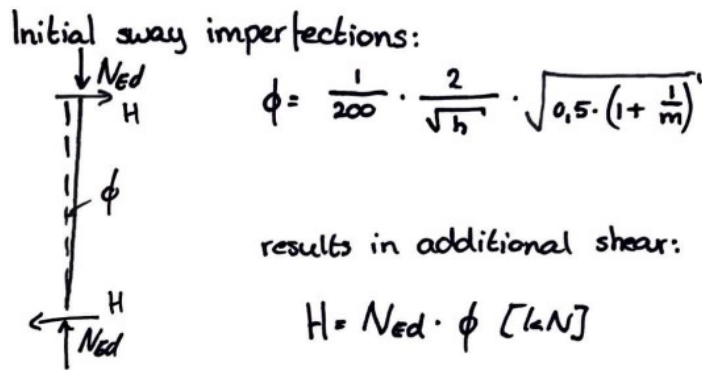


Figure 8.21: Calculating sway imperfections according to Eurocode

To include the initial sway imperfection in the governing load situation, the shear-forces are increased by this additional force and the bending moments are scaled on the same ratio.

To include second-order effects. The structure is analysed under the extreme wind-loading load-combination as this will cause the eccentricity of the vertical forces to create the second-order moment. The second-order moment is taken up by the portal frames. To calculate the additional bending moments, an additional imperfection due to deflection of the building is added to the initial sway imperfection. As the deflection is assumed in earlier models, these limits are used to determine the extra angular rotation of the columns.

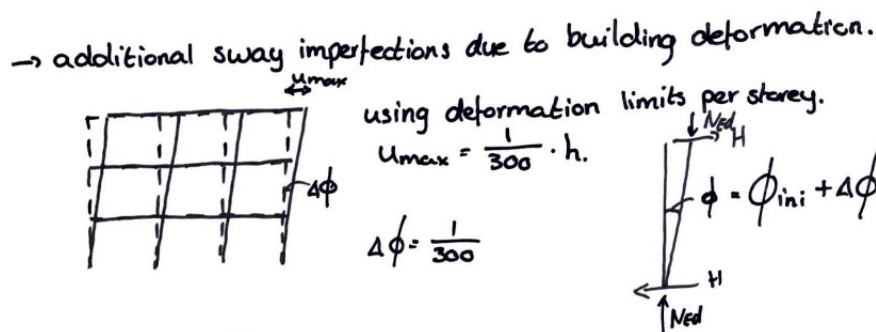


Figure 8.22: Defining the additional angular rotation of the columns to include the second-order effect.

Figure 8.22 indicates that the single storey deformation limit is used to determine the extra angular rotation of the columns on each storey. The worked example in appendix B shows that the analysis used keeps well within these limits but as the deformation per storey is different, this criteria is chosen to make a conservative estimation of the second-order effects for each storey.

To determine the final second-order factor to be applied on the governing load-combination, the first-order moments including initial sway imperfections and the second-order moments in the corners of the portals are evaluated. This leads to the second-order factor, n. The worked example shows how to implement the first order initial sway imperfections and how to calculate the second-order factor.

8.4.5. Loads and load combinations

To carry out the structural analysis, the loads need to be specified as well as the relevant load combinations.

Vertical Loads Figure 8.23 shows the top-view of the structure. The surface-load on the floor consists of two parts: permanent and variable loading. These loads are transferred to the beams as shown in figure 8.23.

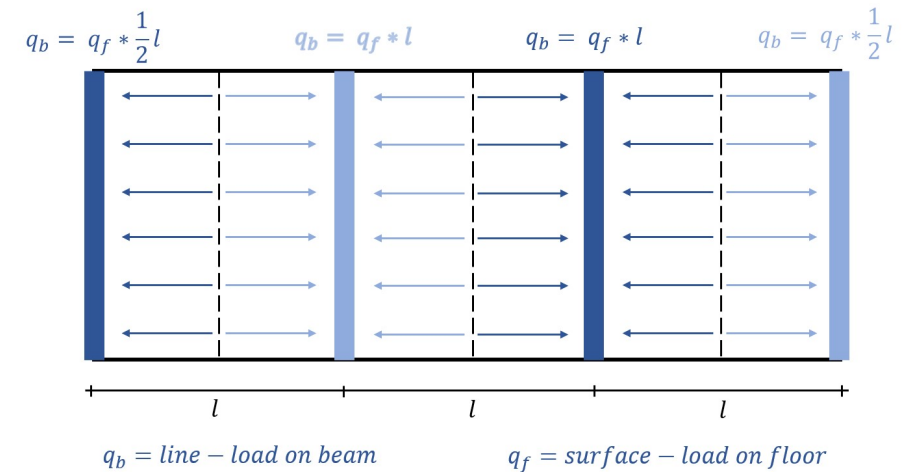


Figure 8.23: Flow of floor loads.

As mentioned in chapter 3, Eurocode specific loads that should be used for CC2 office buildings. A variable floor load of 4.0 kN/m^2 is used in office buildings. This includes lightweight separation walls. The permanent load is the self-weight of the structure consisting of beams, floor slabs, ceilings, installations and floor finishes. In Steel-IT, two types of floor-system can be selected: a wooden and concrete hollow-core slab. The permanent and variable loads for both systems have been summarised in table 8.1.

Type	Description	Load value concrete [kN/m^2]	Load value wood [kN/m^2]
Permanent	selfweight	See table 8.2	See table 8.3
	Floor finishing	1.2	0.45
	Ceilings	0.15	0.15
	Services	0.45	0.45
Variable	Live action + separation walls	4.0	4.0

Table 8.1: Loading assumptions for the two floor-systems.

As seen the loads for the floor finishing are different between the two flooring systems. Concrete hollow core slabs are often finished with a concrete top layer of 5 centimeters. The wooden variant often has a floating screed floor to improve insulation and acoustics. Concrete hollow-core slabs are heavier in both self-weight and floor finish. The thickness and reinforcement of the floor is dependent on loading and span. VBI developed a tool (VBI, n.d.) to calculate which type of slab should be used for given boundary condition. Table 8.2 summarises the hollow-core slab and its weight for the considered grid sizes. The floors have been selected using the specified loads in table 8.1.

Span [m]	Type	Structural height [mm]	Weight [kN/m^2]
3.6	HL200	200	2.83
5.4	HL200	200	2.83
7.2	HL200	200	2.83
10.8	A260	260	3.83

Table 8.2: Weight of concrete hollow-core slabs used for the spans in the structural model.

Kerto Ripa timber hollow core slabs are used for the light weight alternative to the concrete hollow-core slabs. Design software from Metsä (Metsä, 2023) calculates the best configuration for the grid sizes and loads considered in the structural models. Using the loads in table 8.1, the following floor systems have been selected.

Span [m]	Type	Structural height [mm]	Weight [kN/m^2]
3.6	KRB-2400x25-5x45x150-2400x25	200	0.36
5.4	KRB-2400x31-5x45x150-2400x25	206	0.39
7.2	KRB-2400x31-5x45x240-2400x25	296	0.44
10.8	KRB-2400x37-5x63x500-2400x25	562	0.72

Table 8.3: Weight of the timber hollow-core slabs used for the spans in the structural model.

Horizontal loads For horizontal loading, wind loads are taken into account. The maximum total height of the buildings in Steel-IT is 3 storeys. With a storey height of 4 meters, this would mean a total height of 12 meters. It is assumed that the building will be located in an urban area. From design tables it can be concluded that the maximum wind load on the building is 0.87 kN/m^2 . The facade system is attached to the floors and the loads are equally spread between the two connecting floors and results in the following schematization of the flow of forces.

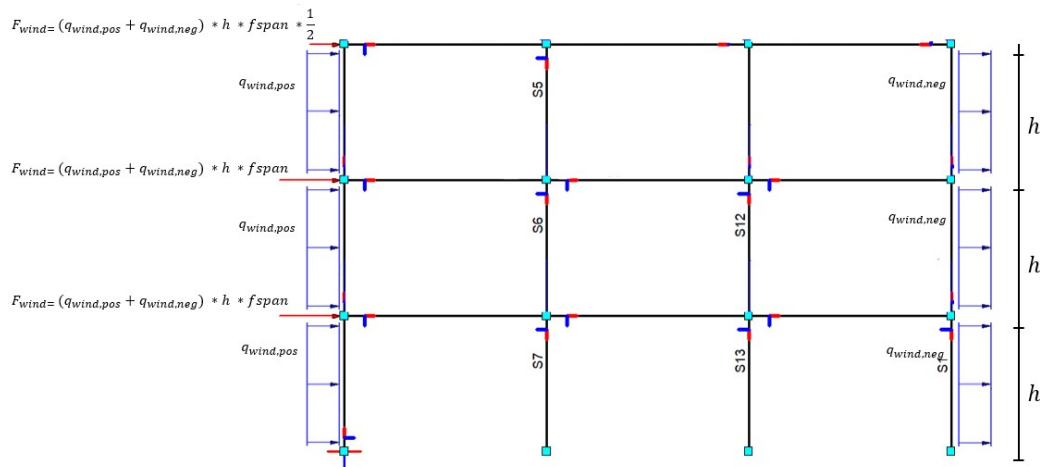


Figure 8.24: Schematisation of the transfer of wind-forces on the facades.

Load combinations To determine the governing bending-moments, normal-forces and minimal required second moments of inertia, all relevant load combinations need to be considered. The following ULS combinations need to be considered to determine the governing bending-moments and normal forces for the beams and columns.

$$1.2 G + 1.5 Q + 1.5 \psi_0 F_{wind}(=0) \quad (8.3)$$

$$1.2 G + 1.5 F_{wind} + 1.5 \psi_0 Q \quad (8.4)$$

$$1.35 G + 1.5 \psi_0 Q + 1.5 \psi_0 F_{wind}(=0) \quad (8.5)$$

To calculate the bending moments to determine the global deformation of the portal frame, the following SLS combination needs to be assessed.

$$1.0 G + 1.0 Q \quad (8.6)$$

$$1.0 G + 1.0 F_{wind} \quad (8.7)$$

8.4.6. Yield-strength

Before the cross-sections in new and reclaimed steel can be assigned, the yield strength needs to be determined. For the new steel, a yield-strength of 355 MPa will be used as this is the industry standard. For the reclaimed steel, some more information is needed to determine the yield-strength.

One of the challenges in this research is to set the yield strength of the donor elements. The flowchart in chapter 5 derived from NTA-8713 (Normcommissie 342086, 2023) is used to determine the yield strength in Steel-IT. However, if the material needs to be tested, it is hard to predict whether the assumed value is correct as the actual test results can not be predicted. In the end, the following flowchart for Steel-IT, which is based on the flowchart of the NTA, is used to determining the yield strength for the donor material.

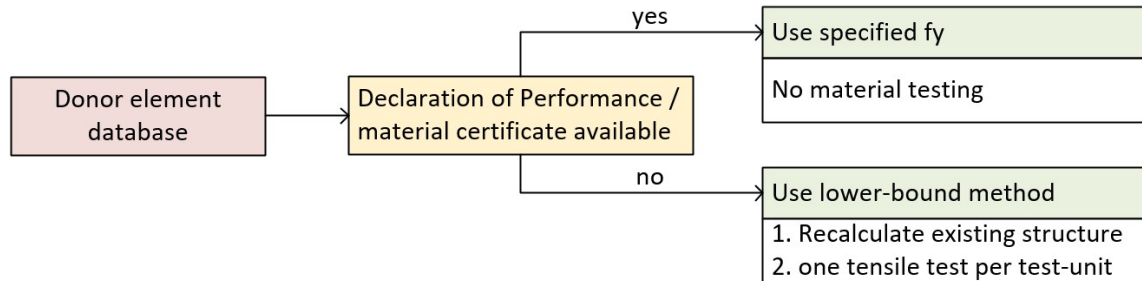


Figure 8.25: Flowchart to determine the yield strength of the donor elements.

NTA-8713 prescribes that testing is necessary in almost all situations. When a declaration of performance or material certificate is provided with the reclaimed elements, it is very likely that the material will pass the tensile tests for the value declared in the documents. If these documents are not present, it is possible to use the yield strength that results from elaborate testing. In Steel-IT, this method can not be used as the results of the tensile tests can not be predicted. In this case, the lower-bound method is used. The production year is required to determine the minimal specification for this period in time. These values can be found in chapter 5 and are repeated below.

Year	f_y [N/mm ²]	f_u [N/mm ²]
1955-1972	235	355
1972-1990	200	300
1990-1997	235	360
1997-2005	235	360
2005-now	235	360

Table 8.4: Lower-bound method yield strength for production periods from 1955 (Normcommissie 342086, 2023).

8.5. Generation of the traditional steel design

The goal of this thesis is to compare the costs of a new steel building with its reclaimed steel alternative. To do this, the new steel design needs to be created. The second structural configuration is used to determine the member's cross-sections. The model uses relatively simple connections and allows for continuous beams which reduces the stresses in the elements and deformation of the beams that support the floors. Furthermore, the use of portals allows for an open floor plan. This type of configuration is often seen in practice and is in line with the typical office building discussed in chapter 3.

8.5.1. Selection of cross-sections

The possible new steel cross-sections that can be assigned to the structure are defined in a database with all relevant information. For beams IPE sections will be assigned and HEA sections will be used for columns. Steel-grade S355 will be used to determine the resistance of the elements.

Profile	Weight	Area	Shear area z-z	Shear area y-y	Second moment of area y	Plastic section modulus	Second moment of area z	Plastic section modulus, I	Buckling about major axis y-y	Buckling about minor axis z-z
HEA100	16.7	2124	756	1600	3.49	83.01	1.34	41.14	b	c
HEA120	19.9	2534	846	1920	6.06	119.50	2.31	58.85	b	c
HEA140	24.7	3142	1012	2380	10.33	173.50	3.89	84.85	b	c
HEA160	30.4	3877	1321	2880	16.73	245.10	6.16	117.60	b	c
HEA180	35.5	4525	1447	3420	25.10	324.90	9.25	156.50	b	c
HEA200	42.3	5383	1808	4000	36.92	429.50	13.36	203.80	b	c
HEA220	50.5	6434	2067	4840	54.10	568.50	19.55	270.60	b	c
HEA240	60.3	7684	2518	5760	77.63	744.60	27.69	351.70	b	c
HEA260	68.2	8682	2876	6500	104.50	919.80	36.68	430.20	b	c
HEA280	76.4	9726	3174	7280	136.70	1112.00	47.63	518.10	b	c
HEA300	88.3	11253	3728	8400	182.60	1383.00	63.10	641.20	b	c

Figure 8.26: Database entries of new steel sections for columns (EurocodeApplied, 2023).

The tables with internal forces and bending-moments are used to select cross-section based on strength. For columns normal force is used to select a cross-section from the database. Before this selection is possible, the normal force capacity of the database of new elements need to be evaluated. For structural configuration 2, the buckling length is equal to 0.7 times the storey height as bottom supports are hinged and top supports are rigid as illustrated in figure 8.11. The normal-force capacity is calculated following the Eurocode procedure.

Secondly, the minimal required second moment of inertia is used to pick a second cross-section for each beam and column. After this selection, the two cross-sections are compared and the bigger cross-section is used and saved to the new steel design together with its weight. The selection is then complete.

8.6. Generation of the reclaimed steel design alternative

In chapter 5, three different methods of automated design from a limited stock of reclaimed elements are discussed: assignment and cutting stock optimisation, the growth method and nodal displacement method. The three methods are summarized shortly.

1. **Assignment optimisation** evaluates the fit of each element in the stock for all locations in the new building geometry. This information is saved to then select the highest ranking 'fit' and assign the donor element to the location in the new building geometry. It keeps doing this until no suitable fits are left over. The fit can be defined using different criteria like weight, costs and environmental impact.
2. **The growth method** starts its design at one specific point in the new design geometry. The methods look for possible fits in the database then moves on to the next building element. The output of this algorithm is different each time it is ran.
3. **The nodal displacement method** uses assignment optimisation but adds a degree of freedom. By moving the nodes within the new design geometry, the length of the elements is changes which can result in a fit that would otherwise not be possible.

In figure 8.27, the disadvantages and advantages are summarised.

Method	Disadvantages	Advantages
Assignment and cutting stock optimisation	<p>The algorithm looks at costs but does not perform additional structural verification after assignment.</p> <p>The method does not allow members to consist of multiple available elements</p>	<p>Effective at evaluating all possible solutions, without global optimisation.</p> <p>The cutting optimisation only works assigned elements of the same cross-section</p>
Growth method	<p>The algorithm does not contain constraints on the position of nodes.</p>	<p>Structural verification is included in the algorithm</p> <p>The algorithm allows the bottom chord to be constructed out of multiple elements</p>
Nodal displacement method	<p>The method does not allow members to consist of multiple available elements.</p>	<p>The combination of assignment optimization and structural verification works well.</p>

Figure 8.27: Disadvantages and advantages of the three algorithms.

The office building that is considered in this thesis consists of multiple floors. There is not enough flexibility to implement algorithms that allow free positioning of nodes like the growth algorithm described in the thesis of van Lookeren Campagne (van Lookeren Campagne, 2022). The assignment method described by Brütting (Brütting et al., 2019) and used in the thesis of Rademaker (Rademaker, 2022), allows to 'swap out' elements in a building design. This method will be used to create a design alternative to the new steel design discussed in the previous section. This method does not allow for creating one element out of multiple donor elements as the element lengths need to be predefined. Both structural configurations have continuous members. To allow for the continuous columns in the braced frames and continuous beams in the portal frames, a modification is done to the algorithm. Table 8.5 gives an overview of the methods used to assign donor steel elements for the different members in each model.

Braced frame	Simply supported beams	Assignment optimisation
	Continuous columns	Modified assignment optimisation
Portal frame	Continuous beams	Modified assignment optimisation
	Single storey columns	Assignment optimisation

Table 8.5: Used methods to create the reclaimed steel design alternatives.

The used methods and the modifications are described in the next part of the report.

8.6.1. Braced frame: Assignment of simply supported beams

Application of the assignment optimisation is directly usable on the assignment of the simply supported beams in the braced frames. To do such an assignment, the fit of the donor elements on all building geometry locations need to be evaluated. The donor elements need to be long and strong enough to be applied and are hard requirements to make a fit possible. The fit itself is a performance indicator of the element in a specific location in the building. To assess the performance, the weight of the reclaimed element will be compared to the weight of the new-steel equivalent, the optimal cross-section. The function to evaluate the fit of a reclaimed element is formulated as:

$$P_{fit} = 1 - \frac{G_{de} * l_{de} - G_{be} * l_{be}}{(W_{mult} - 1) * G_{be} * l_{be}} \quad (8.8)$$

G_{be}	Weight of new element / m	l_{be}	Length of new element
G_{de}	Weight of donor element / m	l_{de}	Length of donor element
W_{mult}	Max multiplication factor of weight (donor / new)		

Table 8.6: Abbreviations used in equation 8.8

The weight of the donor element can be calculated by multiplying the length of the donor element with its mass per meter. If the element is a lot bigger than required, the left-over piece can be reused. In this case the fit is calculated using the required length. When the weight of the reclaimed steel section in question is equal to the weight of the optimal cross-section from a new steel design, the fit scores 1.0. Heavier sections score lower. W_{mult} is the maximum multiplication factor for the weight of the reclaimed steel section compared to the new steel design alternative. If W_{mult} equals 2, sections that are twice as heavy as the optimal cross-section have a fit score of 0. All solutions with a fit lower than 0 are not considered in the assignment optimisation. The result of the evaluation of each donor element is a two dimensional matrix.

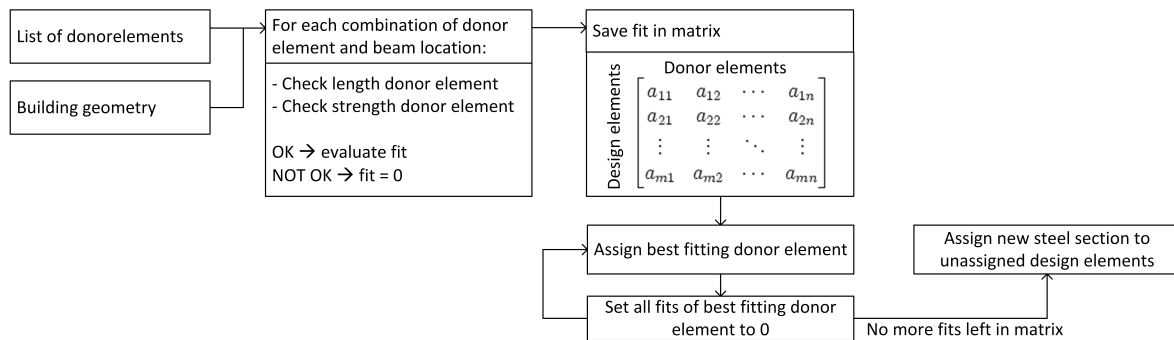


Figure 8.28: Steps in the assignment optimisation of the simply supported beams in model 1.

During assignment, the highest fit is selected first and the corresponding donor element is assigned to the building location. All fits for the building element are then set to 0 as the element does not have to be assigned again. Dependent on the left over length of the donor element, the fits for the donor elements are deleted if only a small piece of cut-off waste is left over. If the left-over piece is big enough to use for another element, the fits for this element are re-evaluated for the new donor length.

8.6.2. Braced frame: Assignment of continuous columns

The braced frame has continuous columns which can consist of multiple reclaimed steel elements. The columns are only loaded with normal-forces as the beams are simply supported and the horizontal loads are transferred through the wind-braces. The location of the splices to connect the donor elements does therefor not matter. The assignment optimisation has been adjusted to allow combinations of elements to build up a continuous column. A brute-force method is developed to consider all possible combinations of the donor elements. The workflow is summarised in figure 8.29.

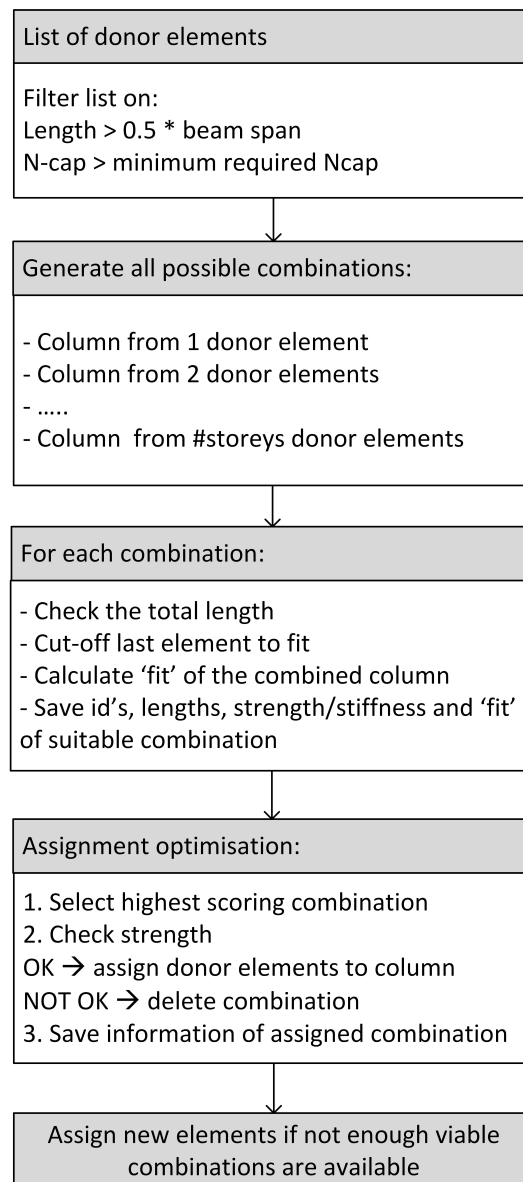


Figure 8.29: Steps in the assignment of the continuous columns for a braced frame.

The amount of elements a continuous column can consist of is limited to the amount of storeys to prevent having columns that consists of a lot of small sections and limit computation time. To further limit computation time, the list of donor elements is filtered on strength, length and weight. Pieces should be longer than 0.5 times the columns height. The weight of the continuous can be a maximum of W_{mult} times the weight of the heaviest new steel beam. The python code that performs the assignment can be found in appendix A.

8.6.3. Portal frame: Assignment of continuous beams

The beams in the portal frame can span the complete frame and can be build up out of multiple reclaimed steel elements. As discussed in chapter 5, the splices that are necessary to create the continuous beams do not have a lot of moment capacity. To ensure monolithic deformation behaviour, the splices need to be placed at the inflection points of the beams where bending-moments are minimal. It is assumed that these points are 0.25 times the span away from each intern column and 0.1 times the span away from each edge column. For a beam that spans four columns, this would give the following optional locations for a splice.

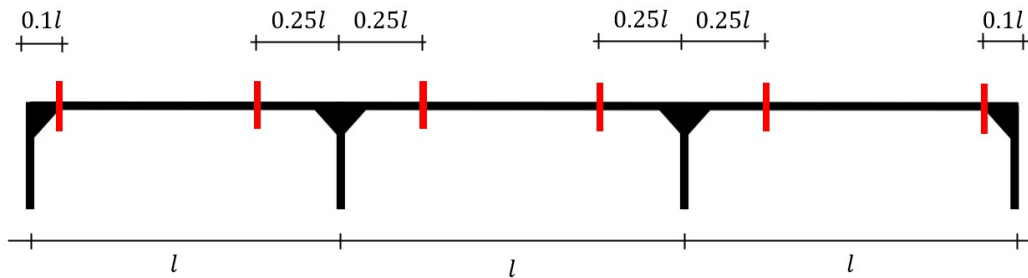


Figure 8.30: Possible locations for a splice to ensure monolithic deformation behaviour.

Splices are costly to make. It is not realistic to build up a beam out of a lot of small pieces. This would mean that for the beam in figure 8.30 could be created using seven reclaimed elements and six splices. To limit the amount of elements in a beam, the maximum allowed amount of elements will be limited to the amount of spans of the beam. By limiting the minimum length of a section to 0.5 times the span of the beam, the smallest pieces of 0.1 times the span are also eliminated from the algorithm. In this way the amount of splices are limited and the beam will not transform into a mechanism under asymmetric loading when the splices will not be stiff enough to provide monolithic deformation behaviour. In the case of figure 8.30, this would mean a maximum of 3 reclaimed elements. A possible solution is visualised in the figure below.

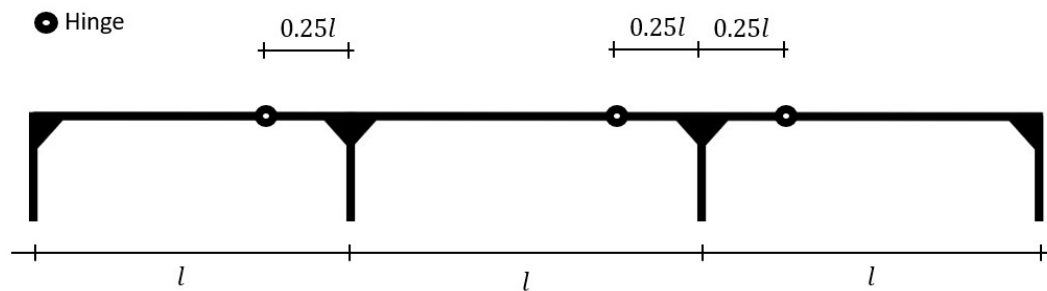


Figure 8.31: Maximum amount of hinges for a beam that spans three bays.

It should be noted that this hinge number restriction is not caused by a deficit in the quality of reclaimed steel but rather a problem that arises in the limited availability and assignment of the elements. Reclaimed steel sections do not perform worse than new steel sections and the same deformation behaviour applies to new steel sections. As the availability of new structural section is not limited, formation of mechanism is not a problem as the newly produced elements are longer than the maximum spans considered in this research.

To select which donor elements will be part of the continuous beams, a modification is done to the way the fit is calculated for the assignment optimisation. The process is summarised in the flowchart of figure 8.32.

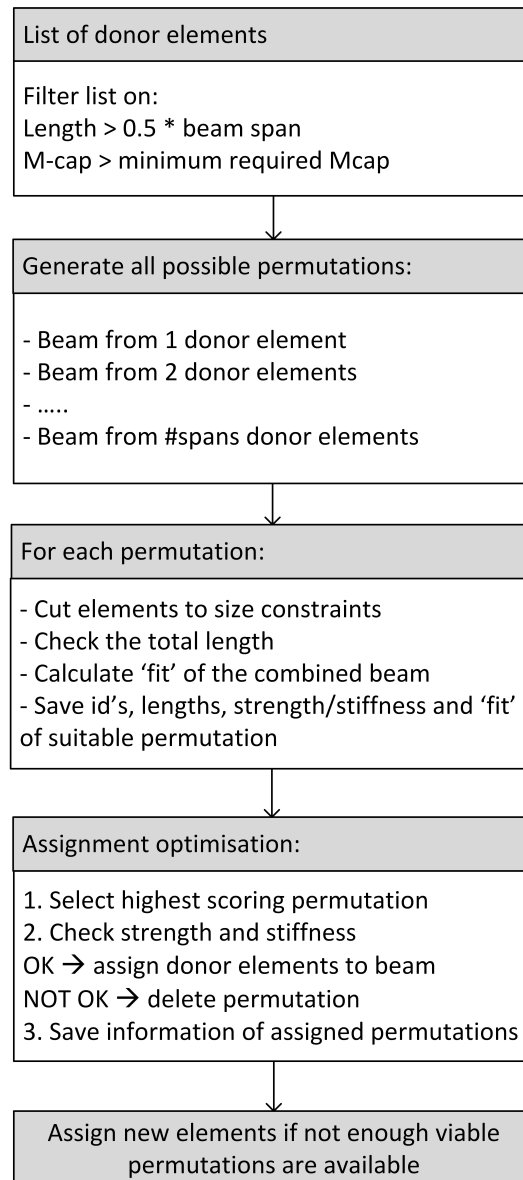


Figure 8.32: Steps in the assignment of the continuous beams for the portal frame model.

8.6.4. Portal frame: Assignment of single storey columns

The assignment of the single storey columns in the portal frame is quite similar to the assignment of the simply supported beams in the braced frame. The same logic is used as in figure 8.28. A matrix is constructed to assess the fit of each donor element on each column location. Each entry is checked on strength and length and if this criteria satisfies the fit is calculated using formula 8.8.

Again, the data-set that is used is filtered on strength and length to limit computation time. The python code that performs the assignment can be found in appendix A.

8.7. Cost model

To calculate the costs of the new steel design and its two design alternatives a costing model is created with the research and interviews performed in this research. The goal of the model is:

To give estimations of the costs of a new steel design and its reclaimed steel design alternatives.

This section will explain the model. It will go into detail about what method is used and which assumptions and information is used to make a good estimation of the costs involved in both designs. The aim is to make estimations that make comparison of design alternatives possible. In chapter 6 describes three methods to determine costs of a project. A brief summary of the three costing methods is given below.

1. **The weight method** uses key-figures established by practice to put a price on a kilogram of construction steel that includes all costs. To account for connections, an additional percentage of fictional steel is added. The percentage that is added has been estimated by the cost engineer.
2. **The percentage of beams weight based on rotational capacity model** considers each element on its own. Just like the first method, a percentage is used to account for the connections. In this method, the rotational stiffness of the joints is used to estimate the extra percentage that should be taken into account per beam. In this way more detail is added to the calculation.
3. **Activity based costing** looks at the activities involved in manufacturing a steel structure. When all activities and hourly rates are known a very precise figure on costs can be provided. This model can become complex and it is hard to keep in control of the results.

Each method has its advantages and disadvantages which are summarised in figure 8.33.

Method	Disadvantages	Advantages
Method 1: Weight-method	<p>The simplicity of the method can make it difficult to include the differences between new and reclaimed steel.</p> <p>There is not a lot of experience in building with reclaimed steel. Key-figures are missing to do an accurate cost-estimation.</p>	<p>Key-figures can give an accurate indication of the costs of new steel structures.</p> <p>The simplicity of the method makes it easy to 'stay in control' of the model.</p>
Method 2: Percentage of beams weight based on rotational capacity	<p>The simplicity of the method can make it difficult to include the differences between new and reclaimed steel.</p> <p>There is not a lot of experience in building with reclaimed steel. Key-figures are missing to do an accurate cost-estimation.</p>	<p>Key-figures can give an accurate indication of the costs of new steel structures.</p> <p>The simplicity of the method makes it easy to 'stay in control' of the model.</p> <p>Difference in connections can be taken into account.</p>
Method 3: Activity-based costing	<p>The level of detail can cause complex models which might not be suitable for each design and situation.</p>	<p>The difference in processes for new and reclaimed steel are different and can be considered in this model.</p>

Figure 8.33: Disadvantages and advantages of the costing models discussed in chapter 6.

The model will be created on the basis of a combination of these methods. The model aims to express the different elements that build-up the costs of a structure and more importantly, differentiate this build up for the different designs that are considered. The difference of the costs of a building with new and reclaimed steel elements will be broken down into different components:

New steel design		Reclaimed steel alternative	
Cost price new steel	S	Cost price new steel	S
		Cost price reclaimed steel	S
		Costs of material testing	E
		Storage	E
Sandblasting and coating new steel	S	Sandblasting and coating new steel	S
Fabrication	S	Fabrication	S
Assembly	S	Assembly	S
Engineering	S	Engineering	S
Risk	S	Risk	S

Table 8.7: Components of the cost model for new and reclaimed steel designs.

Some of these cost elements will be assessed on structure (S) and the others on element (E) scale. This section will go into detail about the elements within the components of table 8.7.

8.7.1. Cost price of new steel

The cost price of new steel fluctuates over time. Tables that are supplied by steel traders do not represent the costs accurately. Discounts on these prices will lead to the final price at which they sell their product. It is important to get an update on the steel price at the moment of using the cost model. Small differences can have a big impact on final costs as large quantities of steel are often required.

$$C_{newsteel} = W_{new} * \epsilon_{steel} \quad (8.9)$$

W_{new}	kg's of new steel in the design	ϵ_{steel}	price per kg. steel section
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As seen in the equation, this cost-component is assessed on building scale. This can be done as the pricing is based on weight.

8.7.2. Cost price of reclaimed steel

Reclaimed steel needs to be harvested from a building by a deconstruction contractor. This process demands more time than traditional demolishing as elements should be handled more delicately. In chapter 6, B-next, Reijrink and Vic Obdam give an advice on what the cost of reclaimed steel should be. From a deconstruction contractors point of view, there are differences in activities in deconstruction and thus costs. Financially, the reclaimed steel they sell will not be sold as scrap. This reduces profits and should be accounted for. Acquiring reclaimed steel cost-free does therefor not seem sustainable or possible in every project. On the other side, less costs are made for land filling. It is unlikely this will cover all the costs of extra activities during deconstruction.

It is likely that the price point of reclaimed steel will lay around the price at which steel scrap can be sold plus an additional fee for the difference in time it takes to carefully deconstruct instead of demolish a structure. In this way, the cost of extra work can be compensated. Hendriks from B-next suggests an 30% addition over the steel scrap price an engineers at Reijrink suggest up to an 100% addition. This model uses the 30% specified by B-next as they have more experience on deconstruction.

$$C_{reclaimedsteel} = W_{rec} * \epsilon_{scrap} * (100\% + \%_{extra}) \quad (8.10)$$

W_{rec}	kg's of reclaimed steel in the design	ϵ_{scrap}	price per kg. steel scrap
$\%_{extra}$	cost addition for deconstruction		

8.7.3. Costs of material testing

The costs for material testing can be determined following two realistic scenarios depending on which stakeholders conduct the validation of material properties.

1. Supply scenario: steel trader/deconstructor conducts tests
2. Demand scenario: client conducts test

In scenario 1, all steel elements are tested by the steel trader or deconstruction contractor. In this way all elements receive a declaration of performance. The client who needs elements pays for the costs that are made for the elements he wants to use. In the second scenario, the client performs the tests for the elements that are needed and credits all costs to the project.

To determine the costs for testing, the protocol described in NTA-8713 is used to determine the required number of tests. As the office building considered in this thesis falls in consequence class two, the following is needed to validate the yield strength of the steel in a test-group.

- Archive information of minimum status 4 or hardness measurements for each element.
- One tensile test.

NTA-8713 states that the chemical composition should be verified if fabrication of the donor elements require welding. If the chemical composition needs to be tested, one test to determine the CEV-value is required per test-group. Nebest indicates the following figures to conduct the activities for such a test program:

- One field-day to create a test-plan/take samples: €2500
- In-situ CEV-test during the field-day: +€700
- One tensile test: €150

These assumptions are based on the assumption that a team of 2 to 3 workers can perform the tasks for 20 test-groups per day. If more tests need to be performed, more days are needed in the field. The total costs can be calculated using equation 8.11. The first term in the equation, $\frac{\#_{tg}}{20}$, should be rounded up to the nearest half. Drive-out time, reporting and set-up is not linear with the amount of test-group that are reported on.

$$C_{testing} = \frac{\#_{tg}}{20} * \epsilon_{fieldday} + \#_{tg} * \epsilon_{tensile} \quad (8.11)$$

$\#_{tg}$	Number of test-groups	$\epsilon_{fieldday}$	Costs of one day in the field
$\epsilon_{tensile}$	Costs of one tensile test		

The total costs can then be spread over the elements which are tested in case of scenario 1. For scenario 2, the complete costs should be taken by the client as it is unlikely that the elements that are not used will be sold on. The total costs for scenario 2 are often lower than scenario 1 as it is likely that not every element from the donor building will be used. Not all test-groups will have to be tested. The final costs will always be higher in scenario 2 as the elements that are not used are not sold on with a part of the research costs.

In the little projects that have been executed with reclaimed steel, scenario 2 is dominant. Demand for reclaimed steel elements is not high enough to incentivise steel traders or deconstruction contractors to start testing in-house. For Steel-IT, scenario 2 is considered in the cost model as it is the most realistic. A more detailed analysis of the two scenarios is added to this report in appendix C.

8.7.4. Costs of storage

The costs of storage which can be applicable to donor elements if they were harvested from a building prior to the construction of the new building need to be determined for each element as the sources in the database may vary. To determine the storage costs for a stored element the following equation is used.

$$C_{storage} = C_{reclaimedsteel} * \%_{expenses} + \epsilon_{handling} * W_{rec} \quad (8.12)$$

$\%_{expense}$	Costs of storage as a percentage of the cost-price
$\text{€}_{handling}$	Element specific costs for handling

In chapter 6 it is mentioned that HP-Staal, a reclaimed steel trader in the Netherlands, needs to sell the reclaimed steel elements for an extra 35% on the cost price and €0.075 per kg for their expenses and activities to create a profitable business model.

8.7.5. Sand-blasting and coating of new steel

New steel is not coated from the factory. The structures environment plays a big role on the choice for a preservation system. In case of this thesis, a one-layered coating will suffice as the structural steel is protected from moisture by the building envelope of the office. Reclaimed steel already received a preservation system in its last life-cycle. This coating can be reused. This implies a big saving on costs compared to new steel.

$$C_{blasting+paint} = W_{new} * \text{€}_{blasting+paint} \quad (8.13)$$

$\text{€}_{blasting+paint}$	Costs of sandblasting and painting new sections
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A value for $\text{€}_{sand,paint}$ of €0.25 per kilo, suggested by engineers at Reijrink, is used for new steel. This value depends on wages, type of preservation system and method of application. This cost component is evaluated on building scale as the total weight of new steel can be multiplied with this key-figure.

8.7.6. Fabrication

Fabrication of a new steel design and reclaimed steel alternatives are significantly different. Indication of Vic Obdam and Reijrink do comply with each other. The following assumptions are included in the model for fabrication:

- Transport of new steel sections is included in the cost price of new steel.
- To modify reclaimed steel, it will need to get cleaned locally.
- Reclaimed steel elements increases cad-drawing time.
- The fabrication of reclaimed steel elements requires manual work which can't be automated.
- The fabrication of the new steel design is assumed to be done manually as well.

To be able to give an indication of costs, some indicative market conform key-figures estimated by engineers at Vic Obdam and Reijrink are used. These figures are summarised in the table.

New steel fabrication		Reclaimed steel fabrication	
		Transport:	€0.05
		Cleaning:	€0.10
Engineering:	€0.05	Engineering:	€0.10
Modifications:	€0.70	Modifications:	€0.90
Total:	€0.75	Total:	€1.15

Table 8.8: Cost breakdown of new and reclaimed steel fabrication.

These figures are based on costs per kilogram of steel. Reijrink gave estimation based on how much more work it is to modify reclaimed steel compared to new steel elements. To be able to make a good estimation of the amount of fabrication work, the amount of reuse-able details need to be estimated. When a structure can be reused, one-to-one, no additional modification needs to be performed and the costs will thus be minimal. When no connections can be reused, the maximum amount of modification is needed and costs will increase. The amount of reusable connections depend on the design that will be realised using the reclaimed steel. If there are big similarities in geometry, elements and structural lay-out might be similar and use with minimal modifications will be possible.

In the environmental product declaration of Bouwen met Staal, they assume that 50% of the current connections can be reused. This is confirmed as a credible assumption. This is however, for a fully elaborated design. For a random design that is generated with an algorithm this might not be the case. Chosen is to use the 50% specified in the EPD as a default value. The user of the model can alter this percentage to a value which is realistic. The user should consider the similarities between the donor-building and new design to estimate the percentage. Some expertise is needed to do this.

In this model, the cost for fabrication of a new structure will be calculated with the following equation:

$$C_{fabr,new} = W_{new} * \epsilon_{fabr,new} \quad (8.14)$$

This equation uses the key-figure indicated by Vic Obdam and assumes fabrication of new steel using manual processes and advanced machinery. To calculate the costs of fabrication of a reclaimed steel design alternative, the next equation is used:

$$C_{fabr,rec} = W_{new} * \epsilon_{fabr,new} + (1 - \%_{reuse}) * W_{new-eq} * \epsilon_{fabr,rec} \quad (8.15)$$

$\epsilon_{fabr,new}$	Fabrication costs new steel sections
$\%_{reuse}$	Reuse percentage connections
W_{new-eq}	New steel equivalent weight of the reclaimed sections
$\epsilon_{fabr,rec}$	Fabrication costs reclaimed steel sections

In-line with the comment of Obdam in chapter 6, the reclaimed steel fabrication costs are calculated with the new steel equivalent weight. The amount of material and type of activities do not differ significantly when a slightly bigger cross-section is used. The activities take longer, which is included in the fabrication costs per kilogram for reclaimed steel. Another important factor to the costs of re-fabrication is conservation system that is present on the reclaimed steel elements. If this paint is toxic, extra care is needed when the elements are cleaned. NTA-8713 specifies that elements need to be cleaned locally. Using the findings in section 6.3.3, the costs for local cleaning are multiplied with a factor 5 if toxic conservation systems are present.

8.7.7. Assembly

Different sources indicate that construction does not differentiate between new and reclaimed steel. It is possible that sections in the reclaimed steel design alternative weigh more but the amount of elements stays the same. IGG uses a key-figure of €0.90 per kilogram of steel for a new steel building. The reclaimed steel design does not differentiate in terms of building geometry. The profiles might be heavier in some places but this will not affect the assembly process too much. It is assumed that the assembly costs for the reclaimed steel alternatives is equal to the new steel office building. The key-figure and assumption result in the following equations for assembly costs.

$$C_{assembly,new} = W_{new} * \epsilon_{assembly} \quad (8.16)$$

$$C_{assembly,rec} = C_{assembly,new} \quad (8.17)$$

$\epsilon_{assembly}$	Assembly costs per kg. of new steel structure
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8.7.8. Engineering

Engineering of a new structure is more straightforward than engineering a structure with reclaimed elements. In chapter 5, the difference and challenges in design have been specified. There is more work in coordination and the design needs to be more flexible. The engineering work is more than in a conventional design, especially during the early stages of the process, the engineer will be more involved. In chapter 6, it is mentioned that IGG estimates engineering costs of a simple frame to 15 cents per kilogram of used steel. Designing a reclaimed steel design will result in 15% extra work and an additional 10% if the donor building needs to be recalculated in the material properties validation

process. The latter is not considered in this cost-component as it is included in determining the testing costs. The resulting equations to determine engineering costs are:

$$C_{eng,new} = W_{new} * \epsilon_{eng} \quad (8.18)$$

$$C_{eng,req} = C_{eng,new} * 115\% \quad (8.19)$$

ϵ_{eng}	Engineering costs per kg of new steel structure
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8.7.9. Risk

Building projects are not without risk. Often things are more expensive than they were estimated to be. In cost estimations, assumptions are done to predict the costs of a project. These assumptions express themselves in key-figures and are often established by experience. To capture the uncertainty, a risk component is added to the total estimation of a building project. To account for risk, the following equation can be used.

$$C_{risk} = C_{structure} * (\%_{risk}) \quad (8.20)$$

$\%_{risk}$	Risk percentage for the type of structure
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In chapter 6 a cost estimation from IGG was reviewed and a percentage of 5% was used to take care of uncertainty in new steel structure cost estimations and 15% for reclaimed steel structures. The cost figures for new steel have been established by looking at many projects and therefore they are quite accurate. Hence the low percentage of risk. For reclaimed steel, no such data is available to base the assumptions on for the cost estimation. This justifies the use of a higher risk percentage.

8.7.10. Complete model

By putting all the components together, the total cost model is established. For new steel structures, the costs can be calculated using the following combined formula:

$$C_{structure,new} = C_{newsteel} + C_{blasting+paint} + C_{fabr,new} + C_{assembly,new} + C_{eng,new} + C_{risk} \quad (8.21)$$

It is noticeable that the components of this equation are all on building level. This is mainly due to the fact that all key-figures used are based on the complete structure. The equation can be directly tied to method 1 discussed in chapter 6. This way of costing for new steel structures is based on experience. For a basic structure like this it is quite accurate. Adding all key-figures up together results in a steel structure price of €2.90 per kilogram. Bouwen met Staal (Bouwen met Staal, 2013) has released similar cost estimates for office buildings for three storeys in 2013. The costs are estimated to be €47 per square meter accounting for around 23 kilograms of steel per square meter. This translates to €2.05 per kilogram of steel. When using the building costs indicator from CBS for 2013 and 2023 (CBS, 2023), this figure of Bouwen met Staal would amount to €2.95 in today's economy.

For reclaimed steel the following equation can be created when all components are added up:

$$C_{structure,rec} = C_{newsteel} + C_{reclaimedsteel} + C_{testing} + C_{storage} + C_{blasting+paint} + C_{fabr,rec} + C_{assembly,rec} + C_{eng,rec} + C_{risk} \quad (8.22)$$

Where i is the number of the donor elements in the reclaimed steel design alternatives (list of elements with a length of n). In this case, element scale costing also plays a role in the cost assessment. The testing and storage costs are dependent on the source of the reclaimed elements. Some components are also dependent on the new steel design ($C_{assembly,new}$ and $C_{eng,new}$). Both cost estimation equations 8.21 and 8.22 will be embedded in the python code that performs the generation of the new and reclaimed steel designs. This code is included in appendix A.

8.8. Environmental impact model

The environmental impact assessment of the new and reclaimed steel buildings will be based on three environmental product declarations:

- New steel
- Reclaimed steel
- Reclaimed steel cut-off waste

The functional unit for each of these declarations is kilogram. The basis for these declarations are the EPD's provided by Bouwen met Staal which are discussed in chapter 7.

8.8.1. Scope of the environmental impact model

The environmental impact model will quantify the impact of a steel structure with a certain amount of new steel, reclaimed steel and cut-off waste.

The life-cycle analysis will be based on the Eurocode procedures. To quantify the environmental impact of each office building alternative, the Environment Cost Indicator (ECI) and Paris Proof Indicator (PPI) will be calculated. The ECI value is legally used to determine the environmental performance of a building (MPG). The life-cycle assessment for this indicator will consist of life-cycle stages A up to and including D.

The PPI is an additional factor to show the direct environmental impact of building the steel structure. For this indicator only life-cycle stage A is included as these describe the short-term impact.

8.8.2. Impact of new steel

The EPD from Bouwen met Staal is accepted in ECI evaluation of building structures in the Netherlands. This declaration will be used to quantify the environmental impact in Steel-IT. The functional unit contains one kilogram of steel that is produced in the Netherlands and used in construction in the Netherlands. It includes all life-cycle modules. The assumptions that are made in this EPD are:

- Transport distance to the construction site: specified by user in Steel-IT.
- Assembly of one ton of steel require 0.66 hours of crane use (50% electric).
- Disassembly requires the same crane use as assembly.
- 16% of the steel is reused at the end-of-life scenario, the rest is recycled.
- For reuse and recycling, the same processes are accounted. This is a conservative approach.
- In module D, reuse omits the production process A1-A3 and 50% of weld-activities and energy consumption in fabrication.

Transport distances can be specified in more detail. The distance from the steelbuilder to the construction site is often known. The Bouwen met Staal EPD uses a distance of 150 for module A2. The value used in the EPD is considered a good standard value for the Netherlands. The same EPD states that assembly and disassembly requires the same amount of work (and thus emissions). This assumption is supported by Hendriks from Bnext and Passchier from cost-engineers IGG. The EPD is accepted by the national database in the Netherlands. Table 8.9 displays the impact across the life-cycle stages for the ECI and PPI indicator.

	description	ECI [€]	GWP [kg CO ₂ -eq]
A1 - A3	Production, transport and manufacturing	124.310	1120
A4	Transport to site	0	0
A5	Assembly	7.711	80.7
B	Use stage	0	0
C	deconstruction, transport, waste process	11.300	80.7
D	reuse, recycling and landfill	-22.872	-219

Table 8.9: Environmental impact for new heavy construction steel per 1000 kg.

The A4 and C2 stage, transport to the building-site and deconstruction-site to end-of-life destination, is assumed to be 0. In chapter 7 it was proven that the effect of transport can not be neglected. To

determine the impact of this stage, the user will have to specify the distance from the steelbuilder to the building site. For the transport distance in C2, 150 kilometers is assumed for the Netherlands. An ECI value for truck transport from the TU Delft database is used to quantify the impact. This value comes down to €0.02 per ton per kilometer or 0.13 kg CO₂-eq per ton per kilometer. The next set of equations are used to determine the ECI value and Paris Proof indicator for new steel sections in the design.

$$ECI_{steel,new} = kg_{steel,new} * (\epsilon_{ECI,A-D} + \frac{\epsilon_{0.02}}{1000} * (D_{mod-site} + 150)) \quad (8.23)$$

$$PPI_{steel,new} = kg_{steel,new} * (GWP_{rec,A1-A5} + \frac{0.13}{1000} * D_{mod-site}) \quad (8.24)$$

8.8.3. Impact of reclaimed steel

The same institution that published the heavy structural steel EPD, also developed an EPD for reclaimed structural steel. The declaration is accepted in LCA assessment of building structures in the Netherlands and the quantitative data will be used as basis in environmental impact model used in Steel-IT. The following assumptions are made in this EPD:

- Reclaimed steel is introduced into the new life-cycle 'free of burden'.
- 10% of the 'new' element will be new steel to account for connections.
- Weld activities and energy consumption is reduced by 50% due to existing details.
- For assembly and disassembly, the same assumptions have been made as in the new steel EPD.
- The end-of-life scenario is identical to the new steel EPD with 16% reuse at the end-of-life.

As the reclaimed steel is reintroduced free of impact in the production stage, the environmental impact is significantly lower than new steel. The most dominant factor in the emissions in stage A1 to A3 is the amount of new steel added and emissions during re-fabrication of the reclaimed elements. In the EPD it is assumed that 50% of the existing connections are re-utilized in the new structure. This assumption is not always correct. Sometimes, no connections can be reused and then the impact will be bigger. The other way around, with more reuse the emissions are lower as no new steel and re-fabrication is needed. Table 8.10 shows the values used in the EPD from Bouwen met Staal.

Life-cycle stage	description	ECI [€]	GWP [kg CO ₂ -eq]
A1 - A3	Production, transport and manufacturing	21.503	198
A4	Transport to site	0	0
A5	Assembly	7.711	67.8
B	Use stage	0	0
C	deconstruction, transport, waste process	11.300	80.7
D	reuse, recycling and landfill	-2.208	-17.1

Table 8.10: Environmental impact for reclaimed heavy construction steel per 1000 kg.

The same methods to determine the A4 and C2 transportation emissions are used for the complete impact of the reclaimed steel sections in a design. To account for the amount of connections that can be reused, the life-cycle stage A1-A3 impact will be scaled accordingly. The basis of this scaling is done on the assumption that for 50% reuse of connections, 10% material is added and 50% of the work is saved. The formulation of the impact assessment for the ECI-value and Paris Proof Indicator for reclaimed steel is displayed in equation 8.25 and 8.26.

$$ECI_{steel,rec} = kg_{steel,rec} * (\epsilon_{ECI,A1-A3} * 2 * (1 - \%_{reuse}) + \epsilon_{ECI,A5-D} + \frac{\epsilon_{0.02}}{1000} * (D_{mod-site} + 150)) \quad (8.25)$$

$$PPI_{steel,rec} = kg_{steel,rec} * (GWP_{rec,A1-A3} * 2 * (1 - \%_{reuse}) + GWP_{rec,A5} + \frac{0.13}{1000} * D_{mod-site}) \quad (8.26)$$

8.8.4. Impact of cut-off waste

Often, reclaimed steel sections that are used in the design are too long. The excess is regarded as waste and does contribute to the emissions in the production stages A1-A3 as no new steel is added and no re-fabrication is required. The emissions resulting from recycling and land-filling of these elements are used to quantify this impact together with extra transport for module C2. It is considered that these emissions are the same as the module C emissions of new and reclaimed steel EPD from Bouwen met Staal. The steel itself is free of burden in terms of production. No impact for modifications is allocated to the cut-off waste as they will not go through the fabrication process. The results used to determine the impact of cut-off waste are based on the values from the reclaimed steel EPD from Bouwen met Staal from table 8.10. The resulting values for all life-stages is summarized in the table below.

Life-cycle stage	description	ECI [€]	GWP [kg CO ₂ -eq]
A1 - A3	Production, transport and manufacturing	0	0
A4	Transport to site	0	0
A5	Assembly	0	0
B	Use stage	0	0
C	deconstruction, transport, waste process	3.589	12.9
D	reuse, recycling and landfill	0	0

Table 8.11: Environmental impact for reclaimed steel cut-off waste per 1000 kg.

The impact in module C is based on emissions from stages C2 - C4. C1, deconstruction is excluded as the waste does not have to be deconstructed. The transportation impact on C2 is calculated using the same key-figures as before. No positive effect of module D have been credited for the cut-off waste as these pieces are small and not use-able. The resulting equations are:

$$ECI_{steel,waste} = kg_{steel,waste} * (ECI_{rec,C2-C4} + \frac{€0.02}{1000} * 150) \quad (8.27)$$

$$PPI_{steel,waste} = kg_{steel,waste} * (GWP_{rec,C2-C4} + \frac{0.13}{1000} * 150) \quad (8.28)$$

8.8.5. Complete impact calculation

The designs generated by the algorithm consist of a combination of new and reclaimed steel. The algorithm that assigns reclaimed steel elements generates the cut-off waste. To determine the combined total impact of a hybrid structure, the components need to be summed up.

$$ECI_{structure} = ECI_{steel,new} + ECI_{steel,rec} + ECI_{steel,waste} \quad (8.29)$$

$$PPI_{structure} = PPI_{steel,new} + PPI_{steel,rec} + PPI_{steel,waste} \quad (8.30)$$

9

Steel-IT: the tool

This chapter will give an elaborate description of Steel-IT. First, the choice of software packages to implement the framework and other functionality in Steel-IT will be elaborated. Secondly, the different components of Steel-IT will be discussed by giving a demo. For this demo, a case study will be used and will result in the first results of the framework discussed above.

9.1. Use of software packages

Figure 8.1 displays the steps the user will go through when using Steel-IT. To be able to facilitate these steps, several software packages will be used to develop the processes behind the different steps in the framework. Steel-IT will be built up out of three environments under which several processes and steps can be allocated. These three environments and the elements that will be included in them will be:

1. Application environment
 - Specification of user input
 - Comparison of design alternatives throughout the iterative process
2. Design environment
 - Creating of the office-designs by the user
3. Scripting environment
 - Structural analysis of the user designs
 - Dimensioning of the new design and reclaimed steel alternatives.
 - Calculation of costs and environmental impact for both design variants.

Most of these processes/steps in the environments have been described in chapter 8. To accommodate all the functions in Steel-IT, multiple software-packages will need to be used. This section will describe and elaborate on the choice of the software that will be used.

9.1.1. Application environment

The application environment will be the place where input and output of the algorithms and models will be gathered and visualised. There are several ways to create a user-interface. This thesis will look at two types: application development software and interfaces for parametric 3D-CAD software. The first focuses on creating a new application from scratch and the second on integrating a user interface in other software.

Application development software

There are several software packages that can be used to create applications. Some examples are Microsoft Visual Studios and Xcode. This type of software will allow for an application design that can communicate with other applications and write and read files. It allows visualisation, file selection and more. There is a big community around these software packages that help solve errors and good documentation on the programming languages and functionality is available.

User interface plug-in for parametric 3D-CAD software

This type is more an extension to an existing software packages. As part of Steel-IT will use a parametric design environment to support the user in creating an office building design, integrating the user interface into this environment can reduce overall complexity. An example of such an extension is Human UI for grasshopper. It can create a window where input and visualisations can be collected in one organised window.

The table below gives the disadvantages and advantages of both software-packages for its intended use in Steel-IT.

Environment	Disadvantages	Advantages
Application development software	No personal experience in application development or the programming languages.	<p>Good compatibility with other software.</p> <p>Good documentation on functionality and online community.</p> <p>Large amount of functions and options.</p>
User interface plug-in for 3D-CAD software	<p>No personal experience in these types of plug-ins.</p> <p>Limited amount of functions and options.</p>	<p>No additional software needed for the user interface.</p> <p>Good documentation on functionality and online community.</p>

Figure 9.1: Advantages and disadvantage of using application development software or integrate UI plug-ins for 3D-CAD software.

9.1.2. Design environment

The iterative process requires that the user creates a design of an office building for the analysis. This input design will need to be changed and is preferable set up in a parametric environment to accommodate this flexibility. It is preferred to work in an environment where the design can be visualised directly. Common used 3D-CAD software packages that support parametric input are Autodesk Revit and Rhino. Both packages have add-ons that allow parametric design: Dynamo for Revit and grasshopper for Rhino.

Rhino - grasshopper

is a plug-in for Rhinoceros 3D software. It uses visual programming language which consists of components that are connected with wires to create geometry and manage data which is directly viewed in the Rhinoceros 3D view port. There are a lot of packages available to extend the functionality of grasshopper. There are add-ons to perform structural analysis, optimisations and that enable linking grasshopper to other applications like Microsoft Excel.

Revit - Dynamo

Dynamo for Revit is quite comparable to what grasshopper is to Rhinosceros 3D. Revit is used more in Building Information Modelling and dynamo provides parametric input using a similar type of visual programming language. A wide variety of packages is available to extend the dynamo functionality and is also able to connect write to and read from excel files.

The table below gives the disadvantages and advantages of both software-packages for its intended use.

Environment	Disadvantages	Advantages
Revit + Dynamo	It is challenging to stay organised in the visual programming language and make changes without redoing the whole script.	<p>The coding language has a low entry level for new users.</p> <p>A lot of add-ons are available to extend its functionality</p> <p>Personal experience / practice with grasshopper and Rhino</p> <p>Rendering geometry from parametric input is quick</p>
Rhino + Grasshopper	<p>It is challenging to stay organised in the visual programming language and make changes without redoing the whole script.</p> <p>Rendering geometry from parametric input is slow</p> <p>No personal experience / practice with dynamo</p>	<p>Revit is used in most engineering firms for BIM</p> <p>Personal experience / practice with Revit</p>

Figure 9.2: Advantages and disadvantage of dynamo and grasshopper.

9.1.3. Scripting environment

This is the environment where most of the elements in the framework will be implemented. Steel-IT will use a python script for the structural analyses, the generations of the new steel design and reclaimed steel design alternatives and implementation of cost and environmental impact models. This script can be written in any coding language but personal experience of the author resulted in the use of the python programming language.

9.1.4. Conclusion

Finally, the best software-packages are chosen to develop the software. For the three environments the choice will be:

1. Application environment: Microsoft Visual Studio (Microsoft, 2022).
2. Design environment: Rhino with grasshopper (Robert McNeel and Associates, 2023).
3. Scripting environment: Python (Python Software Foundation, n.d.).

The scripting environment is chosen based on personal skill and preference. Python is the language of choice. The design environment will be Rhino with grasshopper. The visualisation is quicker which makes Steel-IT easier to use. Rhino is used less in building information modelling but this is not considered a big problem. As Steel-IT will be used in early design stages such a model will not be established yet. Its aim is to steer the design decisions, not to create a starting point for the building information model. The application will be developed in Microsoft Visual Studio as it has a big amount of functions and options. It also has better compatibility with python. Implementing python within grasshopper or dynamo can be difficult as not all desired python packages can be used. Figure 9.3 shows the role of the selected software packages.

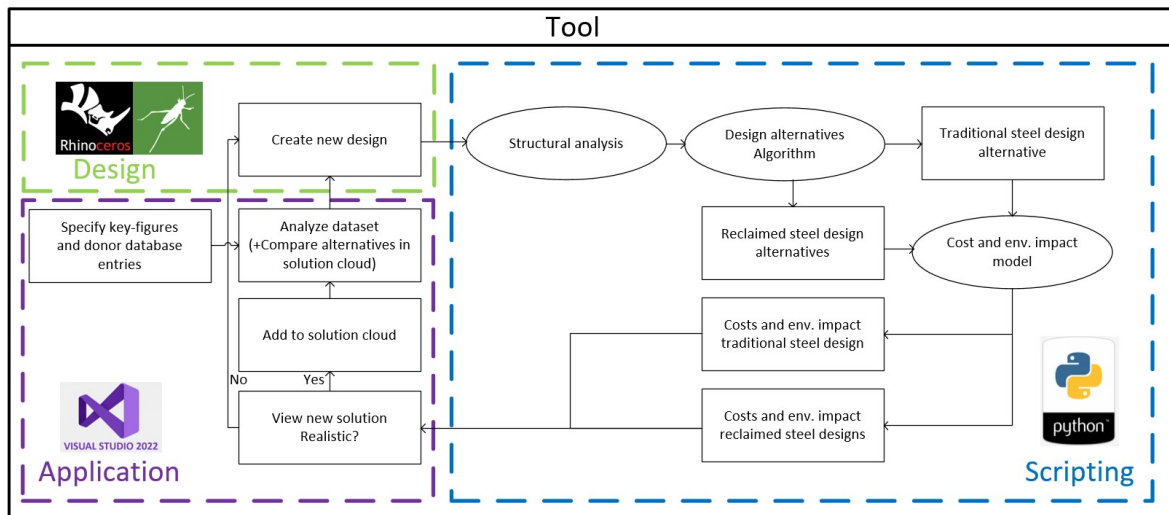


Figure 9.3: Software use and structure of Steel-IT.

9.2. Steel-IT demo: case study

This section will describe how the defined algorithm, cost and impact models and software come together in the final product of this Thesis: the tool Steel-IT. During the demonstration a case study in which a 1000 m² office building is designed will be used. The demo will help to demonstrate the functionality and lay-out of Steel-IT as well as generating results. The demo will follow the steps in the order that is illustrated in figure 9.3.

9.2.1. Case description

The goal of this case is to design an office with the following characteristics:

- a floor-plan of approximately 1000 m².
- 3 storeys with a free floor height of 3.2 meters
- a concrete hollow-core slab flooring system.

The donor elements that can be used in this case is a collection from the "Brede Buurtschool" in The Hague. The structure was engineering by Imd raadgevende ingenieurs and constructed in 2010. The used steel grade is S235. For the purpose of this demo it is assumed that the yield strength is not proven by documentation. Figure 9.4 shows a 3D-view of the steel structure.

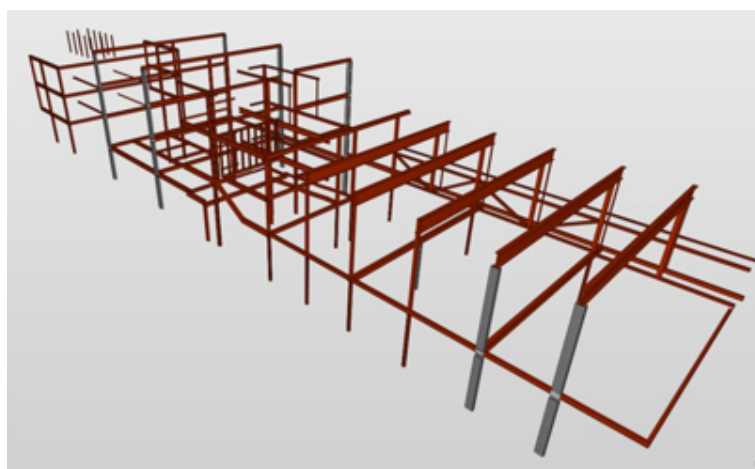


Figure 9.4: 3D view of the steel structure and material information.

9.2.2. Key-figures and database creation

The first step is to specify the key-figures for the cost model and the database of reclaimed steel elements that are used by the algorithm to create the reclaimed steel design alternative. Two types of key-figures are distinguished: required and advanced key-figures. The required key-figures are not pre-defined as they are time dependent and easy to determine. The advanced key-figures are also time dependent but are harder to determine in an early design stage. These values are predefined but can be changed by the user. Figure 9.5 shows the first window of the application with the key-figures filled out in the top section. The key-figures are applicable to the first half of 2023 and result from the literature review and interviews in chapters 5 and 6 of this thesis. For the 'new steel price' and 'steel scrap price', Deltastaal has been contacted to provide up-to-date figures (C. Breekpot, personal communication, July 31 2023). The new steel price contains €0.90/kg and the scrap price is €0.30/kg.

Figure 9.5: The first window of Steel-IT after filling in the key-figures and Brede Buurtschool database.

The bottom half of figure 9.5 is the database creator. With this section, excel-files from donor buildings or stock-piles at reclaimed steel traders can be combined into one. The source, yield strength and validation, steel manufacturing year and presence of toxic conservation systems can be specified by the user. For each entry, an excel-file with elements is required. Using this information, the database is created as described in section 8.2. The excel-file for the Brede Buurtschool and resulting database is included in appendix 7 D.

9.2.3. Database visualisation and office design

The key-figures and database are specified. In the next window of Steel-IT, the design alternatives are created and the resulting costs and impact figures are presented. The first design can now be evaluated with the algorithm. To begin, the created database can be viewed in a graph. This graph

shows the length, cross-sectional height and occurrence in the database. The visualisation is shown in the figure below and is included in the top left in Steel-IT, see figure 9.8.

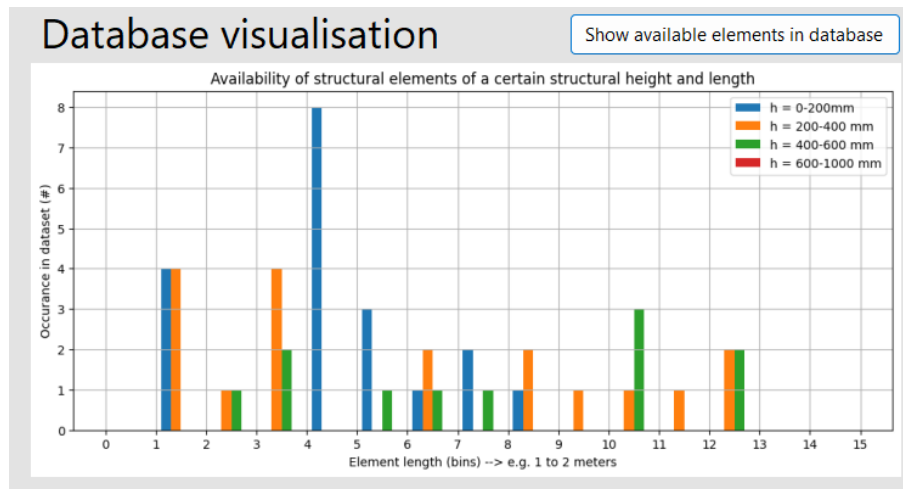


Figure 9.6: Database visualisation for the "Brede Buurtschool" donor elements.

Next, design parameters like grid sizes, storey height and the amount of storeys need to be specified. To make sure the office building fits the scope of the research and algorithm, the design options are limited using a parametric script in rhino-grasshopper. The first design, is a structural lay-out with big 10.8 meter floor spans to create an flexible floor plan. The frames have a column to column distance of 3.6 meters. The storey height is set to the demands of free floor height mentioned before accounting for the structural height. The chosen floor system is the Kerto-Ripa wooden hollow core slab. Figure 9.7 shows the sliders in the grasshopper script than can be used to change the geometry and the resulting steel structure for the parameters mentioned above.

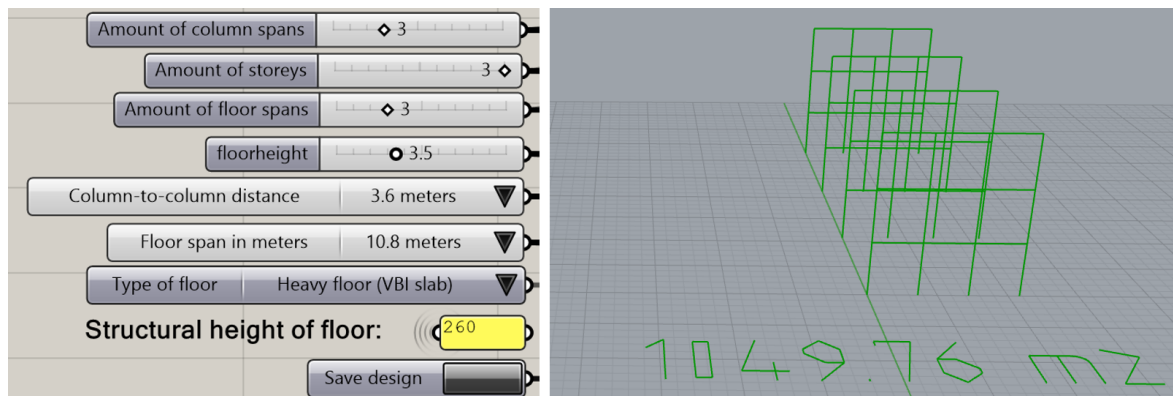


Figure 9.7: Design parameters and resulting office design in Rhino.

The key-figures, database and new office design are specified. Now the new and reclaimed steel design alternatives can be generated using the algorithm. This is done in the top right of the application (figure 9.8). Some algorithm settings need to be defined. The multiplication factor for the maximum allowed weight for the donor elements and the minimum useful cut-off waste length need to be specified. The multiplication factor is set at 1.5. The minimum useful cut-off length is set at 3 meters. The algorithm and cost/impact models can now be executed by pressing the "Steel-IT.." button.

9.2.4. Results and design iterations

After running the algorithm, the overall results are displayed in the application. A complete overview of this window is included in figure 9.8.

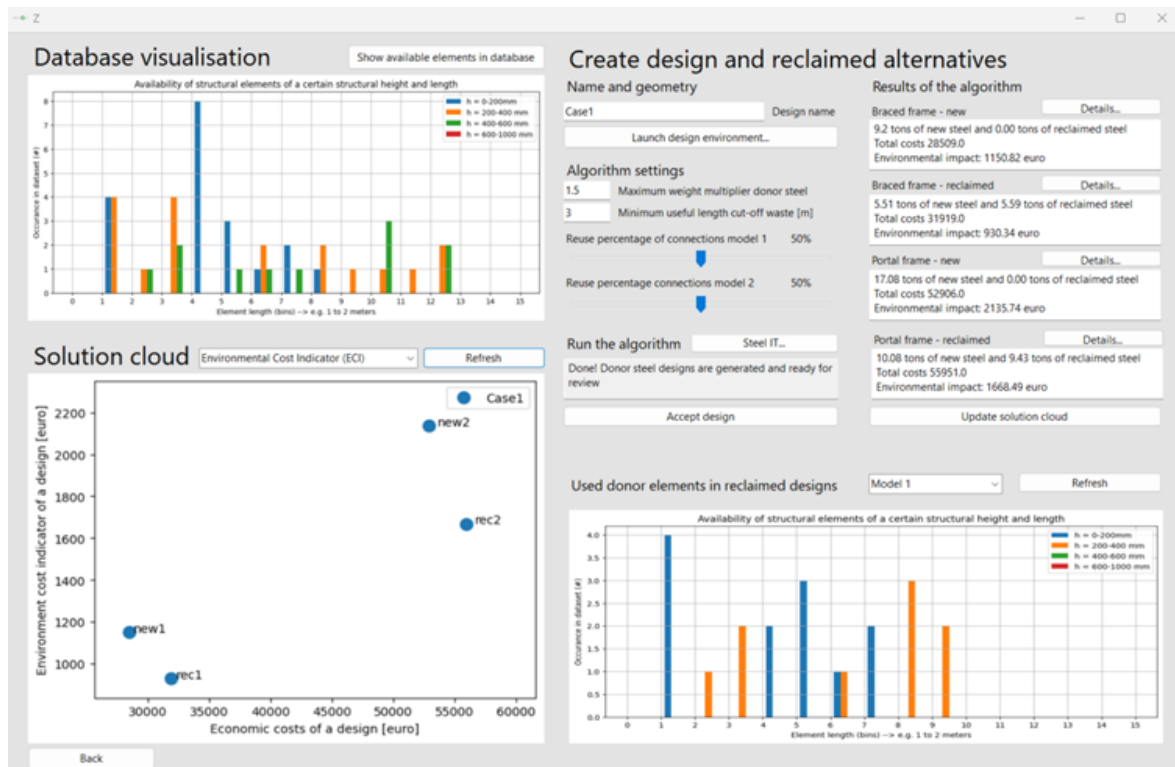


Figure 9.8: The second window in Steel-IT after performing one design iteration.

On the top right, the algorithm settings and results for this design iteration are shown. The text boxes display the amount of new and reclaimed steel used, the costs and environmental impact for each design alternative. For each alternative, a more detailed cost and impact breakdown can be viewed by clicking "Details". On the bottom right, a graph can be viewed which indicated which elements from the database are used in the design. The graph is constructed using the same principles as the database visualisation graph of figure 9.6. The bottom left contains a graph that places the design alternatives based on their costs and impact. The graph can be updated each time a new design is created. This solution cloud can give a direct comparison between the different designs that are evaluated. The same graph can be viewed where the ECI-values on the y-axis is changed for embodied carbon values for each design.

As seen in figure 9.8, the braced frame is not able to include a lot of reclaimed steel and does thus not create a big decrease in environmental impact. To find a design that fits the database better, the geometry is altered. The table below gives an overview of the parameters that have been altered in each of these iterations.

	floor span [m]	column-distance [m]	h_{floor} [m]	floor spans	column spans	W_{mult}
Case1	10.8	3.6	3.7	3	3	1.5
Case2	7.2	5.4	3.5	3	3	1.5
Case3	5.4	7.2	3.5	3	3	1.5
Case4	10.8	5.4	3.7	3	2	1.5

Table 9.1: The design parameters for each design iteration.

9.2.5. Case results and review

The result of valuating the algorithm and cost/impact models for the case in table 9.1, is a solution cloud with the four cases. Figure 9.9 shows the cost/impact-graphs for both the ECI-value and embodied carbon impact indicators. A direct conclusion is that these two graphs show the same trends in terms of impact in relation to costs.

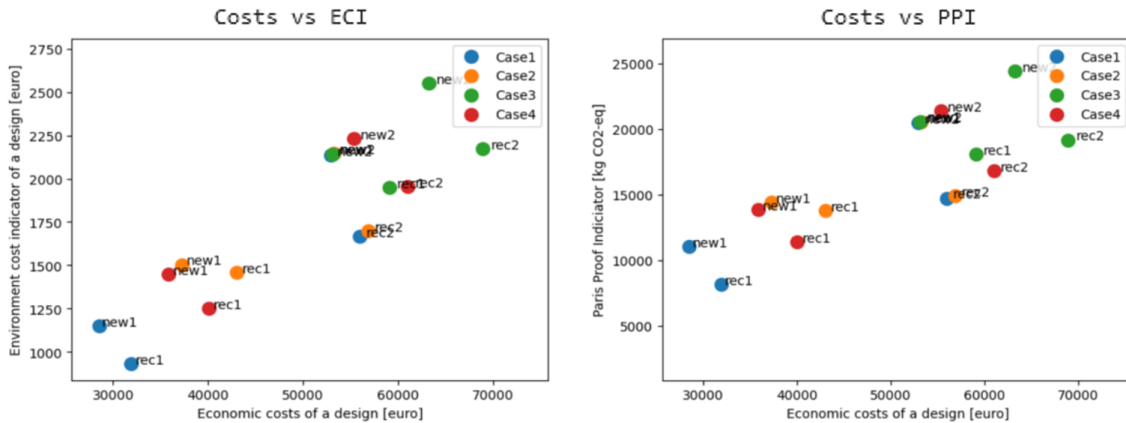


Figure 9.9: Resulting comparison graph of four design iterations for costs versus ECI and PPI.

For both models it can be concluded that the database fits best for the design of case 1. This design has a floor span of 10.8 meters and short column-to-column distances. The database has quite some shorter elements and smaller cross-sections. It can be seen that for both models, the new steel design is still the cheapest solution. The reclaimed steel designs do show a significant drop in environmental impact of around 25% for minimal increase in costs. Higher reductions in impact are possible if the amount of reclaimed steel is increased by either using a bigger or better fitting data-set of donor elements or by increasing the weight multiplication factor. It is likely that the costs will increase if the latter is done as the weight of the structure and thus costs will increase. In figure 9.10, the tons of new and reclaimed steel used in the braced and portal frames for all the cases and are shown.

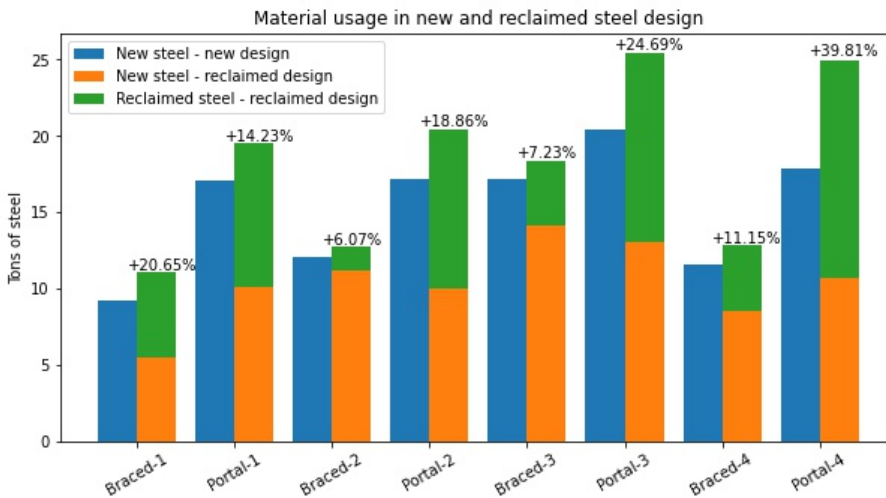


Figure 9.10: Material usage in generated designs for case 1 to 4.

All the reclaimed steel designs have a higher combined weight. This seems logical as the algorithm allows for heavier sections to be applied. As seen in table 9.1 the allowed extra weight is 50%. In practice, this percentage is not achieved. It can be seen that the braced frame often has a more competitive weight compared to the new steel equivalent.

9.2.6. Cost components

The components that build up the total costs, as described in section 8.7, are visualised in figure 9.11 for case 1 of traced and portal frame.

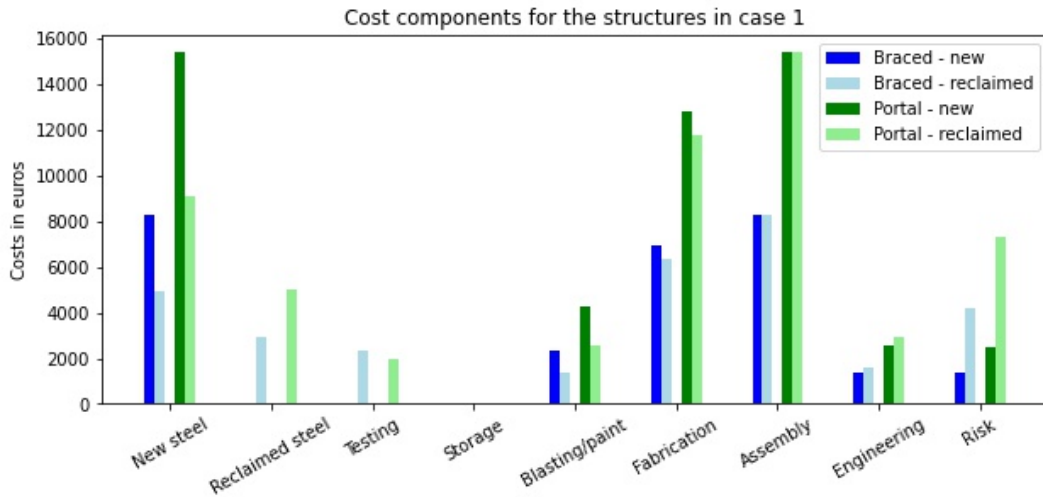


Figure 9.11: Costs component in generated designs for case 1.

In this most competitive case, the total costs are quite close. The braced frame is €3400 and the portal frame is €3000 more expensive in reclaimed steel than their new steel equivalents. The bar plot shows that the reclaimed steel design alternatives have costs for the reclaimed steel and material testing that are not occurring in new steel design. The combined costs for steel material is relatively close to the new steel equivalent. The reclaimed steel designs use more material in total but the reclaimed steel is cheaper. Engineering and risk are a bit higher than for the new steel design.

Blasting and paint is cheaper for the reclaimed steel design alternatives as they contain less new steel sections. The donor steel is not coated as the old conservation systems are reused. The risk component is bigger due to reasons discussed in the literature review and interview with IGG cost-engineers. The storage costs are 0 for all variants. This is due to the fact that the donor source is an existing building. If this same stockpile was sourced from a steel trader, extra costs for storage should be taken into account. For the braced frame this would result in an additional €1025 and for the portal frame an extra €2525. Especially for the portal frame, the extra costs have a big effect on the total costs (~5% extra).

The connection reuse percentage has been set at 50% as defined by the EPD discussed in section 7. This percentage also has impact on the costs and impact of the structure. Figure 9.12 shows the impact of this percentage on the costs of the braced and portal frame designs. It can be seen that it is possible to create a cheaper reclaimed steel structure when high percentages of reuse are applicable for the portal frame.

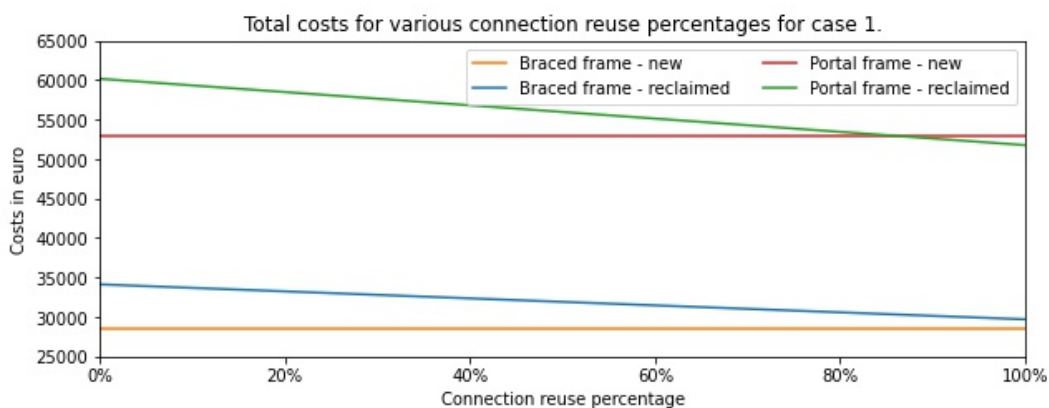


Figure 9.12: Break-even point of the new and reclaimed steel design in relation to connection reuse.

9.2.7. Impact components

A similar graph to figure 9.11 shows the different components of the environmental impact for the same cases in figure 9.13.

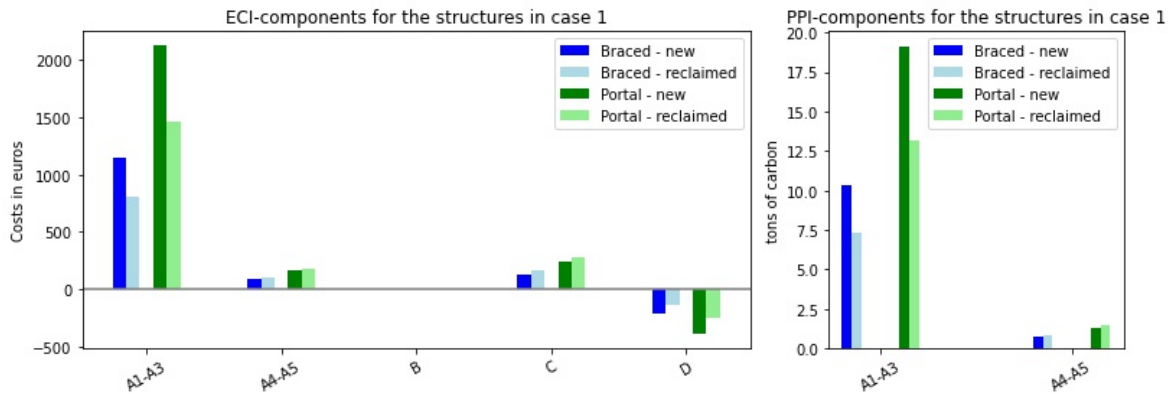


Figure 9.13: The components of the ECI and PPI impact assessment for case 1.

The biggest advantage for the reclaimed steel designs is in the production stages A1-A3. For stages A4-A5 and stage C, the reclaimed steel alternatives make more impact. This is due to the extra weight of these structures. The beyond life-cycle benefits the reverse effect occurs. Due to the way the EPD's are set-up, the omitted impact is based on the products own production stage impact. Therefore, the life-cycle benefits in module D are lower for the reclaimed steel designs. For the embodied carbon, or Paris Proof Indicator (PPI) in this research, the modules C and D are not relevant.

9.2.8. Visualisation

The solution of case 1 is visualised in grasshopper. The green section are reclaimed steel elements and red section represent new steel elements. The figure contains one frame per structural configuration. The green elements consist of reclaimed steel and the red elements of new steel.

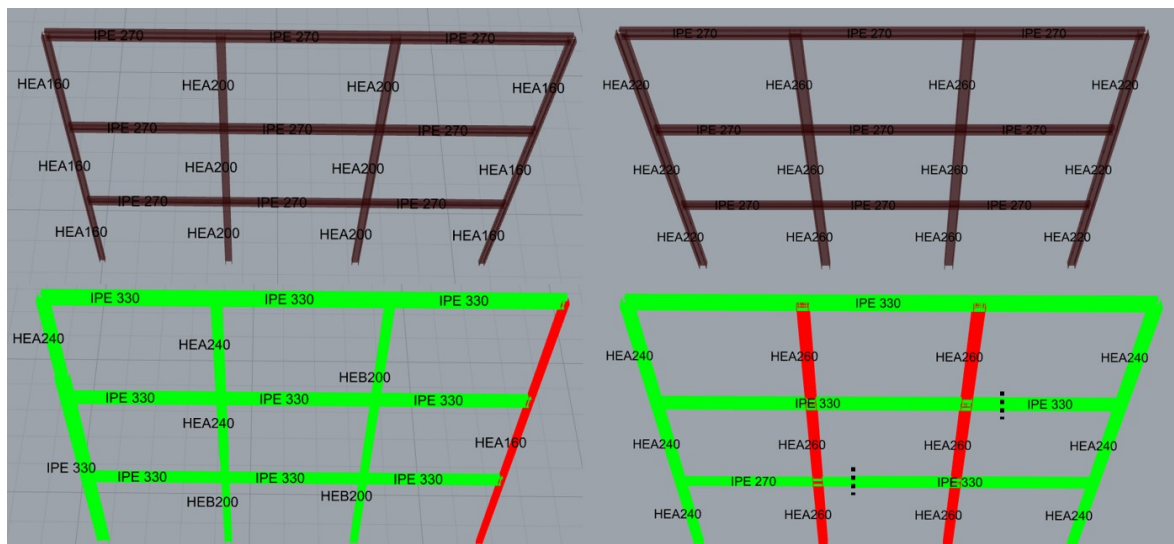


Figure 9.14: New and reclaimed steel use for the designs in case 1.

The top frames represent the new steel structures and the bottom the reclaimed steel alternatives. On the left, the braced frame and on the right the portal frame. The donor elements are all oversized compared to the new steel equivalents. It can be seen that the elements in the braced frame are smaller than the portal frame's elements.

10

Steel-IT: evaluation

In this chapter Steel-IT will be reviewed. This will be done in several ways. First a sensitivity analysis is performed to evaluate the effects of database and design combinations, floor system choice, multiplication factor, the yield strength of the donor steel elements and influence/spread of the assumed cost key-figures on the model outcome.

Next, the influence of different future scenarios is evaluated on the test-case from chapter 9. Centralised material testing, introduction of CO₂-tax and production of green steel all affect the business case of the reclaimed steel design alternative. To conclude this chapter, reviews and comments on my research from (cost-)engineers at IGG and Vic Obdam are included in this chapter.

10.1. Sensitivity analysis

To evaluate the parameters that have influence on the outcomes of Steel-IT, a sensitivity analysis is performed. The effect of changing the assumed values in realistic ranges of uncertainty is analysed. The results of this analysis will reveal which parameters are of high influence. The uncertainty in these parameters needs to be addressed if it is desired to get a better estimation of costs and environmental impact. The analyses performed in this section have been documented thoroughly in appendix E.

10.1.1. Database and office design

The two parameters that have the most influence on costs and impact are the database and office design that the user specifies when using Steel-IT. The relation of available elements in the database of reclaimed elements and the required profiles in the building geometry determines the utilisation of the available donor elements. To illustrate this dependency on the results, 5 designs with the same amount of building area and 5 database have been created using project files at IMd raadgevende ingenieurs. Tables 10.1 and 10.2 includes some information about the databases and designs.

	Tons	Element _{count}	L_{tot} [m]	L_{mean} [m]	G_{mean} [kg/m]	W_{mean} [e6 N/mm ⁴]
DB 1	50.4	58	445	8.0	90.8	2204
DB 2	54.7	78	640	8.2	76.3	1303
DB 3	48.8	73	586	8.0	78.8	1349
DB 4	22.3	45	350	8.0	52.7	738
DB 5	20.5	66	439	6.7	50.0	624.9

Table 10.1: Information about the databases used in the sensitivity analysis.

	floor span [m]	columns-distance [m]	h_{floor} [m]	floor spans	column spans	floors
Design 1	10.8	3.6	4.0	3	3	3
Design 2	7.2	5.4	3.5	3	3	3
Design 3	5.4	7.2	3.5	3	3	3
Design 4	10.8	5.4	3.5	2	3	3
Design 5	10.8	5.4	3.5	3	3	2

Table 10.2: Design parameters that are used in the 5 designs in the sensitivity analysis.

For each database and design combination, the model is evaluated. Appendix E includes the set-up of this analysis as well as a more detailed view of the databases and designs. As highlighted in the figure, each dot in figure 10.1 represent a solution that is created using Steel-IT. All these solutions can be visualised in rhino/grasshopper and breakdowns of the costs and environmental impact are available in Steel-IT itself. For one design, the visualisation and cost breakdown are included in the figure. In appendix E, some solutions are presented in more detail to explain the differences between solutions for this part of the sensitivity analysis.

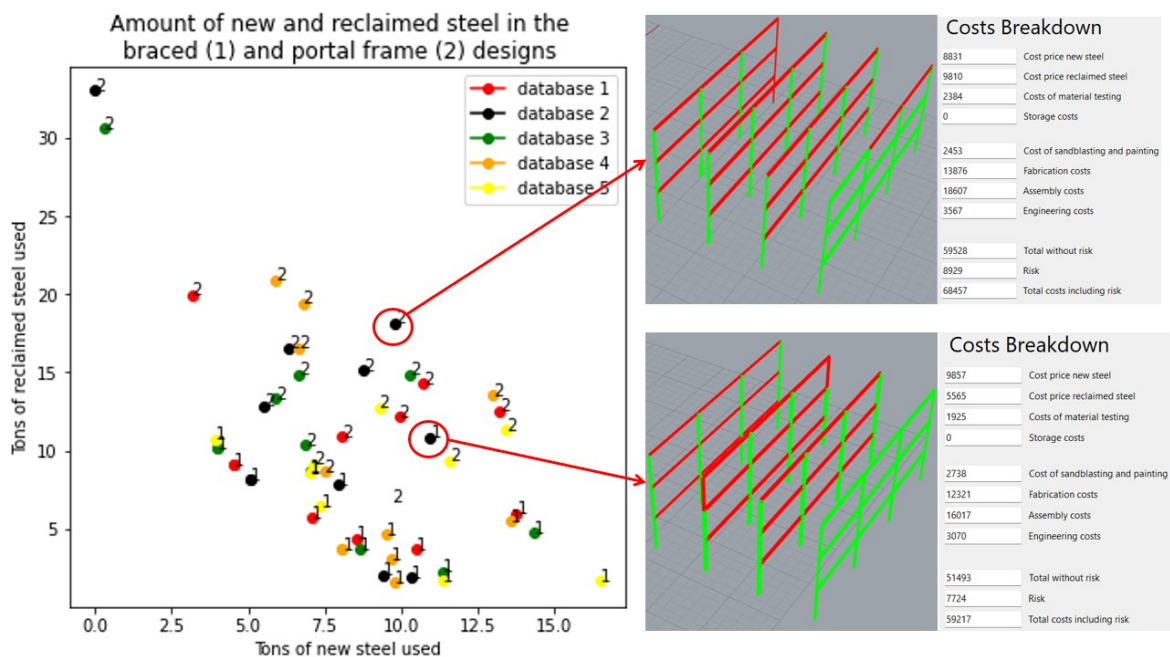


Figure 10.1: New and reclaimed steel usage across 25 design and database combinations.

Figure 10.1 shows the amount of new and reclaimed steel in the 25 model evaluations. Each colour represents a database. For each database/colour, five design are evaluated. The relation between these two tonnages is inversely proportionate. It makes sense that less new steel is needed when more reclaimed steel is used in the design. There is still a big spread in this relation as the amount of reclaimed steel used depends on the database and the design. The fit between the database and the design determines how much reclaimed steel can be used.

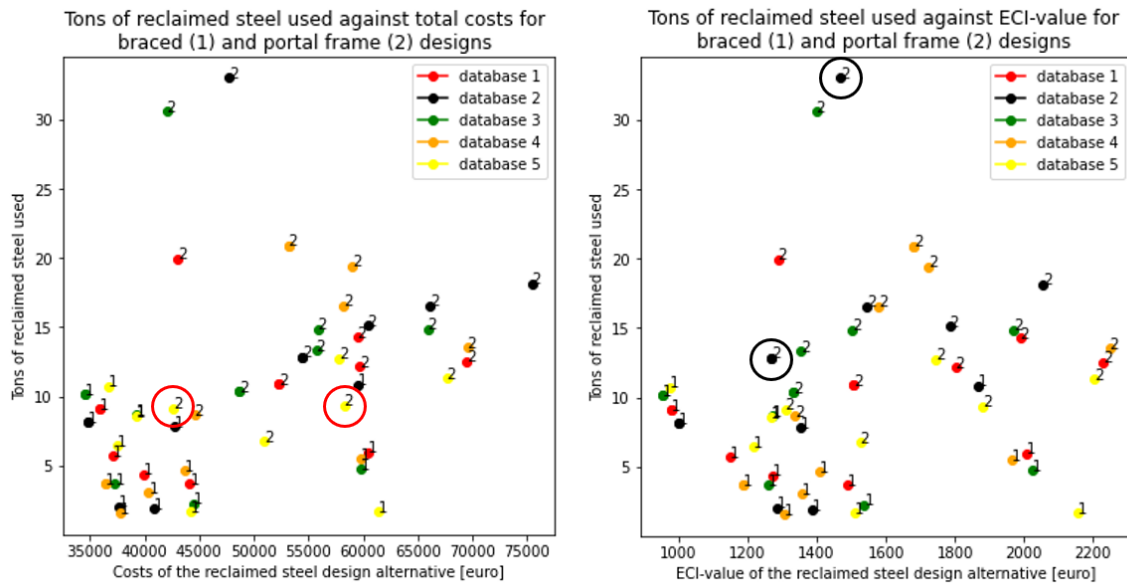


Figure 10.2: Relation between tons of reclaimed steel used and costs or environmental impact across 25 design and database combinations.

Figure 10.2 shows the relation between the amount of reclaimed steel used and the costs and ECI-values of the reclaimed steel designs. As seen there is quite a big spread between databases and different designs. Model one is mostly cheaper but there is less opportunity to reuse the donor steel elements. In the second graph, the portal frame model is more competitive on ECI compared to the competitiveness on costs in the first graph. Between the solutions themselves there are quite some differences. The two solutions on the left graph which are circled in red, include around the same amount of reclaimed steel but differ in costs significantly. This can be explained by looking at the amount of steel used in the design. In appendix E, the total weight of the structure that is represented by the dot in right red circle of figure 10.2 is a lot higher than the other red circled design. As the cost model (partly) depends on weight, the total costs will be higher for the heavier structure.

The two solutions that are circled in black in figure 10.2 use different amount of reclaimed steel. One uses more than twice the amount but scores worse on environmental impact. This can be explained by looking at the efficiency of the utilisation of the donor elements. In appendix E, the two structures are shown. The structure that is 100% reclaimed steel uses the steel less efficiently whereas the other solution has a lot of sections which are identical to the new steel design. Even though there is more reclaimed steel in the top solution, the solution with less reclaimed steel scores better.

The combined result of ECI and costs is presented in figure 10.3. It can be concluded that the result is very dependent on the design and database used. The algorithm developed in this thesis is responsible for generating this relation between input and the costs and impact of the generated structures.

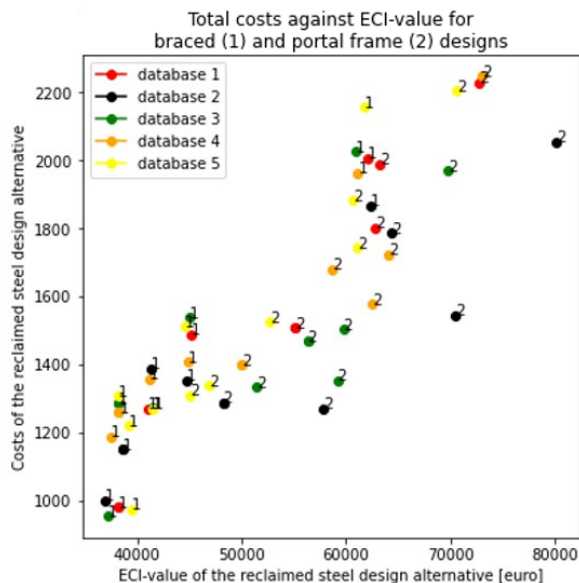


Figure 10.3: Relation between costs and impact across 25 design and database combinations.

Dependent on the preferences of the user, the design and algorithm combination with the best cost and impact trade-off is desired. It is desired to decrease environmental impact while keeping costs to a minimum. In this graph, the solution on the bottom left score best on costs and impact. For both the braced and portal frame alternatives, there are combinations that score significantly better than others. By generating a solution cloud like this, a lot of possible solutions are discovered and the user can choose the preferred solution. What the preferred solution is, depends on the user of Steel-IT and how they value costs and impact in relation to each other. For example, some solution might not be regarded acceptable because of the required grid-sizes. It should be noted that, in the current form of Steel-IT, it takes a lot of time to perform all the model evaluations.

10.1.2. Floor type

In this thesis, two types of flooring system can be selected for the new office design: VBI hollow-core slabs or the Kerto-Ripa wooden equivalent. The wooden floors are lighter than the concrete slabs. This a direct effect on loads and thus required cross-section resistance of the new and donor steel. The analysis from section 10.1.1 has been repeated but for each design, the algorithm has been evaluated for both flooring systems. The box-plots below show the distribution of the effect of the flooring system on the costs and impact of the steel structure. The costs and impact difference between the concrete and wooden floor type is not taken into account.

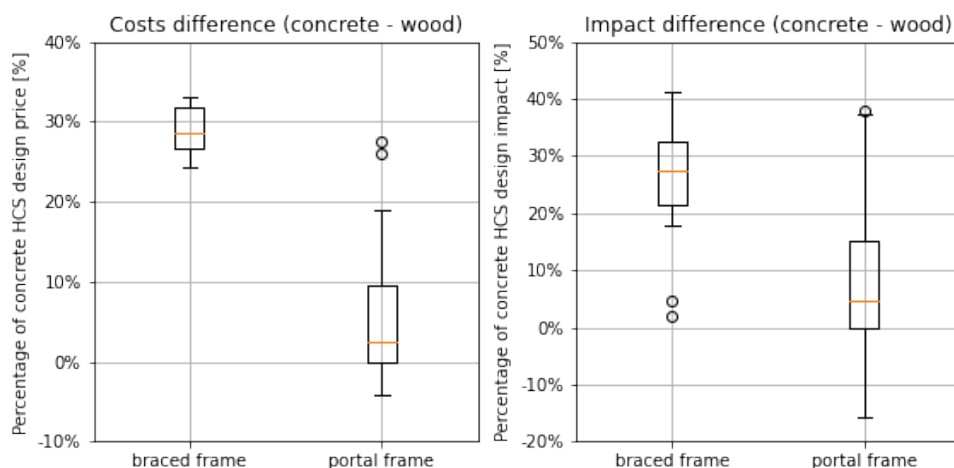


Figure 10.4: The influence of floor choice on costs and environmental impact.

Both costs and impact decrease by choosing for a lighter floor system. The effect is most consistent for the braced frame where a cost decrease of around 30% and an impact decrease of 20 to 40 % can be achieved. The portal frame shows less response to the lighter flooring but a cost and impact decrease of 0 to 10 % can still be achieved. In some instances, an increase in costs and environmental impact can be obtained. The difference in these results can be explained by the dependency on strength for the braced frame and stiffness for the portal frame model. The loads and thus strength requirements are influenced by the floor choice. The design of the brace frame is governed by strength as stability is not provided by the frame. For the portal frame, the stiffness of the elements is often governing.

10.1.3. Model constraints

The model constraints have influence on the donor steel designs that are created in the assignment algorithm and thus also on the costs and environmental impact of the reclaimed steel designs. The weight multiplier describes how many times heavier the reclaimed steel substitute is allowed to be compared to the new steel design. The useful length of cut-off waste has a direct effect on the 'fit' of elements in the building design and the yield strength of the elements influences the unity check and thus application of the elements in the building geometry. To determine the influence and behaviour of these parameters, elementary effect analysis is performed to do an initial screening. This is a method where the solution space of the cost model is explored by varying the parameters one-by-one from different starting points. By calculating the change of the output compared to the change of the input, something can be said over the influence and linearity of the parameter change. The ranges for the three mentioned parameters are indicated in table 10.3. The analysis is performed on two different data-sets. These data-sets and the analysis procedure are described in appendix E.

Parameter	Range
Weight multiplication factor [-]	[1.0, 2.0]
Useful length cut-off waste [m]	[1.0, 4.0]
Yield Strength [MPa]	[200, 355]

Table 10.3: Ranges for the parameters of interest that influence the assignment algorithm.

To be able to analyse and compare the results for the parameters with each other they are normalised to a scale from 0% to 100%. The results of the elementary effect will therefore be the change of costs per percentage of change in the range of that variable. Then the analysis is performed. The procedure, formula's, code and detailed results are documented in Appendix E. Figure 10.5 shows the influence of changing the settings of the algorithm on the costs of the reclaimed steel design alternative. It can be noted that for both the braced and portal frame model, the effect of the weight multiplication factor has a lot of influence on the costs. The influence of this factor differs between the analysed cases. Database 2 for the portal frame model shows a lower influence than the other cases. This influence

is dependent on the amount of reclaimed steel that can be utilised. Database 2 is less suitable for the portal frame design and less reclaimed steel elements can be used. The effect of changing the W_{mult} factor is smaller. The yield strength has a higher influence in the braced frame model for database 1 than for the other cases in the graphs. This phenomena is also caused by the match between the design and donor element database. The minimum useful cut-off waste does not seem to have a lot of influence on the costs. This minimal influence can be explained by the optimisation of placement in the algorithm that creates the design alternatives. As the cut-off length is used to determine the score in the assignment optimisation, cut-off waste is minimised. Changing this cut-off length does therefore not have a big influence on the outcome of the algorithm.

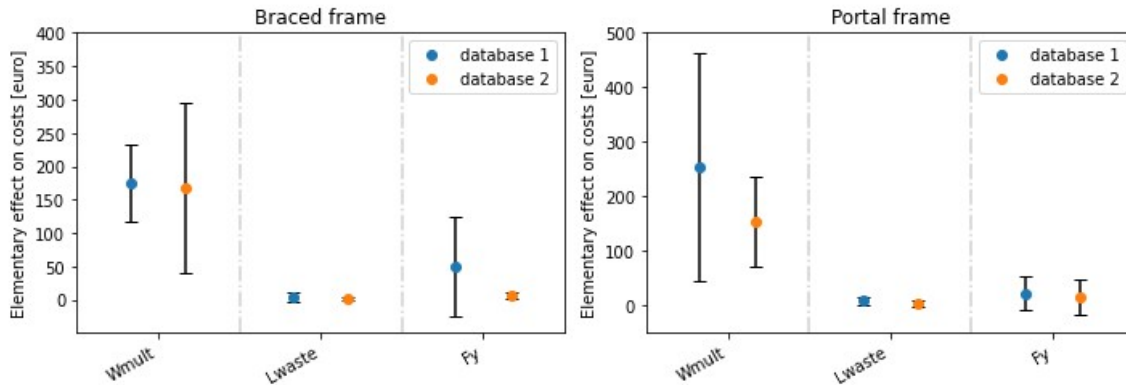


Figure 10.5: The elementary effect of algorithm parameters on costs.

Figure 10.6 shows the effect of the parameters on the ECI-value of the reclaimed steel design. The behaviour is quite similar. Both the weight multiplication factor and the yield strength show a high influence and non-linearity/dependence to the ECI-value of the reclaimed steel design alternatives.

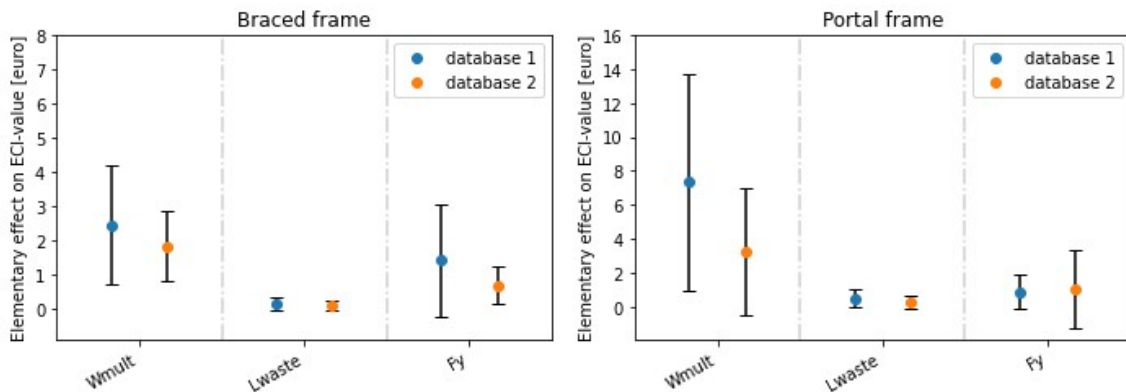


Figure 10.6: The elementary effect of algorithm parameters on environmental impact.

It should be noted that the outcome of the above elementary effect analysis is quite dependent on the design and database which are supplied by the user. This is evident by looking at the difference in elementary effect and deviation from it across the different graphs. The standard deviation to mean elementary effect ratio is also relatively high which indicates a non-linear relation between costs and the weight and yield strength factor. This dependency is shown in the first section of the sensitivity analysis.

Weight multiplication factor

The weight multiplication factor influences the maximum weight of the donor elements which are assigned and thus also costs and impact as these models are mostly based on weight. The algorithm is evaluated with a different multiplication factor for the same two database and one of the designs used before.

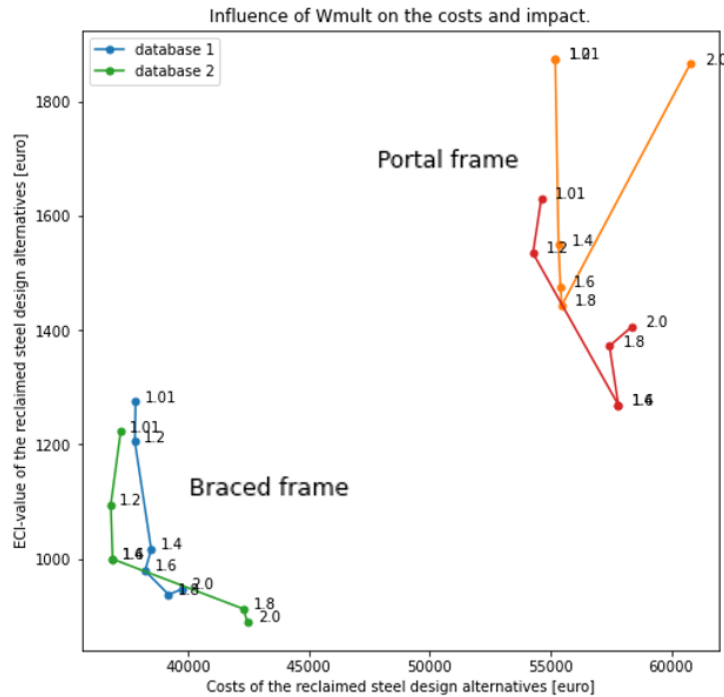


Figure 10.7: Effect of W_{mult} on costs and impact.

For the portal frame model, there seems to be an optimal weight multiplication factor in terms of weight related to costs and environmental impact. It should be noted that this optimum is different for the two data-sets that are analysed. The red-line finds a optimum at a W-mult of 1.8 while the green line shows an optimum at 1.4. The braced frame shows different behaviour. The impact keeps reducing. The rate at which it gets lower does get smaller. For the green line it could be argued whether the reduction in impact is worth the extra costs. This choice is dependent on the preference of the user of Steel-IT.

To generalise the weight factor, these findings would mean that the reclaimed structure will only have sections which are 2 or 3 sizes bigger than the original new steel elements. For a factor of 1.4, a HEA220 could be replaced by a HEA260/IPE400 or smaller. It should be noted that if the weight factor is set to, for example 1.4, it does not mean that the reclaimed steel structure is always 40% heavier than the new structure. Figure 10.8 illustrates how this weight factor compares to the weight multiplication factor in the algorithm for the designs in figure 10.7.

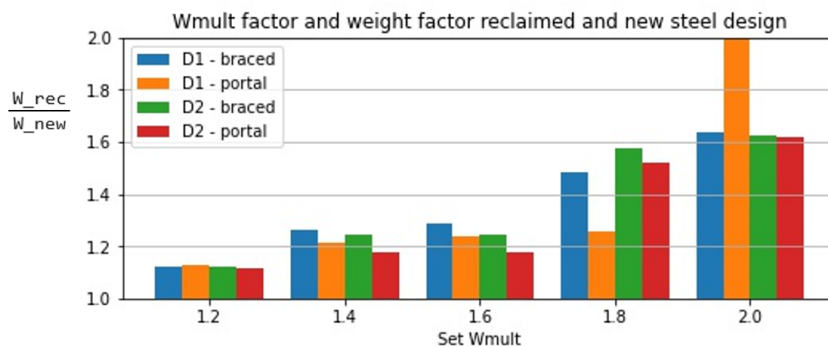


Figure 10.8: The set W_{mult} compared to the weight of the reclaimed and new steel designs.

Yield strength

The yield strength of the elements in the database of donor elements is not a parameter that the user can tweak easily. The yield strength affects the load bearing capacity of the elements and thus the utilisation of them in the office design. A higher steelgrade creates higher capacity for identical cross-sections meaning that some donor elements might be utilised if they are in grade S355 instead of S235. The same analysis as in the section about database and design influence is used to determine the influence of the yield strength on the output of Steel-IT. For each of the 25 design combinations, the algorithm has been evaluated for donor steel yield strength of 200, 235 and 355 mega-pascal. The influence on the reclaimed steel usage, costs and impact have been visualised in the graphs of figure 10.9. The set-up of the analysis is added to appendix E.

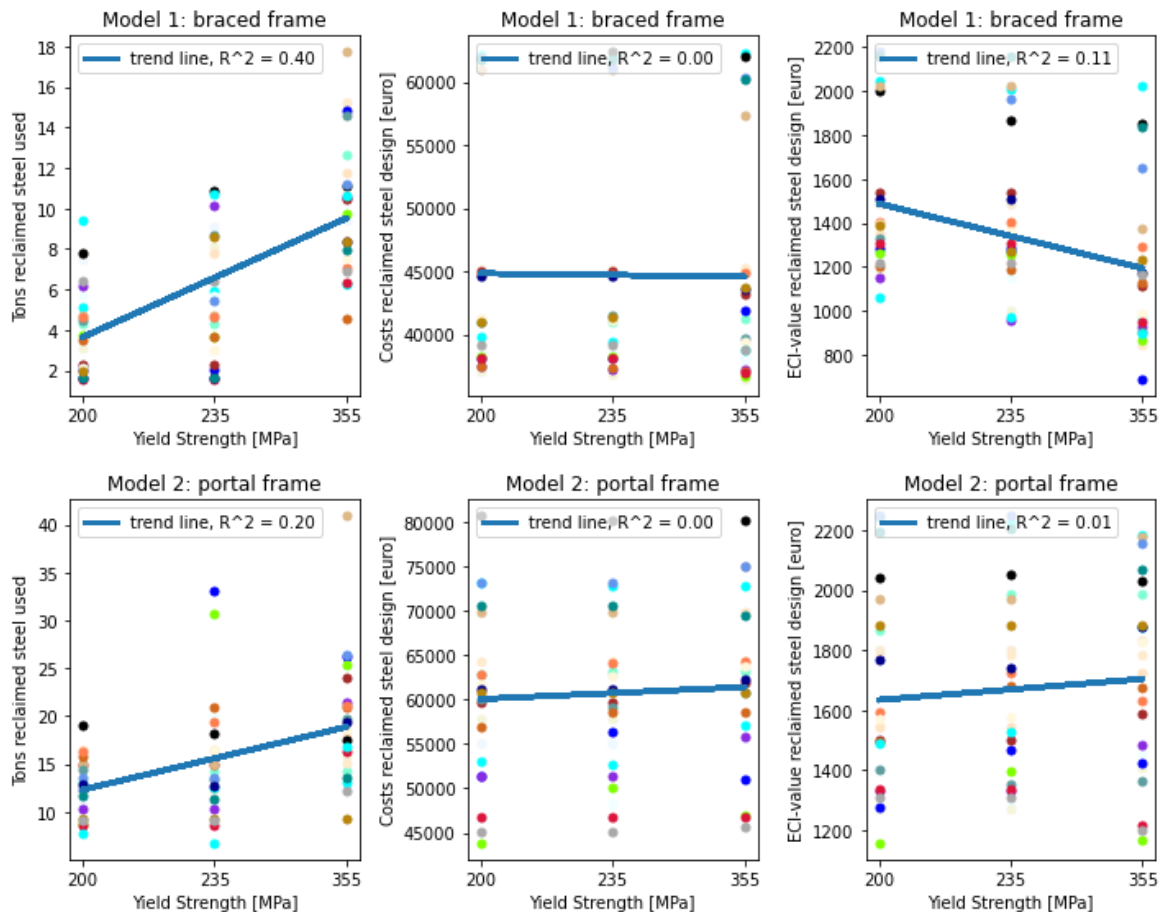


Figure 10.9: Trends of the effect of donor steel yield strength on costs and environmental impact.

The colours in the graph each represent a solution from a database and design combination. For both the braced and portal frame, an increase in yield strength results in an increase in the amount of reclaimed steel that is used in the design. The coefficient of determination (R^2), that indicates the strength of the correlation between model output and the trend-line, is high. What can be seen is that the costs do not seem to increase significantly when the yield strength is increased. This can be due to the fact that lighter donor elements will now be utilised as they are strong enough. Finally, the environmental impact of the braced frame does reduce as the yield-strength increases. This is not the case for the portal frame model. The lower correlation and influence of the yield strength for the portal frame can be caused by the higher dependency on second moment of inertia instead of yield strength. The braced frame only needs to fulfil local deformation criteria and is more dependent on cross-section capacity and thus the yield strength of the material.

10.1.4. Cost-model input

There are several parameters in the cost model that influence the costs of the reclaimed steel design alternatives. To determine the influence and behaviour of these parameters, elementary effect analysis is performed. The possible range of values for the parameters are defined based on the interviews and literature review in this thesis.

Parameter	Range
Price-factor deconstruction of donor steel	[1.0, 2.0]
Fabrication costs of new steel	[0.50, 0.90]
Fabrication costs of reclaimed steel	[1.20, 1.70]
% connections reuse	[0, 100]
Number of test-groups researched per day	[5, 30]
Storage costs	[0.15, 0.25]

Table 10.4: Ranges for the parameters of interest in the cost model.

The following graphs in figures 10.10 are the concluding results on this analysis for the braced (model 1) and portal frame (model 2) for two different types of databases.

The difference in the scale between the graphs is due to the fact that different databases were used and thus the resulting designs are not the same. It can be concluded that the influence of the connection reuse percentage, fabrication, storage and material testing costs have a high influence on the final price of the reclaimed steel design alternative in both cases. The connection reuse percentage, reclaimed steel fabrication costs and material testing have bigger spread in the results and the effect of changing these key-figures is less linear than for the other parameters.

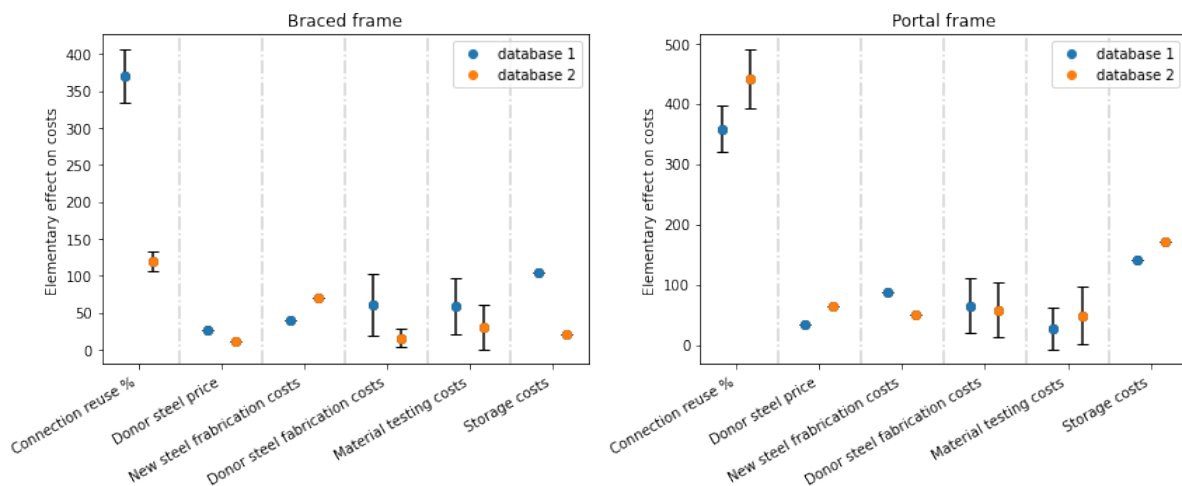


Figure 10.10: Results from the elementary effect analysis on the cost parameters.

Connection reuse percentage

This parameter influences the fabrication costs of the reclaimed steel elements. When the reuse percentage is higher, the fabrication costs are lower and vice versa. As the fabrication costs have a big influence on the total costs, the influence of this parameter is high but linear. This linear behaviour can be shown by generating the costs for the same design with different reuse percentages.

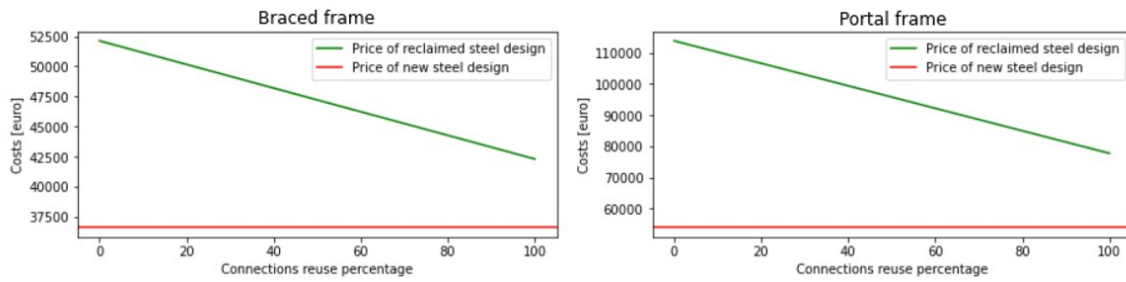


Figure 10.11: The effect of changing the connection reuse percentage on the costs of the reclaimed steel design.

As seen in the figure, the business case for the reclaimed steel design improves significantly if the reuse of the connections is increased. In this particular case, the range is quite significant comprising around 20% of the total costs for the braced frame and 35% for the portal frame model. This range is dependent on the amount of reclaimed steel used. Because of the high influence, it is important that this reuse percentage is estimated accurately. It can be difficult to do this while using Steel-IT. To do this, the user needs to know which connections are required to construct the new frames that are generated by steel it and whether the hardware is already present on the (to be) harvested connections. The influence of the connection reuse percentage on the case from chapter 9 is illustrated in figure 10.12.

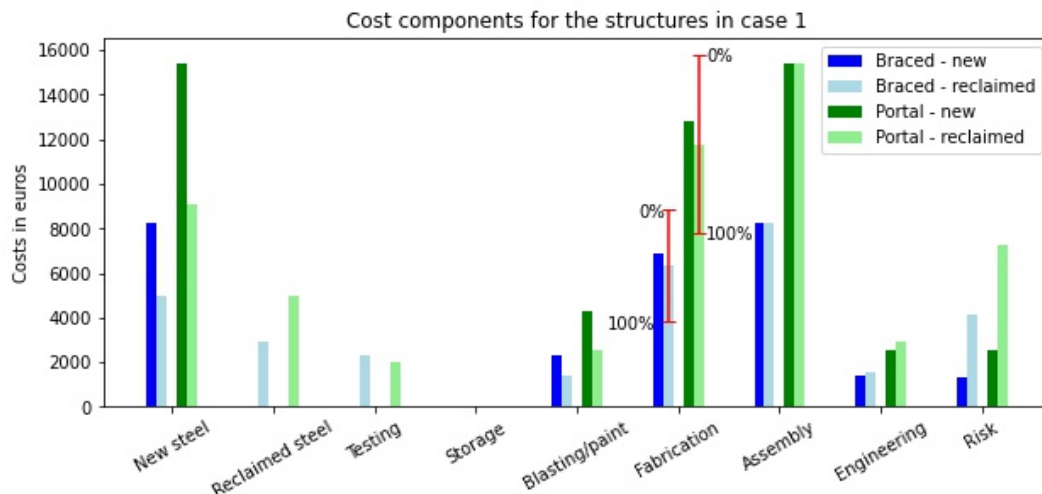


Figure 10.12: Influence of the connection reuse percentage for the case study in chapter 9.

Fabrication costs

The fabrication costs still show a big range. The value that is used for this variable is dependent on uncertainty in fabrication methods and the costs of removing toxic paints. In the worst case the costs per kilogram are €1.70 and the best case shows a cost of €0.90 per kilogram. The influence on the price is visualised in figure 10.13.

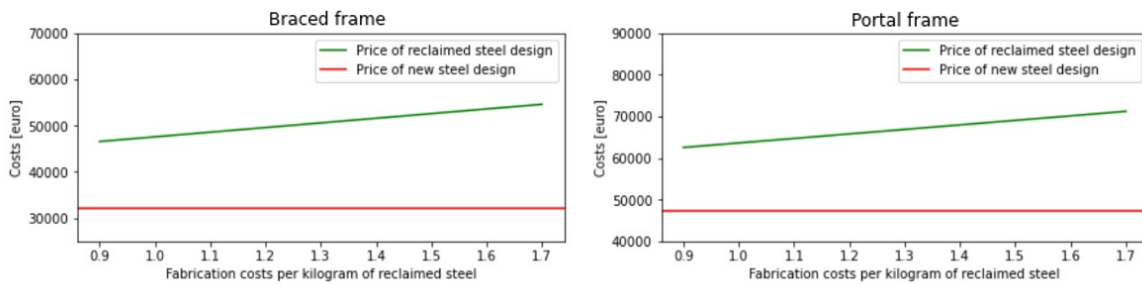


Figure 10.13: The effect of changing the fabrication costs on the total costs of the reclaimed steel design.

In the detailed analysis about the connection reuse percentage it was already identified that the fabrication costs have a big influence on the total costs of a reclaimed steel structure. Removal of toxic paints which are cause a 50% rise in costs en-large the total costs of the structures in the analyzed case with 11% to 15%. This is dependent on the amount of reclaimed steel applied in the structure and the connection reuse percentage as identified earlier.

Storage costs

The storage costs have a respectable influence on the total costs. The storage costs have a linear relationship to the total costs as they are simply multiplied with the amount of reclaimed steel that is used in the design.

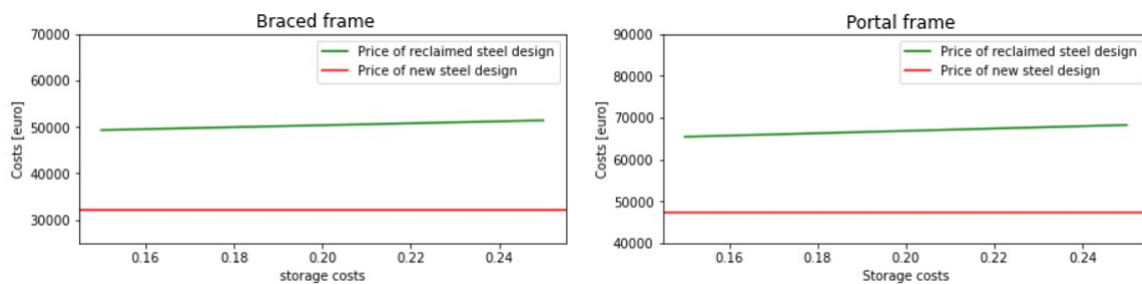


Figure 10.14: The effect of changing the storage costs on the total costs of the reclaimed steel design.

The total range can cause a change of the total costs of 5-6% in the highlighted case. The used value in the model is €0.16 per kilogram and is thus relatively close to the lower bound in the specified range. It benefits the design to reduce storage costs and it has a significant effect on the total costs of the design.

Material testing costs

The assumption on the amount of test-units can be examined in a day has a noticeable influence on the testing costs. Unlike the other cost parameters, the influence is not linear. This is due to the fact that the required amount of days is rounded tot the nearest half day. The change in costs is constant after all the test-units can be examined in half a day or the maximum amount of 'test-units per day' is reached in the range.

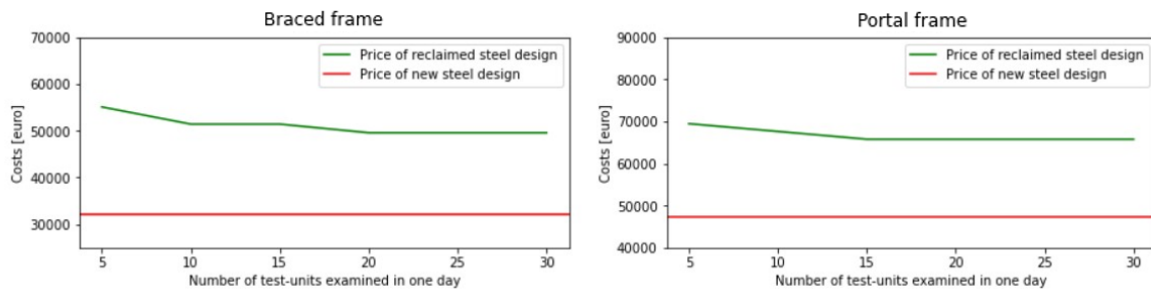


Figure 10.15: The effect of changing the material tests per day on the total costs of the reclaimed steel design.

The influence of this parameters is dependent on the number of test-units that contain elements that are used in the design. When only 5 test-units contain elements that are used, the costs will be equal for all values in the range of this parameter. When the number of utilised test-units grows, the effect and thus sensitivity of this parameter increases.

10.2. Scenario exploration

In section 8.7 the cost-model is elaborated. In the process of developing this cost-model, certain assumptions have been made. The assumptions that lead to the implemented cost-model are based on realistic scenario's in today's building sector. These scenarios are subject to change. This section analyses changes in the assumed scenarios and their effect on the output of Steel-IT. The benchmark will be case 1 analysed in section 9.2 and is displayed in figure 10.16.

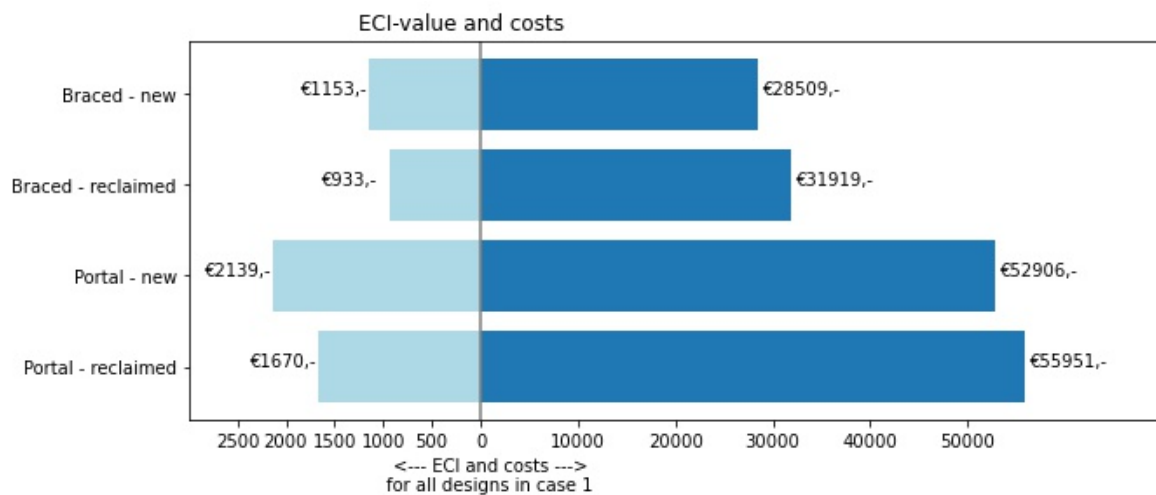


Figure 10.16: ECI-value and costs for case 1 of the case study.

10.2.1. Centralised testing scenario

It is likely that the reuse of structural steel elements will become more relevant when the pressure to reduce material bound impact in the build environment is increased. When demand rises, the second possible scenario for material testing, according to appendix C, could come into effect. The deconstruction contractors will start validating the material properties for the whole donor structure. In the appendix, the effect of this scenario on the costs is indicated. For the case study in the first section of this chapter, the effect has been analysed by modifying the allocation of the test costs.

Instead of counting the test units that are used in the design, the costs are determined for the whole batch of reclaimed elements. The costs are determined using the same method as described in section 8.7. Each element in the database then receives an equal part in the total test costs. To determine the total test costs for a design, the costs per used element is summed up. Figure 10.17 shows the effect on the cost breakdown from the case study. The change in code is included in appendix A.

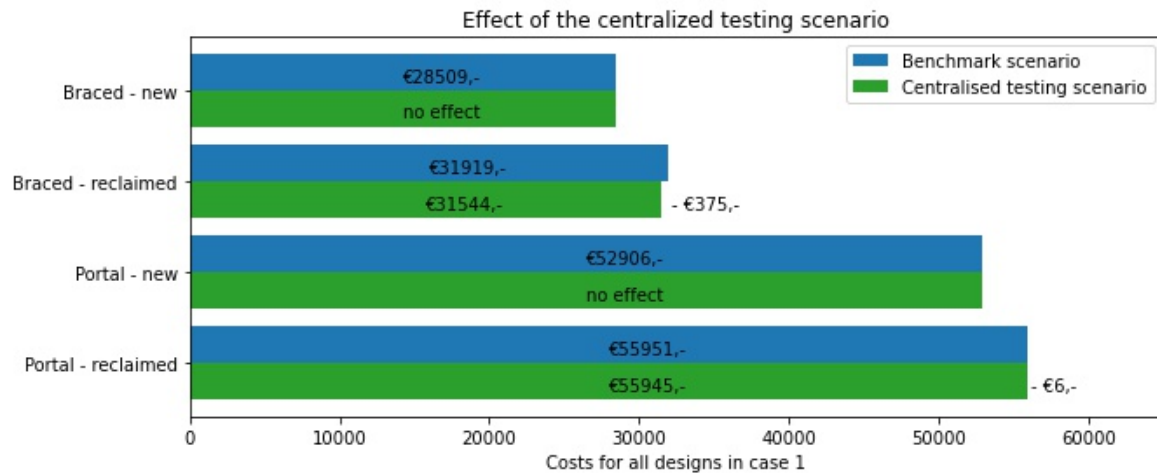


Figure 10.17: Effect of centralised testing on the business-case of donor steel.

The difference in this scenario is minimal. Due to the brute-force method used in the framework, the data-sets of reclaimed elements are kept small to keep computation times down. As these costs are dependent on which elements are used or not, it is possible that the impacts are bigger on bigger databases and design geometries. In this case a lot of reclaimed elements with a similar cross-section are used. This limits the amount of test-units that need to be tested. If more unique cross-sections are used, more individual tests are necessary. In this case, this scenario would have more effect as these test costs will spread over elements which are not used and thus not paid for.

10.2.2. High availability scenario

In the second scenario, it is assumed that the availability of reclaimed steel sections will be a lot higher. In an ideal situation, the availability is limitless so there is always a reclaimed steel section to be used in the new design. In this case, no new steel elements have to be used. Unlimited availability is unlikely. To simulate a high availability, the reclaimed steel database of the Brede Buurtschool has been doubled in size so that all elements are included twice. This database is then used to generate a new reclaimed structure for both models of the Benchmark scenario. The effects on the used tons of new and reclaimed steel compared to the benchmark scenario is significant. A lot more reclaimed steel can be used in the design.

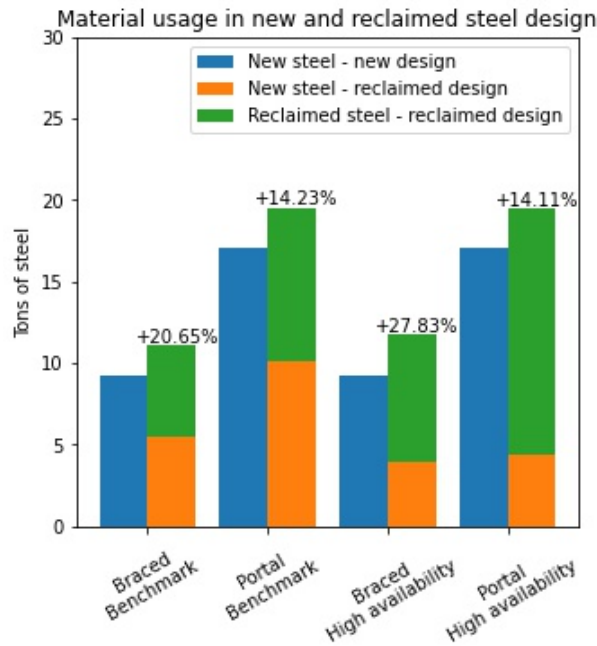


Figure 10.18: Material usage for the benchmark and high availability scenario designs.

Figure 10.19 shows the effect on the costs and ECI-value of the scenario compared to the benchmark. A significant drop in environmental impact is achieved with the bigger database of reclaimed steel elements. The reduction compared to the new steel alternative is 37% for the braced frame and 52% for the portal frame model. The business-case also improves. The costs for the braced frame model decreases and the gap between the new and reclaimed steel alternative shrinks from €3410 to €1553. The portal frame model is even more competitive and is cheaper than the new steel alternative by €2045.

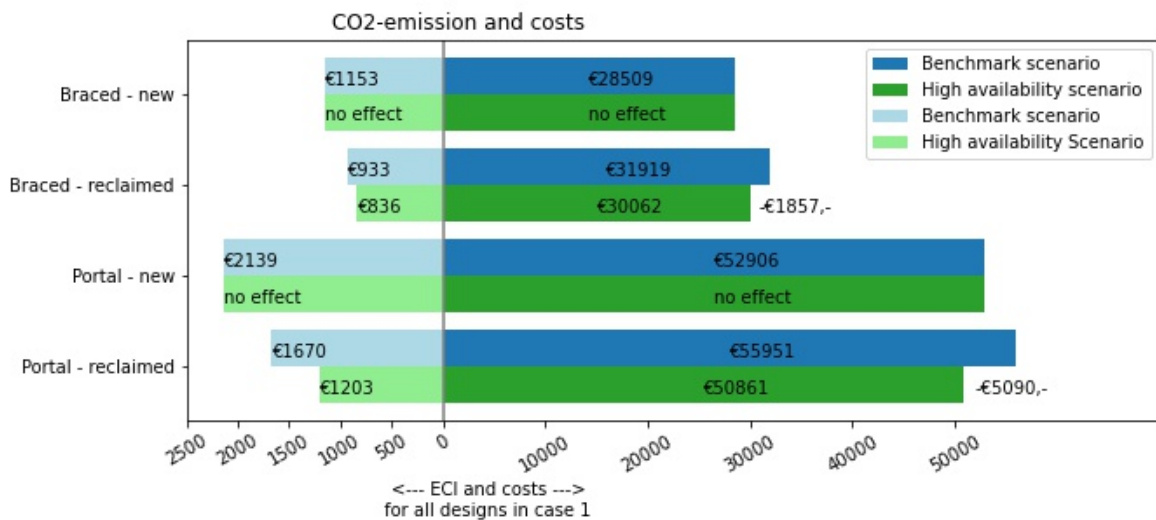


Figure 10.19: Costs and ECI-value comparison between benchmark and high availability scenario.

10.2.3. Emission-tax scenario

This scenario implies a tax on emissions. Two options are considered. The European Union formulated an emission trading system and carbon tax system. A second option would be to make clients pay the ECI value of their products.

Emission trading system and CO₂ - tax

To realise the 55% CO₂ reduction goal for 2030, the European Union has defined a CO₂-tax for industry to incentivise CO₂ reducing measures in the industry. The emissions trading system, or ETS, allocates a limited amount of free CO₂ rights. These are the tons of CO₂ a company can emit freely. If the company emits more, they need pay for more emission permits. The ETS allows to trade the emissions permits between companies and installations within a company. If the CO₂ tax is lower than the price for a emission permit in the ETS, no tax needs to be payed as the costs of emitting carbon is covered by the ETS-price. If the ETS price is lower than the tax, the difference needs to be paid for each ton of CO₂ that is emitted (Nederlandse Emissieautoriteit, 2023b).

Right now the ETS price is €60.78 per ton and the tax is €41.75 per ton. It is hard to say what the ETS price will be in the future. This will depend on the carbon reducing measures implemented at the emitting companies and their effectiveness in respect to the increase in carbon tax rates. The tax rate is set to increase by €11.55 per year up to €136.79 in 2030 (Nederlandse Emissieautoriteit, 2023a). An analysis from Koelemeijer et al. (2022) concludes that a ETS-price of €63 is needed in 2030 to accomplish Dutch CO₂ reduction goals. This would mean that steel manufactures would have to pay €73.79 per ton of emitted CO₂ within and €136.79 per ton of CO₂ emitted outside their ETS-allowance.

Right now, the steel sector is gifted emission permits to stay competitive in the world market. Assuming this trend continues until 2030, the steel sector can reduce the CO₂-tax by €63,-. Meaning, that in 2030, the steel price will increase with €73.79,- per ton of CO₂ that is emitted during its production. To show the effect on the business case for the case study in section 9.2, the embodied carbon (Paris Proof Indicator) is multiplied with the tax and added to the cost price of the new and reclaimed steel elements. Figure 10.20 shows the effects on the cost breakdown.

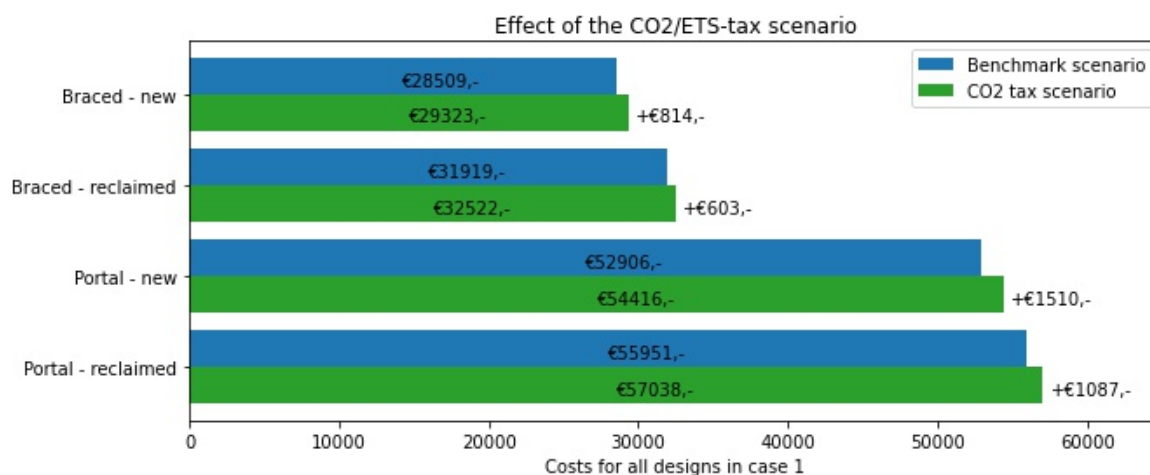


Figure 10.20: Effect of CO₂-taxing on the business-case of donor steel.

The cost-gap between the new and reclaimed steel design shrinks slightly from €3410 to €3200 for the braced frame and from €3050 to €2625 for the portal frame. It is not yet possible to create a cheaper reclaimed steel design in this case.

ECI - tax

The ECI-value represents the sum of money needed to offset the emissions/impact that is created by the production, use and deposition of a product. By making this payment obligatory, this offset could be realised. Chapter 7 discusses how to quantify the ECI-value and chapter 8 shows how the value is computed for the designs. Figure 10.21 shows the effects on the cost breakdown.

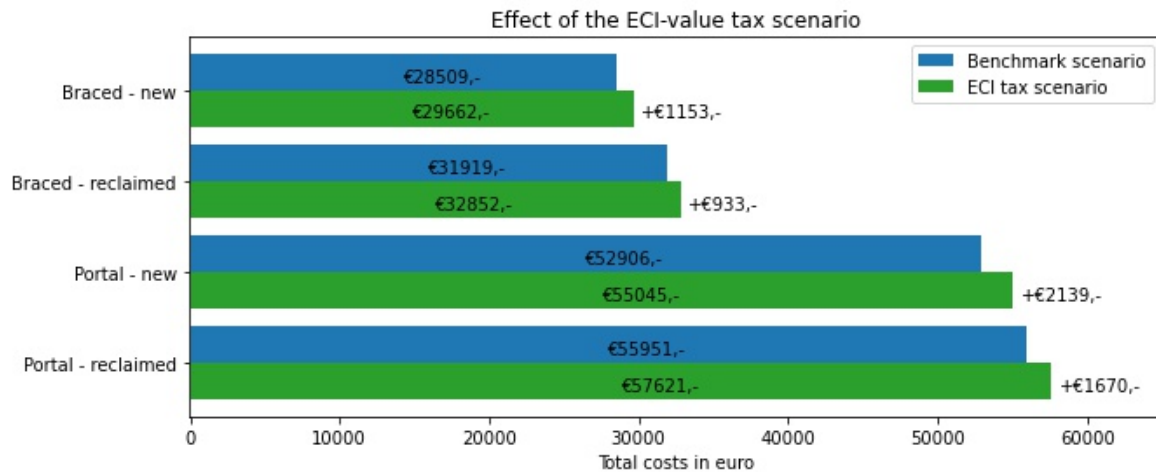


Figure 10.21: Effect of ECI-value taxing on the business-case of donor steel.

The cost-gap between the new and reclaimed steel design shrinks slightly from €3410 to €3190 for the braced frame and from €3050 to €2675 for the portal frame. It is not yet possible to create a cheaper reclaimed steel design in this case. The tax-values for both the CO₂ and ECI taxing scenario are similar and low compared to the total costs of the steel structure (<5%) and even smaller compared to the total building costs.

10.2.4. Green steel

Next to the reuse of structural steel elements, the development of greener production processes is ongoing. Using electric arc furnaces in combination with green hydrogen can cause substantial emission reductions. This steel is referred to as "green steel". A briefing article from the Union (2020) describes the economic potential using hydrogen to de-carbonise the steel industry.

The report states that the production of hydrogen is energy intensive and expensive. In 2020, the price of one kilogram of hydrogen was ranging from €3.6 to €5.3. Big improvements in production technology and up-scaling could cause this price to drop. The lower price of the range, €3.6/kg, would cause a steel price increase of 33% compared to traditional steel production with coal. The document proposes solutions to overcome this economical barrier. Increasing carbon emissions costs and up-scaling renewable energy and green hydrogen production will make the green steel more competitive on price.

To determine the effect of this scenario, it is assumed that the cost-price of new steel will increase by 33%. The impact for new steel then decrease by 85% in the production stage A1 and beyond life-cycle stage D. Figure 10.22 shows the effect of this change on the cost breakdown of the case study in section 9.2.

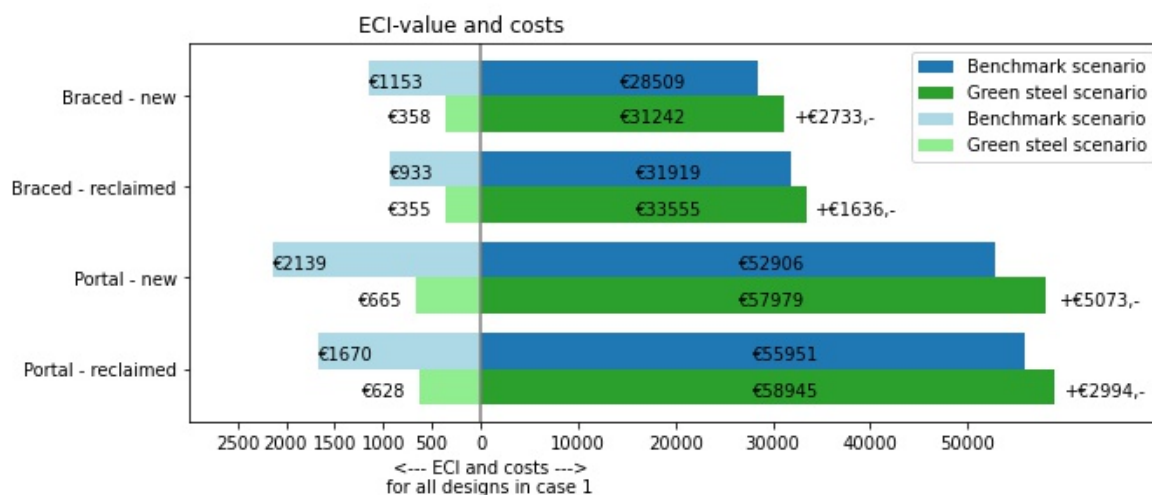


Figure 10.22: Effect of green steel production on the business-case of donor steel.

The difference in environmental reduces significantly when the emissions for new steel production are reduced by 85%. The reclaimed steel design alternatives are marginally better in terms of environmental impact but the differences are small. The costs for the new steel design alternatives rise a lot. Especially for the portal frame, the price of reclaimed steel seems to be competitive as the donor steel design is only around €1000 more expensive. It could be argued whether the small gain in impact is worth the complex process of working with reclaimed steel. It should be noted that it is likely that the 85% reduced impact means that all the energy used in the green steel production is generated without emissions. This will take time, reclaimed steel is available now.

10.2.5. Business-case: break-even point

Figure 9.12 shows the new steel design costs and the reclaimed steel design costs as a function of the connection reuse percentage. The lines for the portal frame cross. This is the break-even point where the business-case for reclaimed steel is equally appealing as the new steel equivalent. For the braced frame, no break-even point is found. This means that even with 100% connection reuse, the new steel structure will be cheaper than the reclaimed steel design in the particular case of the case study. The same kind of analysis is performed with the scenarios described above. Table 10.5 shows which percentage of connection reuse is needed to break-even for the scenarios above for case 1 of the case study. If no break-even point is found, it is stated how much more the reclaimed steel design will cost compared to the new steel equivalent for a connection reuse percentage of 50%.

Scenario	Braced %	Portal %	Braced 50%	Portal 50%
Benchmark	not found	86%	+€3410	+€3050
Centralised testing	not found	86%	+€3490	+€3420
High availability	72%	39%	+€1550	-€2040
CO ₂ -tax	not found	78%	+€3200	+€2620
ECI-value tax	not found	77%	+€3190	+€2580
Green steel	not found	61%	+€2310	+€970
Centralised testing + ECI-tax	not found	82%	+€3200	+€3020

Table 10.5: Break-even point for new and reclaimed steel variants in case 1.

The table shows that it is difficult to find a scenario where reclaimed steel will be cheaper in the case study of this thesis. For most scenarios, high connection reuse percentages are required. The high percentages in the range of 70-90% are not likely to be achieved when steel is reused on an element level as considered in Steel-IT. It is likely that at least half of the existing connections need to be cut-off due to member shortening and change in connection design for demountability or member extension. The high availability scenario thus shows the best prospect for the future in terms of cost neutrality.

The cost differences between the new and reclaimed steel design for a 50% connection reuse percentage is €3490 at most for this case. In context of the total costs of the steel structure this is a difference of less than 15%. Considering that the costs of the steel structure in a building only comprise 7-13% of the total building costs as discussed in section 6.1, this difference can be regarded as small. Compared to the total buildings costs, the differences in the table can even be regarded as negligible.

10.3. Reviews

In the evaluation, the outcome of the cost model is evaluated with engineers from IGG and Vic Obdam. IGG specialises in cost estimation of structures in all stages of the design process. Vic Obdam is a steel manufacturer and their experience on working with donor steel can provide a nice evaluation step.

10.3.1. IGG

The results from the cost model and algorithm has been presented to cost expert Rob Passchier at "IGG-bouweconomie". The overall results are in-line with the expectations but a couple of discussion points came up.

It is important to mention that the data that is used in the cost model is time-dependent. It should be stated in Steel-IT that the preset key-figures are sampled in Q2 of 2023 and use in a different time period might result in unrealistic cost-estimates. A big advantage to Steel-IT is that it includes the actual design that the costs are evaluated for. Generating a design gives an insight into the amount of material needed which does increase the accuracy of the estimate.

As already concluded in the sensitivity analysis, the fabrication costs and its uncertainty range have a big influence on the final costs of the reclaimed steel design. Passchier mentions his concerns about the big range I use in my thesis. For new steel the fabrication costs can be as low as €0.50 up to €0.75 euro per kilogram of steel. For reclaimed steel this figure can range from €1.15 to €1.70, dependent on the present conservation system and steel builder. It is logical that this range is big as cost estimation is dependent on boundary conditions. It could be advantageous to include ranges to pick values from instead of empty text-boxes. This also gives the user some feedback on were the selected key-figure lays in the range.

Rob mentions that the cost model is very use-able as a comparison tool as this time dependency is less relevant when looking at the difference between two designs. The exact value of for example, assembly costs is not as important as they are the same for the new and reclaimed steel design.

10.3.2. Vic Obdam

Engineers at Vic Obdam were informed on the work performed in this thesis. After explaining the algorithm and models, the connection reuse percentage was challenged by the engineers. The conclusion was that this percentage is hard to determine and that details about the fabrication are needed to come to this percentage. The same can be said for the fabrication costs per kilogram.

Currently, Vic Obdam is involved in the fabrication of Upcycle Mall, a reclaimed steel project in Rotterdam. The engineers point out that the connections that I assume are simple and have low re-fabrication costs compared to the more difficult details of the Upcycle Mall projects. Workers in the fabrication hall indicate that cleaning the elements before welding is one of the most time consuming task during the re-fabrication process. Steel-IT assesses costs in the early design stage and therefore it is hard to determine how much fabrication is going to cost. The engineers indicate that costs can be a lot higher if fabrication gets more complicated. An improvement step of Steel-IT would be to look at the process of going from a preliminary design to a more technical version to analyse these costs. A cost assessment on the Upcycle Mall indicates that each kilogram om reclaimed steel costs €1.95,- to re-fabricate. It is however hard to determine the costs for the scope of this thesis. Only angle cleats and end-plates are used where Upcycle mall also extends elements and is subjected to different loads. The connection design in reclaimed steel projects is even more important than for projects in new steel.

11

Discussion

The goal of this thesis is to find out how to create an attractive business-case for a low rise office building with a reclaimed steel structure and how to assess its environmental impact. To do so, a tool is developed to create a design alternative to a new steel office building with reclaimed steel elements from a limited stock. Together with stakeholders in the building- and steel-sector a cost and environmental impact model is established to investigate the main research question.

11.1. Interpretation and validity

The business-case and environmental impact score.

In most of the results generated in Steel-IT, the reclaimed steel design is more expensive than the new steel equivalent. From a case study using the tool it can be concluded that the main difference in costs between a new and reclaimed steel structure comes from the extra costs of material testing, re-fabrication and storage. While the material costs of reclaimed steel are lower (€0.30 versus €0.390 per kilogram), the extra processes involved nullify this advantage. The costs of a steel structure only consists for 27% out of material costs. All other costs are labour induced.

To arrive at an attractive business-case, some things can be taken in consideration in the design and building process. When sourcing reclaimed steel, extra costs can be avoided by sourcing the material before deconstruction. Storage increases the costs of the reclaimed steel elements and might make validation of material properties complicated. From the literature review and interviews with steel builders in chapter 6, it can be concluded that elements with toxic conservation systems should be avoided. They are hard to clean and therefore induce extra cleaning costs during re-fabrication. The case study in section 9.2 is sourced from an existing building and has no toxic paint but is still more expensive than the new steel design and thus confirms this claim. Sensitivity analysis shows that the reuse of connections has a big influence on the fabrication costs of the reclaimed steel structure. With higher reuse, these costs drop and the business-case improves or even becomes favourable. This is in-line with findings from the case-study of Biopartner 5 in chapter 4. This reclaimed steel project lends its success to the principle of reusing elements as they are. In Steel-IT, a certain set of connections is assumed which mostly use end-plates. More reuse of other connections outside this set might be feasible in the project and this makes it difficult to assess the re-fabrication costs.

In terms of design choices, it seems beneficial to choose a light-weight flooring system if the situation allows for it. The sensitivity analysis shows a significant reduction in impact and costs for both structural configurations in the context of the steel structure. This effect is stronger for the braced frame where a reduction of 30% on costs and impact can be achieved compared to a 10% decrease for the portal frame. This is likely due to the fact that the braced frame design is governed by strength instead of stiffness. The lower loads have a bigger effect on the applied sections in this case. Next to floor-choice, high yield-strengths of the reclaimed steel elements often have a positive effect on the amount of reclaimed steel that can be utilised. Especially for the braced frame, this relation is strong (R-squared > 0.40). If material properties are unknown it can reward to validate them through testing instead of using a lower-bound value. Together with the increase of the amount of reclaimed steel that can be

used, the environmental impact often goes down significantly ($R > 0.10$). The impact on costs seem to be minimal outside of testing costs but this relation is less strong.

Reclaimed steel design algorithm

Steel-IT creates the ability to create design solutions. In the case study in section 9.2 it can be seen that through design iterations with different grid-sizes, possible solution can be generated. This design iteration results in a portal and braced frame that reduce the impact by around 25% for limited extra costs. The business case and environmental impact score is highly dependent on the combination of the design and database that are used in the tool. When a design and database align, more elements can be reused. From the sensitivity analysis is concluded that the amount of reclaimed steel in a design does not hold a direct relation to the costs and environmental impact score. It is more about the location these elements get used in.

This efficient use of reclaimed steel in the developed algorithm for Steel-IT is controlled by the weight multiplication factor. The sensitivity analysis on this factor shows that for the braced frame a trade-off between costs and environmental impact reduction is forced upon the user of the tool. The portal frame shows a clear optimum. The optimal weight factor (W_{mult}) depends on the database and design combination but generally seems to be between 1.4 and 2.0 for the portal frame. This is in-line with research from Brütting, Vandervaeren, et al. (2020) described in chapter 5, where the optimum structure is described as a hybrid between new and reclaimed steel. In Steel-IT, a multiplication factor of 1.5 does not imply that the donor structure is 50% heavier but that the maximum allowed weight of a substitute is 1.5 times the weight of the new steel equivalent. Finding the best weight factor takes some iteration and thus time.

Future scenarios

From likely future scenario's it can be concluded that reclaimed steel can have a important role in the transition to a circular building sector. Likely future emission taxes improve the business-case for reclaimed steel slightly. Between the Emission Trading System and ECI-value tax, the latter seems to be slightly more effective for the key-figures that are suggested for 2030. With this tax it is however still difficult to reach the break-even point of a new and reclaimed steel design in the case study of section 9.2. It can be argued that the suggested taxes are low compared to the price of a steel structure (<5%) and even smaller compared to the total building costs. Further benefits like centralised testing of reclaimed steel elements are hard to predict. Direct effects on the total costs of a small project as considered in this thesis seems to be small for the case study in section 9.2. It will however contribute to a wider range of available elements and take away risks from the clients as material properties are know beforehand. Both availability and risk are mentioned in the introduction of this thesis as barriers to wider reuse of donor steel. In the high availability scenario it is directly seen that the reclaimed steel design improves significantly and even becomes favourable.

A potential treat to the wider use of reclaimed steel is the development of a green steel production process. The increased production costs for the new steel elements neutralises the cost difference between new and reclaimed steel structures, making reclaimed steel an attractive option in the case study of this thesis. However, the benefit of reducing the environmental impact of the structure diminishes as the impact of production of the new steel is reduced by 85%. This reduction assumes 100% carbon free energy used in the production process. It will take time to roll-out the new process and create enough carbon free energy to fully replace the carbon intensive steel industry. Furthermore, recycling scrap to produce new green steel is still a lower mode of circularity compared to reuse. With this process, the material loop is not being closed. Steel reuse should be considered before scrapping steel elements to produce new steel sections.

11.2. Limitations

In this thesis, the scope and assumptions that have been made have implied limitations to the use of the tool. The results should be interpreted while keeping the following limitations due to the scope and assumptions in mind.

Scope

The use of the tool is limited to creating reclaimed steel designs for low-rise office buildings. The key-findings do therefore not apply to other building types and bigger size structures. Next to this, the generated structures are limited to two structural lay-outs. This implies that the optimal structural configuration for the available donor elements is often not an option when using the tool. Furthermore, the tool only assesses the costs and impact of the steel structure. Design choice like the choice of flooring system can have other effects on the environmental impact and costs of the structure. The effect of the structural grid-sizes and floor system on the rest of the building are not included in this research.

Tool algorithm

The tool and algorithm itself takes a lot of information like grid sizes, settings and key-figures for the cost and impact assessment. This in combination with a long computation time due to the use of brute-force algorithms makes it easy to 'skip' the best solution. The iterative process to find the best solution is manual and as seen in the sensitivity analysis, automating it will allow the user to look at a lot more solutions. Next to this big solution space, the algorithm that selects which reclaimed steel elements are used is controlled by a weight factor. This limits the weight and is related to the costs and environmental impact but does not ensure the optimal solution in terms of impact or costs. Figure 10.7 shows that there is an optimum on the weight factor in terms of costs and environmental impact. Finding this optimum again takes some iteration and thus time. Automating seeking for this optimum or changing the objective function into a cost and/or impact based one would make it easier to find this optimum. Furthermore, the algorithm needs to be provided with a percentage of connections that are reused. This is quite hard to determine in a preliminary design by the user of the tool but the results are quite sensitive to this parameter.

Cost and impact models

The result of the cost model is based on cost parameters for Q2/Q3 of 2023. When prices change, the cost estimation changes. New steel and scrap steel prices change a lot over time. This ratio as well as other parameters like storage costs influence the cost components and thus business case of the donor skeleton. Fabrication and material testing costs depend on the situation and the resulting ranges of realistic values can have cause for a big spread in possible outcomes. This is not uncommon in cost-estimation. For users of the tool it is important to use key-figures applicable to the current situation. The most critical user-set parameter is the connection reuse percentage. Connection design is critical to successful use of donor steel. Re-fabrication can be costly and clever detailing as in the Biopartner 5 case can make a big difference in the amount of re-fabrication that is needed.

The way that the life-cycle assessment is set-up, the emission regarding stage A4-A5 is different to the way costs are determined for the related activities. For the assembly stage the emissions are based on the amount of kilos or reclaimed steel while in the interview with IGG it was concluded that construction does not differ significantly between a reclaimed and equivalent reclaimed steel design. The cost model uses this information and credits equal costs while the impact model results in different outcomes for the subsequent life cycle stages. A different approach to life cycle assessment could be created specifically for the application of this tool to get a more realistic impact profile.

11.3. Importance and application

This research was originated to contribute to the meta-goal of increasing the reuse of structural steel elements. This thesis contributes to this goal in two ways. First of all, this thesis research gathered information from multiple stakeholders in the building- and steel-sector and their view on reusing steel elements. This collection of information can give the readers and overview of the parties and tasks involved in designing, fabricating and building with reclaimed steel. Secondly, the tool that results from this research gives direct insights in the costs and impact of reclaimed steel frames in low rise office buildings. This contributes to overcoming the barriers of design and costs associated with using donor steel. Steel-It also allows comparison between the new steel and reclaimed steel hybrid design based on costs and environmental impact. In this way a design can be tweaked to fit the database or the other way around. This can contribute to the design process and search for donor buildings. As the

tool is parametric, it can also be used to conduct bigger experiments to determine the effects of certain parameters. This has been done in this research for the test costs, yield-strength and weight-factor.

Steel-IT gives an indication of what is possible with the provided list of reclaimed steel elements. The tool could be used by multiple parties. Design teams could use it to get an indication on the usability of a donor structure and make decisions based on this outcome. By changing their design or searching for new donor steel sources, the connection between supply and demand can be established earlier in the design process which can make implementation and thus reuse more likely. Deconstruction contractors could also use the tool to advertise their demounted steel elements with. By seeking the best structural configuration in the tool, an advise can be given on which building properties would create a good fit. These results could be added to the advertisement on their circular trading platforms. In these ways Steel-IT can contribute to more use of donor steel which, in the end, is the most essential factor to achieve wide scale application and reduce the environmental impact of steel structures to achieve the 2050 circularity goals.

12

Conclusion and recommendations

12.1. Conclusion

The aim of this thesis was to gain insights into the business case of using reclaimed steel elements in low-rise office buildings. To do so, Steel-IT is developed to generate reclaimed steel designs and evaluate their costs and environmental impact. Using Steel-IT, an answer to the main research question of this thesis can be formulated.

Main research question

“What is needed to create an attractive business-case and environmental impact score for the preliminary design of reclaimed steel, low-rise office building?”

This research is divided into four parts with separate sub-questions. Each part contributes to creating Steel-IT and answering the main research question.

1. Case study Biopartner 5: qualitative difference between new and reclaimed steel.
2. Literature review and interviews: qualitative difference between new and reclaimed steel.
3. Development Steel-IT: Use the obtained knowledge to develop Steel-IT.
4. Steel-IT analysis: Use Steel-IT to investigate the business-case of reclaimed steel.

The sub-questions in the first part are answered in chapter 4. They are answered by doing a process analysis of the Biopartner 5 project. The main difference between using new and reclaimed steel is the design approach and more involvement of the different stakeholders in this design process. Early involvement of engineers and the steel builders makes it possible to keep a flexible design and make optimal use of opportunities for reuse. Extra costs associated with reclaimed steel are results of extra processes that require more labour. If this extra labour is kept to a minimum by making smart design choices and clever detailing, big environmental impact reduction against minimal cost increase is possible.

In the literature review and interviews, the qualitative difference in design, costs and impact is researched. The sub-questions regarding these topics are answered in chapters 5, 6 and 7. Reclaimed steel designs are often hybrid designs between new and reclaimed steel elements due to availability and efficient use of the reused sections. Connections and beam configurations need to be designed with care for costs and rigidity. The reclaimed material itself performs similar to new steel but material properties need to be validated to ensure structural safety. To assess the costs, multiple methods can be used but complexity should be kept to a minimum to keep track of the model. Interviews with different stakeholders provided this research with the required information and key-figures for the cost model. The environmental impact of reclaimed steel is 'free of burden' in the production stages as this step is omitted by direct reuse of the steel sections. For new connections, some new steel is required. Transportation plays a significant part in the environmental impact of new and reclaimed steel sections.

In the third part, the knowledge obtained is used to create Steel-IT. Chapter 8 discusses how the information is used to create the framework that consist of a design algorithm, cost model and impact model. In chapters 9 and 10, the last part of this research, Steel-IT is evaluated and used to analyse the business-case of donor steel. With this an answer to the main research question can be formulated. The key-findings, regarding the business-case and environmental impact score of the preliminary design of low-rise office buildings that include reclaimed steel, are summarised below.

Key-findings

- With a good match between donor elements and building geometry, an environmental impact reduction of 25% against minimal cost increase can be achieved.
- Reclaimed steel designs are often more expensive than their new steel equivalents due to extra processes that are involved like re-fabrication, material testing and storage.
- The best source of reclaimed elements is an existing building as this prevents extra costs for storage.
- Toxic conservation systems ruin the business-case for reclaimed steel as they induce a lot of extra work during re-fabrication.
- Light-weight flooring systems can decrease costs and impact of the steel structure by 10-30% depending on the structural configuration of the steel structure.
- There is a strong correlation between higher yield strengths and increase in reuse of donor steel elements ($R = 0.4$) as well as a reduced environmental impact ($R = 0.11$) against a minimal cost increase.
- Connection design is important to successful implementation of reclaimed steel. Limiting re-fabrication by using elements and connections 'as they are' reduces costs.
- Reclaimed steel elements should be used efficiently. The extra weight factor of the reclaimed steel substitutes optimally is 1.4 to 2.0 for the portal frame. A trade-off between costs and impact is forced upon the user for the braced frame.
- Currently suggested values for emissions taxing do not improve the business-case of reclaimed steel significantly (<5% in the case study).
- When reclaimed steel is used more, the higher availability and more wide-scale testing will increase the reuse potential and make donor steel designs more competitive on costs.
- Reclaimed steel is a better alternative to reducing environmental impact compared to new steel produced with green energy as it closes the material loop.

Steel-IT can be used to find a good match between a building geometry and the reclaimed steel database and vice versa. As seen in the table, there are several elements to consider in the design like design geometry, floor choice and connection design. The type of source, conservation systems and existing connection design is important when searching for a source of donor elements and have an influence on the costs of the project. If it is possible to test the elements to increase the yield strength that is allowed to be used, this is worth it as it allows more donor steel to be used in the design. To stimulate reuse, emission taxing could be used to improve the business-case. In the scenario exploration, the effect of this taxing seems to be rather small compared to the total costs. It is unlikely that this small change will have an influence on the decision-making of clients. This argument however, can also be used the other way around.

When a good combination of design an database is found in Steel-IT, the price difference between the new and reclaimed steel design in the case study is relatively small (<15%). Considering that the steel structure only comprises 7.5-15% of the total building's costs, this increase is even smaller on the total scale of the building costs. Achieved impact reductions are big compared to the cost increase. The framing of an office building can comprise 35% of the material-bound emissions. When the design and donor elements are aligned, a donor steel design can be competitive and big impact reductions

are possible. Steel-IT helps finding this match and lowers the boundaries on designing with reclaimed steel and the associated costs in such a project. The sector should start closing the material loop of structural steel by reusing steel more as this will help achieve the sustainability goals for circularity and emissions. Steel-IT could support this transition by supporting the match between demand and supply. Engineers can use it to explore the possibilities with the elements for a donor steel design and deconstruction contractors and traders can use it to advertise with a specific application for their stockpile. To reduce the boundaries and costs for reuse even further, more experience and research is needed. This research pays a contribution to this goal.

12.2. Recommendations

From the research in this thesis, recommendations can be made for expanding this thesis research, relevant future research and for practical application of Steel-IT. To expand this thesis research and Steel-IT, the following recommendations can be formulated:

- Improve the cost model to determine fabrication costs based on the number of connections.
- Improve the speed of the algorithm to allow for quicker (and broader) solution space exploration.
- Include a W_{mult} optimisation in the algorithm to remove the manual iteration to find the optimum.
- Allow the user to use different objective functions in the assignment optimisation.
- Implement reuse of complete components like frames and trusses.

The first improvement would be to adopt a more detailed model to determine the fabrication cost. Now the user needs to estimate which percentage of connections can be reused. The tool could use the assumed connections and available connections to compute this percentage or even determine the costs per joint. In this way the cost model's sensitivity to fabrication costs can be lowered. By improving the algorithm as described in the bullet-points in the middle, it is easier to explore the possible solutions, find the best algorithm settings and control the way the elements are assigned. Being able to choose an objective function that looks at impact instead of weight would make it easier to find a solution with a low environmental impact for example. Next to these improvements regarding this thesis, some recommendation for relevant future research can be formulated:

- Determine the best connections types for reclaimed steel projects and their costs.
- Perform similar research for other types of buildings.
- Develop methods of deconstruction to increase reuse.
- Determine the effect on costs of using reclaimed steel on other parts of the building.

Steel-IT highlights that connection design is very important for the business case of reclaimed steel structures. Estimating the fabrication costs is complex and by choosing a fixed set of connections for the donor steel design, potential reuse of other connection types is wasted. Investigating suitable connection types and their costs for reclaimed steel projects can make cost estimations more accurate and can improve reuse of connections. In general it is needed to get more knowledge about working with reclaimed steel. Better deconstruction approaches and more practice will lower the boundaries for reuse further. Steel-IT helps designing a office building project and similar research can be conducted for other building types to close the knowledge gap on design and costs. This is also where Steel-IT can play a role in practical applications.

This thesis provides the tool Steel-IT to assess the costs and environmental impact of a design alternative in reclaimed steel. The knowledge gathered and the tool that is developed could be used to match donor buildings and new office designs. In this way demand and supply can be matched early on and the barriers to reuse might be lowered a bit by the insights in costs and potential gains in environmental impact the framework defines. Creating a bigger market by undertaking more projects using donor steel can decrease costs associated with reclaimed steel and make reclaimed sections more available. Using the new NTA on structural steel reuse is part of this development. Developments and research like this thesis should be used to gain insights and convince clients to make steps to a more circular building sector.

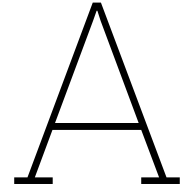
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Appendix: Developed python code used in the tool.

This appendix contains the python code that is used to create the design alternatives and determine their costs and environmental impact. The grasshopper code and visual studio code is difficult to visualise on paper. Therefore, this script, the grasshopper code and the visual studio code of application is coded can be found on GitHub:

https://github.com/koenaardoom/MsC_Thesis_DonorSteel

```
1 ## Load all necessary packages
2 from itertools import combinations
3 from itertools import permutations
4 from sys import argv
5 import matplotlib.pyplot as plt
6 import numpy as np
7 import pandas as pd
8
9 ## Command that prevents iteration error in pandas
10 pd.options.mode.chained_assignment = None # default='warn'
11
12 ## Structural analysis code for model 1 horizontal forces
13 def Model1Horizontal(h, b, bays, floors, F1, LF):
14     forces = np.ones(int(floors)) * F1 * LF
15     forces[0] = F1/2 * LF
16     columns = np.zeros(shape = (3, int(floors), int(bays+1)))
17     beams = np.zeros(shape = (3, int(floors), int(bays)))
18     adj = int(np.floor(bays/2))
19
20     for i in range(int(floors)): ## per floor
21         Vc = np.zeros(int(bays+1))
22         Nc = np.zeros(int(bays+1))
23         Mc = np.zeros(int(bays+1))
24
25         Vb = np.zeros(int(bays))
26         Nb = np.zeros(int(bays))
27         Mb = np.zeros(int(bays))
28
29         if i == 0:
30             N = forces[i] * h / b
31             Nc[adj] = N
32             Nc[adj+1] = N
33         elif i == 1:
34             M = forces[i] * h + forces[i-1] * (2*h)
35             N = M / b
36             Nc[adj] = N
37             Nc[adj+1] = N
38         else:
39             M = forces[i] * h + forces[i-1] * (2*h) + forces[i-2] * (3*h)
```

```

40         N = M / b
41         Nc[adj] = N
42         Nc[adj+1] = N
43
44         columns[0][i] = Vc
45         columns[1][i:] = Nc
46         columns[2][i] = Mc
47
48         beams[0][i] = Vb
49         beams[1][i] = Nb
50         beams[2][i] = Mb
51     return(columns, beams)
52
53 ## Structural analysis code for model 1 vertical forces
54 def Model1Vertical(h, b, bays, floors, floorspan, LF, G, Qf, Qr, Gfact, Qfact, psiQf, psiQr,
55     extreme):
56     columns = np.zeros(shape = (3, int(floors), int(bays+1)))
57     beams = np.zeros(shape = (3, int(floors), int(bays)))
58
59     for i in range(int(floors)):
60         if i == 0:
61             q = (Gfact * G + Qfact * Qr * psiQr) * LF * floorspan
62         else:
63             q = (Gfact * G + Qfact * Qr * psiQf) * LF * floorspan
64
65         if extreme == 1 and i == 0 and floors == 3:
66             q = (1.2*G + 1.5*Qr*0) * LF * floorspan
67
68         Vc = np.zeros(int(bays+1))
69         Nc = np.ones(int(bays+1))
70         Mc = np.zeros(int(bays+1))
71
72         Vb = np.ones(int(bays))
73         Nb = np.zeros(int(bays))
74         Mb = np.ones(int(bays))
75
76         Mb = Mb * (1/8) * q * b**2
77         Nc = Nc * q * b
78         Nc[0] = Nc[0] / 2
79         Nc[-1] = Nc[-1] / 2
80
81         Vb = Vb * ( ((1/8) * q * b**2 * 2) / (b/2) )
82
83         columns[0][i] = Vc
84         columns[1][i:] += Nc
85         columns[2][i] = Mc
86
87         beams[0][i] = Vb
88         beams[1][i] = Nb
89         beams[2][i] = Mb
90     return(columns, beams)
91
92 ## Structural analysis code for model 2 horizontal forces
93 def Model2Horizontal(h, b, bays, floors, F1, LF):
94     forces = np.ones(int(floors)) * F1 * LF
95     forces[0] = F1/2 * LF
96     columns = np.zeros(shape = (3, int(floors), int(bays+1)))
97     beams = np.zeros(shape = (3, int(floors), int(bays)))
98     Force = 0
99     for i in range(int(floors)):    ## per floor
100         Vc = np.zeros(int(bays+1))
101         Nc = np.zeros(int(bays+1))
102         Mc = np.zeros(int(bays+1))
103
104         Vb = np.zeros(int(bays))
105         Nb = np.zeros(int(bays))
106         Mb = np.zeros(int(bays))
107         Force += forces[i]
108
109     if i == 0:    ## First floor
110         ## Shearforce in columns

```

```

110     Vc = np.ones(int(bays+1)) * Force * (2 / (int(bays-1)*2 + 2* 1))
111     Vc[0] /= 2
112     Vc[-1] /= 2
113     ## Moment in top of columns
114     Mc = Vc * h
115     ## Normal force in beams
116     Fres = forces[i]
117     for j in range(int(bays)):
118         Nb[j] = Fres - Vc[j]
119         if j == int(bays - 1):
120             Vb[j] = Vb[j - 1]
121             Mb[j] = np.max( [Mc[-1], abs(Mc[-1] - b * Vb[j])] )
122         elif j == 0:
123             Vb[j] = ((Fres - Nb[j]) * h ) / (b/2)
124             Mb[j] = np.max( [Mc[0], abs(Mc[0] - b*Vb[j])] )
125         else:
126             Vb[j] = ((Fres - Nb[j]) * h - Vb[j-1] * (b/2)) / (b/2)
127             Mb[j] = np.max( [abs(Mb[j-1] - Mc[j]), abs(abs(Mb[j-1] - Mc[j]) - Vb[j] *
128                 h)] )
129             Fres = Nb[j]
130
131     ## Normalforce in columns
132     for j in range(int(bays+1)):
133         if j ==0:
134             Nc[j] = Vb[j]
135         elif j == int(bays):
136             Nc[j] = Vb[-1]
137         else:
138             Nc[j] = np.round(Vb[j-1] - Vb[j])
139
140     else:
141         Vc = np.ones(int(bays+1)) * Force * (2 / (int(bays-1)*2 + 2* 1))
142         Vc[0] /= 2
143         Vc[-1] /= 2
144         Mc = Vc * h
145
146         Fres = forces[i]
147         for j in range(int(bays)):
148             Nb[j] = columns[0][i-1][j] + Fres - Vc[j]
149
150             if j == int(bays - 1):
151                 Vb[j] = Vb[j - 1]
152                 Mb[j] = np.max( [Mc[-1], abs(Mc[-1] - b * Vb[j])] )
153             elif j == 0:
154                 Vb[j] = ((columns[0][i-1][j] + Fres - Nb[j]) * h ) / (b/2)
155                 Mb[j] = np.max( [Mc[0], abs(Mc[0] - b*Vb[j])] )
156             else:
157                 Vb[j] = ((columns[0][i-1][j] + Fres - Nb[j]) * h - Vb[j-1] * (b/2)) / (b
158                     /2)
159                 Mb[j] = np.max( [abs(Mb[j-1] - Mc[j]), abs(abs(Mb[j-1] - Mc[j]) - Vb[j] *
160                     h)] )
161                 Fres = Nb[j]
162
163         for j in range(int(bays+1)):
164             if j ==0:
165                 Nc[j] = Vb[0] + columns[1][i-1][j]
166             elif j == int(bays):
167                 Nc[j] = Vb[-1] + columns[1][i-1][j]
168             else:
169                 Nc[j] = Vb[j-1] - Vb[j] + columns[1][i-1][j]
170
171         columns[0][i] = Vc
172         columns[1][i] = Nc
173         columns[2][i] = Mc
174
175         beams[0][i] = Vb
176         beams[1][i] = Nb
177         beams[2][i] = Mb
178
179     utot = (1/500) * floors * h * 10**3
180     us = (1/300) * h * 10**3

```



```

178 EI1 = 0
179 EI2 = 0
180 res = []
181 for i in range(int(floors)):
182     if i == int(floors-1):
183         tot1 = (((beams[2][i][0]*10**6 * ((b*10**3)/2)) / 3) * (h*10**3) + (np.max(
184             columns[0][i]*10**3 * (h*10**3)**3) / 3)
185         tot2 = ( ((beams[2][i][0]*10**6 * ((b*10**3)/2)) / 3) * (h*10**3) + (np.min(
186             columns[0][i]*10**3 * (h*10**3)**3) / 3)
187         EI1 += tot1
188         EI2 += tot2
189         res.append(1/ (us / tot1) / 210e3 / 1e6)
190         res.append(1/ (us / tot2) / 210e3 / 1e6)
191     else:
192         tot1 = (((beams[2][i][0]*10**6 * ((b*10**3)/2)) / 3) * (h*10**3) + (np.max(
193             columns[0][i]*10**3 * (h*10**3)**3) / 3)
194         tot2 = (((beams[2][i][0]*10**6 * ((b*10**3)/2)) / 3) * (h*10**3) + (np.min(
195             columns[0][i]*10**3 * (h*10**3)**3) / 3)
196         EI1 += tot1
197         EI2 += tot2
198         res.append(1/ (us / tot1) / 210e3 / 1e6)
199         res.append(1/ (us / tot2) / 210e3 / 1e6)
200     res.append(1/ (utot / EI1) / 210e3 / 1e6)
201     res.append(1/ (utot / EI2) / 210e3 / 1e6)
202 return(columns, beams,res)
203
204 ## Structural analysis code for model 2 vertical forces
205 def Model2Vertical(h, b, bays, floors, floorspan,LF, G, Qf, Qr, Gfact, Qfact, psiQf, psiQr,
206 extreme):
207     columns = np.zeros(shape = (3, int(floors), int(bays+1)))
208     beams = np.zeros(shape = (3, int(floors), int(bays)))
209     for i in range(int(floors)): ## per floor
210         if i == 0:
211             q1 = (Gfact * G + Qfact * Qr * psiQr) * LF * floorspan
212         else:
213             q1 = (Gfact * G + Qfact * Qr * psiQf) * LF * floorspan
214         if extreme == 1 and i == 0 and floors == 3:
215             q1 = (1.2*G + 1.5*Qr*0) * LF * floorspan
216     Vc = np.zeros(int(bays+1))
217     Nc = np.zeros(int(bays+1))
218     Mc = np.zeros(int(bays+1))
219     Vb = np.zeros(int(bays))
220     Nb = np.zeros(int(bays))
221     Mb = np.zeros(int(bays))
222     q12 = (1/8) * q1 * b**2
223     M = (0.8 * b * q1 / 2) * (0.1 * b) + (0.1 * b * q1) * (0.05 * b)
224     ## Maximum moments beams
225     Mb = np.ones(int(bays)) * M * 2
226     ## Moments outer columns
227     Mc[0] = M
228     Mc[-1] = M
229     ## Shearforce columns
230     Vc = Mc/h
231     ## Normalforce columns
232     for j in range(int(bays+1)):
233         if j == 0 or j == int(bays):
234             M1 = Mc[0]
235             M2 = M*2
236             V = (abs(((M1 + M2) / 2) - 2 * q12) + Mc[0]) / (b/2)
237             Nc[j] = V
238         else:
239             V = (abs(M*2 - 2 * q12) + 2*M) / (b/2)

```

```

244         Nc[j] = 2 * V
245
246     ## Maximum shearforce beams
247     Vb = (abs(M*2 - 2 * ql2) + 2*M) / (b/2)
248
249     columns[0][i] = Vc
250     columns[1][i:] += Nc
251     columns[2][i] = Mc
252
253     beams[0][i] = Vb
254     beams[1][i] = Nb
255     beams[2][i] = Mb
256     return(columns,beams)
257
258 ## Function to determine require I to fulfill local deformation limits beams model 1
259 def llocal1(b, q):
260     Ireq = (1/0.003) * ((5*q*(b*10**3)**3) / (384*210e3))
261     return(Ireq/1e6)
262
263 ## Function to determine require I to fulfill local deformation limits beams model 2
264 def llocal2(b, q, kspanc):
265     if kspanc == 1:
266         Ireq = (1/0.003) * ((5*q*(b*10**3)**3) / (384*210e3))
267     elif kspanc == 2:
268         Ireq = (1/0.003) * ((q*(b*10**3)**3) / (110*102*210e3))
269     elif kspanc == 3:
270         Ireq = (1/0.003) * ((q*(b*10**3)**3) / (101*102*210e3))
271     else:
272         Ireq = (1/0.003) * ((q*(b*10**3)**3) / (102*102*210e3))
273     return(Ireq/1e6)
274
275 ## Function to determine normal force capacity under buckling conditions
276 def Nrd(minor, lbuc, I, A, fy):
277     m = ["a", "b", "c", "d"]
278     alphas = [0.21, 0.34, 0.49, 0.76]
279     a = alphas[m.index(minor)]
280     Ncr = (np.pi**2 * 210e3 * I) / (lbuc*10**3)**2
281     lamb = np.sqrt((A * fy) / Ncr)
282     n = a * (lamb - 0.2)
283     g = 0.5 * (1 + n + lamb**2)
284     chi = 1 / (g + np.sqrt(g**2 - lamb**2))
285     return((chi * A * fy) / 1000)
286
287 ## The function to generate and evaluate the designs
288 def TheCode(Wmult, Useful, Designname, percreuse1, percreuse2):
289     ## Load all parameters from the tool and grasshopper design.
290     Wmult = float(Wmult)
291     Useful = float(Useful)
292     reusepercentage1 = float(percreuse1) / 100
293     reusepercentage2 = float(percreuse2) / 100
294
295     GHparams = pd.read_excel("GHuitvoer.xlsx", sheet_name = "inputarg")
296     GHbeams = pd.read_excel("GHuitvoer.xlsx", sheet_name = "geometrybeams")
297     GHcolumns = pd.read_excel("GHuitvoer.xlsx", sheet_name = "geometrycolumns")
298     NewElems = pd.read_excel("NewElements.xlsx", skiprows = [1,2])
299
300     hoh = float(GHparams.hohkolom)
301     kspanc = float(GHparams["#kolomspans"])
302     floors = float(GHparams["#verdiepingen"])
303     floorheight = float(GHparams.verdiepingshoogte)
304     fspanc = float(GHparams["#floorspans"])
305     fspan = float(GHparams.floorspan)
306     Gfloor = float(GHparams.Gfloor)
307
308     ## Determine the floorloads based on floor type and floor span
309     if Gfloor == 1:
310         if fspan == 3.6:
311             G = 0.36 + 1.05
312         elif fspan == 5.4:
313             G = 0.39 + 1.05
314         elif fspan == 7.2:

```

```

315         G = 0.44 + 1.05
316     else:
317         G = 0.72 + 1.05
318 elif Gfloor == 3:
319     if fspan == 10.8:
320         G = 3.83 + 1.8
321     else:
322         G = 2.83 + 1.8
323
324 ## Set variable floor load
325 Q = 4 ## including light seperation walls
326
327 ## Calculate wind-forces on building envelope
328 hd = (floors * floorheight) / (hoh * kspanc)
329 hps = [1,2,3,4,5,6,7,8,9,10,15,20]
330 qps = [0.69, 0.69, 0.69, 0.69, 0.69, 0.69, 0.69, 0.73, 0.77, 0.81, 0.96, 1.07]
331 qp = np.interp(floors * floorheight, hps, qps)
332
333 if hd >= 5:
334     Q_wind = qp * (1.0 + 0.7)
335 elif hd < 5 and hd > 1:
336     c_r = ((hd - 1) / 4) * 0.15 + 0.85
337     Q_wind = qp * (0.8 * 0.5) * c_r
338 else:
339     Q_wind = qp * (0.7 + 0.3) * 0.85
340
341 Fw = fspan * floorheight * Q_wind
342
343 ## Create empty columns to save governing design laods from structural analysis.
344 GHcolumns["N1"] = np.zeros(len(GHcolumns))
345 GHbeams["V1"] = np.zeros(len(GHbeams))
346 GHbeams["M1"] = np.zeros(len(GHbeams))
347 GHbeams["I1"] = np.zeros(len(GHbeams))
348
349
350 GHcolumns["N2"] = np.zeros(len(GHcolumns))
351 GHcolumns["I2"] = np.zeros(len(GHcolumns))
352 GHcolumns["V2"] = np.zeros(len(GHcolumns))
353 GHbeams["V2"] = np.zeros(len(GHbeams))
354 GHbeams["M2"] = np.zeros(len(GHbeams))
355 GHbeams["I2"] = np.zeros(len(GHbeams))
356
357 for i in range(int(fspanc+1)):
358
359     ## Set load-factor for edge and internal frame
360     if i == 0 or i == int(fspanc):
361         factor = 0.5
362     else:
363         factor = 1
364
365     ##Model 1 analysis ULS
366     maxQ1beam = Model1Vertical(floorheight, hoh, kspanc, floors, fspan, factor, G, Q, 2,
367                               1.2, 1.5, 1, 1, 0)[1]
368     maxG1beam = Model1Vertical(floorheight, hoh, kspanc, floors, fspan, factor, G, Q, 2,
369                               1.35, 1.5, 0.5, 0, 0)[1]
370     wind1beam = Model1Horizontal(floorheight, hoh, kspanc, floors, 1.5*Fw, factor)[1] +
371                 Model1Vertical(floorheight, hoh, kspanc, floors, fspan, factor, G, Q, 2, 1.2,
372                               1.5, 0.5, 0, 0)[1]
373
374     maxG1col = Model1Vertical(floorheight, hoh, kspanc, floors, fspan, factor, G, Q, 2,
375                               1.35, 1.5, 0.5, 0, 0)[0]
376     extremeQ1col = Model1Vertical(floorheight, hoh, kspanc, floors, fspan, factor, G, Q,
377                                   2, 1.2, 1.5, 1, 1, 1)[0]
378     wind1col = Model1Horizontal(floorheight, hoh, kspanc, floors, 1.5*Fw, factor)[1] +
379                 Model1Vertical(floorheight, hoh, kspanc, floors, fspan, factor, G, Q, 2, 1.2,
380                               1.5,0.5,0,0)[1]
381
382     ##Model 2 analysis ULS
383     maxQ2beam = Model2Vertical(floorheight, hoh, kspanc, floors, fspan, factor, G, Q, 2,
384                               1.2, 1.5, 1, 1, 0)[1]

```

```

376 maxG2beam = Model2Vertical(floorheight, hoh, kspanc, floors, fspan, factor, G, Q, 2,
377 1.35, 1.5, 0.5, 0, 0)[1]
wind2beam = Model2Horizontal(floorheight, hoh, kspanc, floors, 1.5*Fw, factor)[1] +
Model2Vertical(floorheight, hoh, kspanc, floors, fspan, factor, G, Q, 2, 1.2,
1.5, 0.5, 0, 0)[1]
378
379 maxG2col = Model2Vertical(floorheight, hoh, kspanc, floors, fspan, factor, G, Q, 2,
1.35, 1.5, 0.5, 0, 0)[0]
380 extremeQ2col = Model2Vertical(floorheight, hoh, kspanc, floors, fspan, factor, G, Q,
2, 1.2, 1.5, 1, 1, 1)[0]
381 wind2col = Model2Horizontal(floorheight, hoh, kspanc, floors, 1.5*Fw, factor)[0] +
Model2Vertical(floorheight, hoh, kspanc, floors, fspan, factor, G, Q, 2, 1.2,
1.5, 1, 1, 1)[0]
382
383 ## Model 2 analysis global deformation (SLS combination)
384 EIreq = Model2Horizontal(floorheight, hoh, kspanc, floors, Fw, factor)[2]
385
386 for j in range(int(floors)):
387     ##Model 1 assignment
388     for x in range(int(kspanc+1)):
389         GHcolumns.N1.iloc[int(i * (kspanc+1) * floors + j * (kspanc+1)) + x] = np.max(
([maxG1col[1][int(floors)-(j+1)][x], wind2col[1][int(floors)-(j+1)][x],
extremeQ2col[1][int(floors)-(j+1)][x]])
390     for x in range(int(kspanc)):
391         GHbeams.V1.iloc[int(i * (kspanc) * floors + j * (kspanc)) + x] = np.max([
maxQ1beam[0][int(floors)-(j+1)][x], maxG1beam[0][int(floors)-(j+1)][x],
wind1beam[0][int(floors)-(j+1)][x]])
392         GHbeams.M1.iloc[int(i * (kspanc) * floors + j * (kspanc)) + x] = np.max([
maxQ1beam[2][int(floors)-(j+1)][x], maxG1beam[2][int(floors)-(j+1)][x],
wind1beam[2][int(floors)-(j+1)][x]])
393         GHbeams.I1.iloc[int(i * (kspanc) * floors + j * (kspanc)) + x] = Ilocal1(hoh,
1*G + 1*Q)
394
395     ## Model 2 assignment
396     for x in range(int(kspanc+1)):
397         GHcolumns.N2.iloc[int(i * (kspanc+1) * floors + j * (kspanc+1)) + x] = np.max(
([maxG2col[1][int(floors)-(j+1)][x], wind2col[1][int(floors)-(j+1)][x],
extremeQ2col[1][int(floors)-(j+1)][x]])
398         GHcolumns.V2.iloc[int(i * (kspanc+1) * floors + j * (kspanc+1)) + x] = np.max(
([maxG2col[0][int(floors)-(j+1)][x], wind2col[0][int(floors)-(j+1)][x],
extremeQ2col[0][int(floors)-(j+1)][x]])
399         if x == 0 or x == int(kspanc):
400             GHcolumns.I2.iloc[int(i * (kspanc+1) * floors + j * (kspanc+1)) + x] = np
.max([EIreq[j*2 + 1], EIreq[-1]])
401         else:
402             GHcolumns.I2.iloc[int(i * (kspanc+1) * floors + j * (kspanc+1)) + x] = np
.max([EIreq[j*2], EIreq[-2]])
403
404     for x in range(int(kspanc)):
405         GHbeams.V2.iloc[int(i * (kspanc) * floors + j * (kspanc)) + x] = np.max([
maxQ2beam[0][int(floors)-(j+1)][x], maxG2beam[0][int(floors)-(j+1)][x],
wind2beam[0][int(floors)-(j+1)][x]])
406         GHbeams.M2.iloc[int(i * (kspanc) * floors + j * (kspanc)) + x] = np.max([
maxQ2beam[2][int(floors)-(j+1)][x], maxG2beam[2][int(floors)-(j+1)][x],
wind2beam[2][int(floors)-(j+1)][x]])
407         GHbeams.I2.iloc[int(i * (kspanc) * floors + j * (kspanc)) + x] = np.max([
Ilocal2(hoh, 1*G+1*Q, kspanc), EIreq[j], EIreq[-1]])
408
409 ## Initial sway-imperfections and second-order effects
410 theta0 = 1/200 ## Initial sway-imperfection for steel
columns
411 am = np.sqrt(0.5 * (1 + 1/kspanc + 1)) ## Reduction factor for contributing columns
412 ah = 2 / np.sqrt(floors * floorheight) ## Reduction factor for building height
413 theta = theta0 * ah * am + (1/300) ## Total rotation of each column: initial
sway imperfection and displacement due windloading.
414 N = np.array(GHcolumns.N2)
415 V = np.array(GHcolumns.V2)
416 H = N * theta ## Equivalent horizontal forces due to total
displacement of the column
417 factor = (H/V + 1) ## Moment factor (initial sway imperfections
+ second order effect) per column

```

```

418
419     for i in range(int(fspanc+1)):
420         for j in range(int(floors)):
421             n = factor[j * int(kspanc+1) + i * int(floors)*int(kspanc)]           ## Determine
                second-order+initial sway imp factor per storey.
422             GHbeams.M2.iloc[j*int(kspanc) + i * int(floors)*int(kspanc):(j+1)*int(kspanc) + i
                * int(floors)*int(kspanc)] *= n           ## Multiply bending moments accordingly
                per storey
423
424
425     ## Determine normal force capacity including buckling for new steel elements
426     NewElems["Nrd1"] = np.zeros(len(NewElems))
427     NewElems["Nrd2"] = np.zeros(len(NewElems))
428     for i in range(len(NewElems)):
429         NewElems["Nrd1"].iloc[i] = Nrd(NewElems["Buckling about minor axis z-z"].iloc[i],
                floorheight*1.0, NewElems["Second moment of area z"].iloc[i] * 10**6, NewElems.
                Area.iloc[i], 355);
430         NewElems["Nrd2"].iloc[i] = Nrd(NewElems["Buckling about minor axis z-z"].iloc[i],
                floorheight*0.7, NewElems["Second moment of area z"].iloc[i] * 10**6, NewElems.
                Area.iloc[i], 355);
431         NewElems["MrdN"] = NewElems["Plastic section modulus"] * 355 /1000
432
433     GHcolumns["NCS1"] = np.zeros(len(GHcolumns))
434     GHcolumns["NG1"] = np.zeros(len(GHcolumns))
435     GHbeams["NCS1"] = np.zeros(len(GHbeams))
436     GHbeams["NG1"] = np.zeros(len(GHbeams))
437
438     GHcolumns["NCS2"] = np.zeros(len(GHcolumns))
439     GHcolumns["NG2"] = np.zeros(len(GHcolumns))
440     GHbeams["NCS2"] = np.zeros(len(GHbeams))
441     GHbeams["NG2"] = np.zeros(len(GHbeams))
442
443     ## Create the new steel design alternatives using minimum required I and M
444     for f in range(int(fspanc+1)):           ## Structural configuration 1: braced frame
445         model1G = []
446         model1I = []
447         model2G = []
448         model2I = []
449         for i in range(int(kspanc+1)):
450             Nlead2 = (NewElems[18:42].Profile.loc[NewElems.Nrd2 > GHcolumns.N2.iloc[f*int( (
                kspanc+1) * floors) + i]].tolist()[0])
451             Ilead2 = (NewElems[18:42].Profile.loc[NewElems["Second moment of area y"] >
                GHcolumns.I2.iloc[f*int( (kspanc+1) * floors) + i]].tolist()[0])
452
453             model1I.append(NewElems[18:42].Profile.loc[NewElems.Nrd1 > GHcolumns.N1.iloc[f*
                int( (kspanc+1) * floors) + i]].tolist()[0])
454             model1G.append(NewElems[18:42].Weight.loc[NewElems.Nrd1 > GHcolumns.N1.iloc[f*int
                ( (kspanc+1) * floors) + i]].tolist()[0])
455
456             if int(Nlead2[-3:]) > int(Ilead2[-3:]):
457                 model2I.append(Nlead2)
458                 model2G.append(NewElems[18:42].Weight.loc[NewElems.Nrd2 > GHcolumns.N2.iloc[f
                *int( (kspanc+1) * floors) + i]].tolist()[0])
459             else:
460                 model2I.append(Ilead2)
461                 model2G.append(NewElems[18:42].Weight.loc[NewElems["Second moment of area y"]
                > GHcolumns.I2.iloc[f*int( (kspanc+1) * floors) + i]].tolist()[0])
462
463
464         for i in range(int(floors)):
465             GHcolumns.NCS1.iloc[int(f*(kspanc+1)*floors + i * (kspanc+1)):int(f*(kspanc+1)*
                floors + (i+1) * (kspanc+1))] = model1I
466             GHcolumns.NG1.iloc[int(f*(kspanc+1)*floors + i * (kspanc+1)):int(f*(kspanc+1)*
                floors + (i+1) * (kspanc+1))] = model1G
467             GHcolumns.NCS2.iloc[int(f*(kspanc+1)*floors + i * (kspanc+1)):int(f*(kspanc+1)*
                floors + (i+1) * (kspanc+1))] = model2I
468             GHcolumns.NG2.iloc[int(f*(kspanc+1)*floors + i * (kspanc+1)):int(f*(kspanc+1)*
                floors + (i+1) * (kspanc+1))] = model2G
469
470         model2G = []
471         model2I = []

```

```

472     model1G = []
473     model1I = []
474
475     for i in range(int(kspanc)):      ## Structural configuration 2: portal frame
476         Ilead1 = (NewElems.Profile.loc[NewElems["Second moment of area y"] > GHbeams.I1.
477             iloc[f*int(kspanc * floors)+1]].tolist()[0])
478         Mlead1 = (NewElems.Profile.loc[NewElems.MrdN > GHbeams.M1.iloc[f*int(kspanc *
479             floors)+1]].tolist()[0])
480         Ilead2 = (NewElems.Profile.loc[NewElems["Second moment of area y"] > GHbeams.I2.
481             iloc[f*int(kspanc * floors)+1]].tolist()[0])
482         Mlead2 = (NewElems.Profile.loc[NewElems.MrdN > GHbeams.M2.iloc[f*int(kspanc *
483             floors)+1]].tolist()[0])
484
485         if int(Mlead2[-3:]) > int(Ilead2[-3:]):
486             model2I.append(Mlead2)
487             model2G.append(NewElems.Weight.loc[NewElems.MrdN > GHbeams.M2.iloc[f*int(
488                 kspanc * floors)+1]].tolist()[0])
489         else:
490             model2I.append(Ilead2)
491             model2G.append(NewElems.Weight.loc[NewElems["Second moment of area y"] >
492                 GHbeams.I2.iloc[f*int(kspanc * floors)+1]].tolist()[0])
493
494         if int(Mlead1[-3:]) > int(Ilead1[-3:]):
495             model1I.append(Mlead1)
496             model1G.append(NewElems.Weight.loc[NewElems.MrdN > GHbeams.M1.iloc[f*int(
497                 kspanc * floors)+1]].tolist()[0])
498         else:
499             model1I.append(Ilead1)
500             model1G.append(NewElems.Weight.loc[NewElems["Second moment of area y"] >
501                 GHbeams.I1.iloc[f*int(kspanc * floors)+1]].tolist()[0])
502
503     for i in range(int(floors)):
504         GHbeams.NCS1.iloc[int(f*(kspanc)*floors + i * (kspanc)):int(f*(kspanc)*floors + (
505             i+1) * (kspanc))] = model1I
506         GHbeams.NG1.iloc[int(f*(kspanc)*floors + i * (kspanc)):int(f*(kspanc)*floors + (i
507             +1) * (kspanc))] = model1G
508         GHbeams.NCS2.iloc[int(f*(kspanc)*floors + i * (kspanc)):int(f*(kspanc)*floors + (
509             i+1) * (kspanc))] = model2I
510         GHbeams.NG2.iloc[int(f*(kspanc)*floors + i * (kspanc)):int(f*(kspanc)*floors + (i
511             +1) * (kspanc))] = model2G
512
513     ## Load database of donor elements from tool
514     ddata = pd.read_excel('Database.xlsx')
515     ddata['Mcap'] = (ddata.W * ddata.Fy) / 1000      ## Calculate the moment-capacity for
516     all donor elements
517     ddata['Npl'] = np.zeros(len(ddata))
518     ddata['Nrd1'] = np.zeros(len(ddata))
519     ddata['Nrd2'] = np.zeros(len(ddata))
520
521     ## Calculate normal-force capacity for all donor elements
522     for i in range(len(ddata)):
523         ddata.Npl.iloc[i] = ddata.A.iloc[i] * ddata.Fy.iloc[i] / 1000
524         ddata.Nrd1.iloc[i] = Nrd(ddata["bucmin"].iloc[i], floorheight*1, ddata.Iz.iloc[i] *
525             10**6, ddata.A.iloc[i], ddata.Fy.iloc[i]);
526         ddata.Nrd2.iloc[i] = Nrd(ddata["bucmin"].iloc[i], floorheight*0.7, ddata.Iz.iloc[i] *
527             10**6, ddata.A.iloc[i], ddata.Fy.iloc[i]);
528
529     ## Assignment model 1 columns (continuous)
530     ids = list(ddata.index)
531     lengths = list(ddata.Length)
532     G = list(ddata.G)
533     Wd = list(ddata.Nrd1)
534     target = floors * floorheight
535
536     ## Exclude elements that are not strong/long enough
537     ids1 = ddata.index[ddata.Nrd1 > GHcolumns.N1.min()].tolist()
538     ids2 = ddata.index[ddata.Length > 0.5 * floorheight].tolist()
539     idschecked = np.intersect1d(ids1, ids2)
540
541     ## Create empty arrays to store valid combinations

```

```

528 lengthperms = []
529 fits = []
530 fit = []
531 strength = []
532 MaxG = NewElems[18:42].Weight.loc[NewElems.Nrd1 > GHcolumns.N1.max()].tolist()[0]
533
534 for i in range(int(floors)):
535     perms = list(combinations(idschecked, i+1))    ## Create all permutations for i
536     amount of elements in one columns
537     lengthperms.append(len(perms))                ## Keep track of amount of options per
538     i
539     for perm in range(len(perms)):                ## Loop through all permutations
540         lres = target
541         W = 0
542         s = []
543
544         for p in perms[perm]:                    ## Loop through parts of permutation
545             l = lengths[p]                      ## Length of part
546             Gd = G[p]
547             if lres - l > 0:                      ## If resultant length > 0: save
548                 weight and strength
549                 lres -= l
550                 W += Gd * l
551                 s.append(Wd[p])
552
553             else:                                ## If resultant length < 0 ..
554                 if lres - l < 0 and p != perms[perm][-1]: ## .. and not the last piece
555                     --> perm not possible
556                     break
557
558                 elif lres - l > Useful:          ## .. and bigger than Useful rest
559                     length --> possible calc weight with required length
560                     W += Gd * lres
561                     s.append(Wd[p])
562
563                 else:                            ## .. and smaller than Useful rest
564                     length --> possible calc weight with part length
565                     W += Gd * l
566                     s.append(Wd[p])
567
568             if W < MaxG * floorheight * Wmult * floors: ## If total weight is
569                 smaller than limit save perm information
570                 fits.append(perms[perm])
571                 fit.append(W)
572                 strength.append(np.min(s))
573
574     colsf = int(kspanc + 1) * int(floors)
575     ass1 = np.zeros(len(ddata))
576     Wlreq = 0
577     Wlnew = 0
578     Wastel = 0
579     assC1 = np.zeros( (int(fspanc+1) * int(kspanc+1), len(ddata)) )
580     fitass = fit
581
582     for frame in range(int(fspanc+1)):           ## Loop through each frame
583
584         for col in range(int(kspanc+1)):         ## Loop through each frame'
585             s columns
586             Weis = GHcolumns.N1.iloc[frame * colsf + col] ## Determine minimum N
587             for j in range(len(fitass)):         ## Loop through all
588                 possible combinations
589                 if np.isnan(fitass) <= 0:
590                     break
591
592                 else:
593                     bestfit = np.nanargmin(fitass) ## Find best fit
594                     Wbestfit = fitass[bestfit]   ## Determine weight
595                     best fit
596
597                     Sbestfit = strength[bestfit] ## Determine strength
598                     best fit
599
600             if np.isnan(fitass) <= 0:

```



```

651
652     ## Save rest length or waste
653     if dl - lreq >= Useful:
654         lengths[col] = dl - lreq
655     else:
656         lengths[col] = 0
657         Wastel += ddata.G.iloc[col] * (dl - lreq)
658
659     Wireq += ddata.G.iloc[col] * (lreq) ## Add weight of fitted element
660     count+=1
661     FitB1[row] = 0 ## Remove donor element from fit-array
662     else:
663         FitB1[row,col] = 0 ## Remove fit from array
664
665     ## Calculate weight of new steel beams in reclaimed steel structure (braced frame)
666     for i in range(len(GHbeams)):
667         if np.sum(assB1[i]) == 0:
668             Wlnew += GHbeams.NG1.iloc[i] * GHbeams.Length.iloc[i]
669
670     count = 0
671     c = np.arange(kspanc+1, (kspanc+1)*(fspanc+1), kspanc+1)
672     ## Calculate weight of new steel columns in reclaimed steel structure (braced frame)
673     for i in range(len(assC1)):
674         if np.count_nonzero(c==i):
675             count += 1
676         if np.sum(assC1[i]) == 0:
677             Wlnew += GHcolumns.NG1.iloc[i + count * int(kspanc+1) * int(floors-1)] * floors *
678                 floorheight
679
680     ## Assignment of beams model 2 (portal frame)
681     ids = list(ddata.index)
682     lengths = list(ddata.Length)
683     G = list(ddata.G)
684     Id = list(ddata.Iy)
685     Wd = list(ddata.Mcap)
686     target = kspanc * hoh
687
688     ## Remove donor elements that are not strong/long enough
689     ids1 = ddata.index[ddata.Mcap > GHbeams.M2.min()].tolist()
690     ids2 = ddata.index[ddata.Length > 0.5 * hoh].tolist()
691     idschecked = np.intersect1d(ids1, ids2)
692
693     ## Create empty arrays to save valid combinations
694     lengthperms = []
695     fits = []
696     fit = []
697     strength = []
698     Is = []
699     ls = []
700
701     lsfl = np.arange(hoh * (3/4), hoh * kspanc - hoh/2, 1/2 * hoh)
702     lsm = np.arange(0.5 * hoh, 1.5 * hoh, 0.5 * hoh)
703     for i in range(int(kspanc)):
704         perms = list(permutations(idschecked, i+1)) ## Create all permutations for i
705             amount of elements in one columns
706         lengthperms.append(len(perms)) ## Keep track of amount of options per
707             i
708
709         for perm in range(len(perms)): ## Loop through all permutations
710             lreq = target
711             lt = 0
712             l = []
713             I = []
714             W = 0
715             s = []
716
717             for p in perms[perm]: ## Loop through parts of permutation
718                 lt += lengths[p] ## Length of part
719                 if lt >= lreq:
720                     for p in perms[perm]:
721                         ## Check length condition

```

```

719         if lreq - lengths[p] < 0 and p != perms[perm][-1]:
720             break
721     ## Last piece - length criteria
722     elif p == perms[perm][-1]:
723         if lreq - lengths[p] > 0:
724             break
725         else:
726             l.append(np.round(lreq, 2))
727             W += G[p] * lreq
728             s.append(Wd[p])
729             I.append(Id[p])
730             ## Check strength --> if okay add combination
731             if W < GHbeams.NG2.max()* GHbeams.Length.max() * kspanc * Wmult:
732                 fit.append(W)
733                 ls.append(l)
734                 fits.append(perms[perm])
735                 strength.append(np.min(s))
736                 Is.append(np.min(I))
737     ## first piece - length criteria
738     elif p == perms[perm][0]:
739         ltred = lsfl - lengths[p]
740         if ltred[0] < 0:
741             ltb = np.max(ltred[ltred<0]) + lengths[p]
742             l.append(np.round(ltb,2))
743             lreq -= ltb
744             W += G[p] * ltb
745             s.append(Wd[p])
746             I.append(Id[p])
747         else:
748             break
749     ## Middle pieces - length criteria
750     else:
751         ltred = lsm - lengths[p]
752         ltb = np.max(ltred[ltred<0]) + lengths[p]
753         l.append(np.round(ltb,2))
754         lreq -= ltb
755         W += G[p] * ltb
756         s.append(Wd[p])
757         I.append(Id[p])
758
759     ## Assignment of beam combinations from code above
760     bpf = kspanc * floors
761     ass2 = np.zeros(len(ddata))
762     assB2 = np.zeros( (int(floors * (fspanc+1)), len(ddata)) )
763     W2req = 0
764     W2new = 0
765     Waste2 = 0
766     fitass = fit
767     for frame in range(int(fspanc+1)):
768
769         for beam in range(int(floors)):
770             ## Determine minimum required W and I for beam in geometry
771             Weis = GHbeams.M2.iloc[int(frame * bpf + beam*kspanc):int(frame*bpf + (1+beam)*
772                 kspanc)].max()
773             Ieis = GHbeams.I2.iloc[int(frame * bpf + beam*kspanc):int(frame*bpf + (1+beam)*
774                 kspanc)].max()
775
776         for j in range(len(fitass)): ## Loop through all possible combinations
777             if np.isnan(fitass) <= 0: ## If no more combinations --> stop
778                 break
779         else:
780             bestfit = np.nanargmin(fitass) ## Find best fit
781             if bestfit == np.nan:
782                 break
783             Wbestfit = fitass[bestfit] ## Determine weight best fit
784             Sbestfit = strength[bestfit] ## Determine W best fit
785             Ibestfit = Is[bestfit] ## Determine I best fit
786
787         if Weis <= Sbestfit and Ieis <= Ibestfit: # Check strength
788             asscheck = 0

```

```

788         l = ls[bestfit] ## Get length
789         for d in fits[bestfit]: ## Check if elements
790             are still available
791             asscheck += ass2[d]
792             if asscheck == 0: ## If yes --> assign
793                 element in assignment matrix
794                 lreq = hoh * kspanc
795                 W2req += fitass[bestfit]
796                 ids = fits[bestfit]
797
798         for d in range(len(fits[bestfit])):
799             ass2[ids[d]] = 1 ## Set to assigned
800             fitass[bestfit] = np.nan ## Delete fit for
801             future selection
802             if lreq - l[d] >= 0: ## Set length to
803                 length of elements if total length is not reached
804                 assB2[int(frame * floors + beam), ids[d]] = l[d]
805                 W2req += l[d] * G[ids[d]]
806             else: ## Set length to rest
807                 length if total length is reached
808                 assB2[int(frame * floors + beam), ids[d]] = lreq
809                 W2req += lreq * G[ids[d]]
810                 lengths[ids[d]] = lreq - l[d]
811                 lreq -= l[d] ## Update rest length
812             break ## If assigned stop
813             look for this column
814
815         else:
816             fitass[bestfit] = np.nan
817     else:
818         fitass[bestfit] = np.nan
819
820 ## Assignment model 2 columns --> 'Simple' Assignment Matrix
821 FitC2 = np.zeros((len(GHcolumns), len(ddata)))
822
823 for i in range(len(GHcolumns)):
824     Gn = GHcolumns.NG2.iloc[i] ## Determine new steel equivalent weight
825     bl = GHcolumns.Length.iloc[i] ## Determine new steel equivalent length
826     Nmin2 = GHcolumns.N2.iloc[i] ## Determine required normal force capacity
827     Imin2 = GHcolumns.I2.iloc[i] ## Determine required I
828     for j in range(len(ddata)):
829         dl = ddata.Length.iloc[j] ## Determine donor length
830         Iyd = ddata.Iy.iloc[j] ## Determine donor I
831         Nrd2 = ddata.Nrd2.iloc[j] ## Determine donor Ncap
832         if Iyd >= Imin2 and Nrd2 >= Nmin2 and dl >= bl: ## Check strength (I and Ncap)
833             Gd = ddata.G.iloc[j] ## Determine donor steel element weight
834
835             ## Calculate fit
836             if dl - bl >= Useful:
837                 FitC2[i,j] = 1 - ((Gd * bl - Gn * bl) / ((Wmult-1)* Gn * bl))
838             else:
839                 FitC2[i,j] = 1 - ((Gd * dl - Gn * bl) / ((Wmult-1)* Gn * bl))
840
841 FitC2[FitC2<0] = 0 ## Delete all fits lower than 0 (do not fullfil weight requirement
842 )
843
844 ## Assignment of elements based on fit
845 assC2 = np.zeros( (len(GHcolumns), len(ddata)) )
846 count = 0
847 for i in range(len(GHcolumns) * len(ddata)):
848     if np.sum(FitC2) > 0: ## Check if any fits left
849         bestfit = np.max(FitC2) ## Select best fit
850         bestfitid = np.argmax(FitC2)
851         row = int(np.trunc(bestfitid / len(ddata)))
852         col = int(bestfitid - row * len(ddata))
853         dl = lengths[col]
854         lreq = GHcolumns.Length.iloc[row]
855         if dl >= lreq: ## Check length
856             assC2[row,col] = 1 ## Assign element
857             ## Determine rest piece or waste
858             if dl - lreq >= Useful:

```

```

852         lengths[col] = d1 - lreq
853     else:
854         lengths[col] = 0
855         Waste2 += ddata.G.iloc[col] * (d1 - lreq)
856         W2req += ddata.G.iloc[col] * (lreq)
857         count+=1
858         FitC2[row] = 0      ## remove donor element from fit-array
859     else:
860         FitC2[row,col] = 0  ## remove fit
861     else:
862         break
863 ## Calculate weight new steel columns in reclaimed steel design
864 for i in range(len(GHcolumns)):
865     if np.sum(assC2[i]) == 0:
866         W2new += GHcolumns.NG2.iloc[i] * GHcolumns.Length.iloc[i]
867
868 ## Calculate weight new steel beams in reclaimed steel design
869 for i in range(int(len(GHbeams)/kspanc)):
870     if np.sum(assB2[i]) == 0:
871         W2new += GHbeams.NG2.iloc[int(i*kspanc)] * kspanc * hoh
872
873 # Model 1 beams - save assignment info for database plot and grasshopper visualisation
874 H000200 = []
875 H200400 = []
876 H400600 = []
877 H6001000 = []
878 labelz = ["h = 0-200mm", "h = 200-400 mm", "h = 400-600 mm", "h = 600-1000 mm"]
879
880 B1 = []
881 D = []
882 G = []
883 for i in range(len(GHbeams)):
884     if np.sum(assB1[i]) > 0:
885         ids = np.argwhere(assB1[i]>0)
886         B1.append(ddata["Cross-section"].iloc[ids[0]].values[0])
887         G.append(ddata.G.iloc[ids[0]].values[0])
888         D.append("yes")
889
890         h = ddata.h.iloc[ids[0][0]]
891         l = ddata.Length.iloc[ids[0][0]]
892         if h <= 200:
893             H000200.append(1)
894         elif h > 200 and h <= 400:
895             H200400.append(1)
896         elif h > 400 and h <= 600:
897             H400600.append(1)
898         else:
899             H6001000.append(1)
900
901     else:
902         Ilead = (NewElems.Profile.loc[NewElems["Second moment of area y"] > GHbeams.I1.
903             iloc[i]].tolist()[0])
904         Nlead = (NewElems.Profile.loc[NewElems.MrdN > GHbeams.M1.iloc[i]].tolist()[0])
905         if int(Nlead[-3:]) > int(Ilead[-3:]):
906             B1.append(Nlead)
907         else:
908             B1.append(Ilead)
909         G.append("nvt")
910         D.append("no")
911 GHbeams["RCS1"] = B1
912 GHbeams["DG1"] = G
913 GHbeams["donor"] = D
914
915 # Model 1 columns - save assignment info for database plot and grasshopper visualisation
916 C1 = []
917 L = []
918 D = []
919
920 c = np.arange(kspanc+1, (kspanc+1)*(fspanc+1), kspanc+1)
921 count = 0

```

```

922 for i in range(len(assC1)):
923     k = []
924     l = []
925
926     if np.count_nonzero(c==i):
927         count += 1
928
929     if np.sum(assC1[i]) > 0:
930         ids = np.argwhere(assC1[i] > 0)
931         for j in ids:
932             k.append(ddata["Cross-section"].iloc[j].values[0])
933             l.append(assC1[i][j][0])
934
935             h = ddata.h.iloc[j[0]]
936             lg = ddata.Length.iloc[j[0]]
937             if h <= 200:
938                 H000200.append(lg)
939             elif h > 200 and h <= 400:
940                 H200400.append(lg)
941             elif h > 400 and h <= 600:
942                 H400600.append(lg)
943             else:
944                 H6001000.append(lg)
945
946         C1.append(k)
947         L.append(l)
948         D.append("yes")
949     else:
950         C1.append([NewElems[18:42].Profile.loc[NewElems.Nrd1 > GHcolumns.N1.iloc[i +
951             count * int(kspanc+1) * int(floors-1)]].tolist()[0]])
952         D.append("no")
953         L.append([floors * floorheight])
954
955 CD1 = pd.DataFrame(C1)
956 CL1 = pd.DataFrame(L)
957 arr = [H000200, H200400, H400600, H6001000]
958
959 ## Create database usage plot for model 1: braced frame
960 plt.figure(figsize = (12,5))
961 plt.hist(arr, label = labelz, bins = np.arange(0, 16,1))
962 plt.grid()
963 plt.xticks(np.arange(0, 16,1))
964 plt.legend()
965 plt.title("Availability of structural elements of a certain structural height and length"
966 )
967 plt.ylabel(f"Occurance in dataset (#)")
968 plt.xlabel(f"Element length (bins) --> e.g. 1 to 2 meters")
969 plt.savefig(f"DonorUse1.png", bbox_inches = 'tight')
970
971 # Model 2 beams - save assignment info for database plot and grasshopper visualisation
972 H000200 = []
973 H200400 = []
974 H400600 = []
975 H6001000 = []
976 labelz = ["h = 0-200mm", "h = 200-400 mm", "h = 400-600 mm", "h = 600-1000 mm"]
977
978 B2 = []
979 G = []
980 D = []
981 L = []
982
983 for i in range(len(assB2)):
984     k = []
985     l = []
986
987     if np.sum(assB2[i]) > 0:
988         ids = np.argwhere(assB2[i] > 0)
989         for j in ids:
990             k.append(ddata["Cross-section"].iloc[j].values[0])
991             l.append(assB2[i][j][0])

```

```

991         h = ddata.h.iloc[j[0]]
992         lg = ddata.Length.iloc[j[0]]
993         if h <= 200:
994             H000200.append(lg)
995         elif h > 200 and h <= 400:
996             H200400.append(lg)
997         elif h > 400 and h <= 600:
998             H400600.append(lg)
999         else:
1000             H6001000.append(lg)
1001
1002     B2.append(k)
1003     L.append(l)
1004     D.append("yes")
1005 else:
1006     B2.append([GHbeams.NCS2.iloc[int(i*kspanc)]])
1007     D.append("no")
1008     L.append([kspanc*hoh])
1009 BD2 = pd.DataFrame(B2)
1010 BL2 = pd.DataFrame(L)
1011
1012 # Model 2 columns - save assignment info for database plot and grasshopper visualisation
1013 C2 = []
1014 D = []
1015 for i in range(len(GHcolumns)):
1016     if np.sum(assC2[i]) > 0:
1017         ids = np.argwhere(assC2[i]>0)
1018         C2.append(ddata["Cross-section"].iloc[ids[0]].values[0])
1019         G.append(ddata.G.iloc[ids[0]].values[0])
1020         D.append("yes")
1021
1022         h = ddata.h.iloc[ids[0][0]]
1023         l = ddata.Length.iloc[ids[0][0]]
1024         if h <= 200:
1025             H000200.append(l)
1026         elif h > 200 and h <= 400:
1027             H200400.append(l)
1028         elif h > 400 and h <= 600:
1029             H400600.append(l)
1030         else:
1031             H6001000.append(l)
1032
1033     else:
1034         C2.append(GHcolumns.NCS2.iloc[i])
1035         G.append("nvt")
1036         D.append("no")
1037 arr = [H000200, H200400, H400600, H6001000]
1038
1039 ## Create database usage plot for model 2: portal frame
1040 plt.figure(figsize = (12,5))
1041 plt.hist(arr, label = labelz, bins = np.arange(0, 16,1))
1042 plt.grid()
1043 plt.xticks(np.arange(0, 16,1))
1044 plt.legend()
1045 plt.title("Availability of structural elements of a certain structural height and length"
1046 )
1047 plt.ylabel(f"Occurance in dataset (#)")
1048 plt.xlabel(f"Element length (bins) --> e.g. 1 to 2 meters")
1049 plt.savefig(f"DonorUse2.png", bbox_inches = 'tight')
1050
1051 GHcolumns["RCS2"] = C2
1052 GHcolumns["DG2"] = G
1053 GHcolumns["donor"] = D
1054
1055 ## Determine total weight new steel structures
1056 TotalNew1 = np.sum(GHcolumns.Length * GHcolumns.NG1) + np.sum(GHbeams.Length * GHbeams.
1057     NG1)
1058 TotalNew2 = np.sum(GHcolumns.Length * GHcolumns.NG2) + np.sum(GHbeams.Length * GHbeams.
1059     NG2)
1060
1061 ## load and save cost parameters from tool

```

```

1059 costresult = np.zeros((4,9))
1060 costparam = np.loadtxt("costparams.txt", delimiter = ",", encoding = "utf-8-sig")
1061
1062 NSP = costparam[0]
1063 SSP = costparam[1]
1064 SPP = costparam[2]
1065 FCN = costparam[3]
1066 FCR = costparam[4]
1067 ASC = costparam[5]
1068 ENC = costparam[6]
1069 Distance = costparam[7]
1070
1071 ## New Steel 1 cost evaluation
1072 Inkoop = TotalNew1 * NSP
1073 Sandblastingpaint = TotalNew1 * SPP
1074 Fabcosts = TotalNew1 * FCN
1075 AssemblyN1 = TotalNew1 * ASC
1076 EngineeringN1 = TotalNew1 * ENC
1077 costresult[0,0] = Inkoop
1078 costresult[0,4] = Sandblastingpaint
1079 costresult[0,5] = Fabcosts
1080 costresult[0,6] = AssemblyN1
1081 costresult[0,7] = EngineeringN1
1082 costresult[0,8] = np.sum(costresult[0]) * 0.05
1083
1084 ## New Steel 2 cost evaluation
1085 Inkoop = TotalNew2 * NSP
1086 Sandblastingpaint = TotalNew2 * SPP
1087 Fabcosts = TotalNew2 * FCN
1088 AssemblyN2 = TotalNew2 * ASC
1089 EngineeringN2 = TotalNew2 * ENC
1090 costresult[1,0] = Inkoop
1091 costresult[1,4] = Sandblastingpaint
1092 costresult[1,5] = Fabcosts
1093 costresult[1,6] = AssemblyN2
1094 costresult[1,7] = EngineeringN2
1095 costresult[1,8] = np.sum(costresult[1]) * 0.05
1096
1097 ## Load donor steel database information for cost estimation
1098 di = np.loadtxt("Databases.txt", delimiter = ",", encoding = "utf-8-sig", dtype = str)
1099
1100 ## Reclaimed steel 1 cost estimation
1101 Inkoopnieuw = W1new * NSP
1102 Inkoopreq = (W1req + Wastel) * (SSP+0.20)
1103 Sandblastingcoating = W1new * SPP
1104 Assembly1 = AssemblyN1
1105 Engineering1 = EngineeringN1 * 1.15
1106
1107 ## Determine fabrication costs columns
1108 Usedelems1 = []
1109 UsedelemsL1 = []
1110 Fabcosts1 = 0
1111 for i in range(len(assC1)):
1112     ids = np.where(assC1[i] > 0)
1113     idNG = i + np.floor(i/(kspanc+1)) * (kspanc+1) * floors - np.floor(i/(kspanc+1)) * (
1114         kspanc+1)
1115     if np.sum(ids[0]) > 0:
1116         for j in ids[0]:
1117             Usedelems1.append(j)
1118             UsedelemsL1.append(assC1[i][j])
1119             Fabcosts1 += ddata.G.iloc[j] * assC1[i][j] * FCR * 2 * (1-reusepercentage1)
1120             Fabcosts1 += ddata.ToxicFabCosts.iloc[j] * 2 * (1-reusepercentage1)
1121     else:
1122         Fabcosts1 += floors * floorheight * GHcolumns.NG1.loc[int(idNG)] * FCN
1123
1124 for i in range(len(assB1)):
1125     id = np.where(assB1[i]>0)
1126     if np.sum(id[0]) > 0:
1127         Usedelems1.append(id[0][0])
1128         UsedelemsL1.append(hoh)

```

```

1129     ## Determine test costs following client test scenario
1130     Testcosts = 0
1131     TestcostsM2 = 0
1132     Storecosts = 0
1133
1134     usedcs = ddata["Cross-section"].iloc[Usedelems1]
1135     useddb = ddata.Identifier.iloc[Usedelems1]
1136     if np.shape(di)[0] == 1:
1137         Cday = []
1138
1139     for i in useddb.unique():
1140         tg = []
1141         if np.ndim(di) == 1:
1142             Cday = float(di[3])
1143         else:
1144             Cday = float(di[np.where(di[:,0]== str(i))[0][0],-1])
1145         for j in range(len(usedcs.values)):
1146             if useddb.values[j] == i:
1147                 tg.append(usedcs.values[j])
1148             testunits = len(np.unique(tg))
1149             rrange = np.arange(0, testunits+1, 0.5)
1150             multi = testunits/20
1151             diff = rrange-multi
1152             index = [i for i, x in enumerate(diff) if x >= 0]
1153             TestcostsM2 += testunits * 150 + Cday * rrange[index[0]]
1154
1155     ## Determine storage costs and test costs centralized testing
1156     for i in Usedelems1:
1157         Testcosts += ddata.TestCosts.iloc[i]     ## Test costs centralized testing
1158         Storecosts += ddata.StoreCosts.iloc[i]
1159
1160     ## Determine fabrication costs beams
1161     for i in range(len(GHbeams)):
1162         if GHbeams.donor.iloc[i] == "yes":
1163             Fabcosts1 += GHbeams.DG1.iloc[i] * GHbeams.Length.iloc[i] * FCR * 2 * (1-
1164                 reusepercentage1)
1165         else:
1166             Fabcosts1 += GHbeams.NG1.iloc[i] * GHbeams.Length.iloc[i] * FCN
1167
1168     costresult[2,0] = Inkoopnieuw
1169     costresult[2,1] = Inkoopreq
1170     costresult[2,2] = TestcostsM2             ## Set to TestcostsM2 to switch so scenario 2
1171     costresult[2,3] = Storecosts
1172     costresult[2,4] = Sandblastingcoating
1173     costresult[2,5] = W1new * FCN + (TotalNew1 - W1new) * FCR * (1-reusepercentage1)
1174     costresult[2,6] = Assembly1
1175     costresult[2,7] = Engineering1
1176     costresult[2,8] = np.sum(costresult[2]) * 0.15
1177
1178     ## Reclaimed steel 2 cost estimation
1179     Inkoopnieuw = W2new * NSP
1180     Inkoopreq = (W2req + Waste2) * (SSP+0.20)
1181     Sandblastingcoating = W2new * SPP
1182     Assembly2 = AssemblyN2
1183     Engineering2 = EngineeringN2 * 1.15
1184
1185     ## Determine fabrication costs beams
1186     Usedelems2 = []
1187     UsedelemsL2 = []
1188     Fabcosts2 = 0
1189     for i in range(len(assB2)):
1190         ids = np.where(assB2[i] > 0)
1191         idNG = i * kspanc
1192         if np.sum(ids[0]) > 0:
1193             for j in ids[0]:
1194                 Usedelems2.append(j)
1195                 UsedelemsL2.append(assC1[i][j])
1196                 Fabcosts2 += ddata.G.iloc[j] * assB2[i][j] * FCR * 2 * (1-reusepercentage2)
1197                 Fabcosts2 += ddata.ToxicFabCosts.iloc[j] * 2 * (1-reusepercentage2)
1198             else:
1199                 Fabcosts2 += hoh * kspanc * GHcolumns.NG2.iloc[int(idNG)] * FCN

```



```

1199
1200     for i in range(len(assC2)):
1201         id = np.where(assC2[i]>0)
1202         if np.sum(id[0]) > 0:
1203             Usedelems2.append(id[0][0])
1204             UsedelemsL2.append(floorheight)
1205
1206     ## Determine test costs following client test scenario
1207     Testcosts = 0
1208     TestcostsM2 = 0
1209     Storecosts = 0
1210
1211     usedcs = ddata["Cross-section"].iloc[Usedelems2]
1212     useddb = ddata.Identifier.iloc[Usedelems2]
1213
1214     for i in useddb.unique():
1215         tg = []
1216         if np.ndim(di) == 1:
1217             Cday = float(di[3])
1218         else:
1219             Cday = float(di[np.where(di[:,0]== str(i))[0][0],-1])
1220         for j in range(len(usedcs.values)):
1221             if useddb.values[j] == i:
1222                 tg.append(usedcs.values[j])
1223         testunits = len(np.unique(tg))
1224         rrange = np.arange(0, testunits+1, 0.5)
1225         multi = testunits/20
1226         diff = rrange-multi
1227         index = [i for i, x in enumerate(diff) if x >= 0]
1228         TestcostsM2 += testunits * 150 + Cday * rrange[index[0]]
1229
1230     ## Determine storage costs and test costs centralized testing
1231     for i in Usedelems2:
1232         Testcosts += ddata.TestCosts.iloc[i]     ## Test costs centralized testing
1233         Storecosts += ddata.StoreCosts.iloc[i]
1234
1235     ## Determine fabrication costs columns
1236     for i in range(len(GHcolumns)):
1237         if GHcolumns.donor.iloc[i] == "yes":
1238             Fabcosts2 += GHcolumns.DG2.iloc[i] * GHcolumns.Length.iloc[i] * FCR * 2 * (1-
1239                 reusepercentage2)
1240         else:
1241             Fabcosts2 += GHcolumns.NG2.iloc[i] * GHcolumns.Length.iloc[i] * FCN
1242
1243     costresult[3,0] = Inkoopnieuw
1244     costresult[3,1] = Inkoopreq
1245     costresult[3,2] = TestcostsM2     ## Set to TestcostsM2 to switch so scenario 2
1246     costresult[3,3] = Storecosts
1247     costresult[3,4] = Sandblastingcoating
1248     costresult[3,5] = W2new * FCN + (TotalNew2 - W2new) * FCR * (1-reusepercentage2)
1249     costresult[3,6] = Assembly2
1250     costresult[3,7] = Engineering2
1251     costresult[3,8] = np.sum(costresult[3]) * 0.15
1252
1253     ## Save cost results in a dataframe
1254     costresult = np.ceil(costresult)
1255     costs = pd.DataFrame(costresult, columns = ["NewSteel", "ReclaimedSteel", "Testing", "
1256         Storage", "Sandblasting/coating", "Fabrication", "Assembly", "Engineering", "Risk"])
1257
1258     ## Set up environmental impact profiles
1259     TeciA4 = 0.02 * Distance / 1000
1260     TeciC2 = 0.02 * 150 / 1000
1261     ECIa = [[0.124309, TeciA4 + 0.007711, 0, TeciC2 + 0.0113, -0.022872],
1262             [0.021503 * 2 * (1-reusepercentage1), TeciA4 + 0.007711, 0, TeciC2 + 0.0113,
1263              -0.00221],
1264             [0, 0, 0, TeciC2 + 0.003589, 0]]
1265     ECIb = [[0.124309, TeciA4 + 0.007711, 0, TeciC2 + 0.0113, -0.022872],
1266             [0.021503 * 2 * (1-reusepercentage2), TeciA4 + 0.007711, 0, TeciC2 + 0.0113,
1267              -0.00221],
1268             [0, 0, 0, TeciC2 + 0.003589, 0]]

```

```

1266 TppA4 = 0.13 * Distance / 1000
1267 TppC2 = 0.13 * 150 / 1000
1268 PPa = [[1.12, TppA4 + 0.0678, 0, 0, -0],
1269        [0.198 * 2 * (1-reusepercentage1), TppA4 + 0.0678, 0, 0, 0],
1270        [TppC2 + 0.0807, 0, 0, 0, 0]]
1271 PPb = [[1.12, TppA4 + 0.0678, 0, 0, -0],
1272        [0.198 * 2 * (1-reusepercentage2), TppA4 + 0.0678, 0, 0, 0],
1273        [TppC2 + 0.0807, 0, 0, 0, 0]]
1274
1275 ## Calculate environmental impact
1276 ECI2a = np.sum(ECIa, axis = 1)
1277 ECI2b = np.sum(ECIb, axis = 1)
1278 PP2a = np.sum(PPa, axis =1)
1279 PP2b = np.sum(PPb, axis =1)
1280 A1 = np.array([TotalNew1, 0, 0])
1281 A2 = np.array([TotalNew2, 0, 0])
1282 A3 = np.array([W1new, W1req, Waste1])
1283 A4 = np.array([W2new, W2req, Waste2])
1284 Impact1 = np.sum(A1*ECI2a)
1285 Impact2 = np.sum(A2*ECI2a)
1286 Impact3 = np.sum(A3*ECI2a)
1287 Impact4 = np.sum(A4*ECI2b)
1288 Impact5 = np.sum(A1*PP2a)
1289 Impact6 = np.sum(A2*PP2a)
1290 Impact7 = np.sum(A3*PP2a)
1291 Impact8 = np.sum(A4*PP2b)
1292
1293 ## Save environmental impact in arrays and dataframe
1294 impactresults = np.zeros((4,5)) ## Array
1295 impactresults[0] = np.array(ECIa[0]) * TotalNew1
1296 impactresults[1] = np.array(ECIa[0]) * TotalNew2
1297 impactresults[2] = np.array(ECIa[0]) * W1new + np.array(ECIa[1]) * W1req + np.array(ECIa
1298        [2]) * Waste1
1299 impactresults[3] = np.array(ECIb[0]) * W2new + np.array(ECIb[1]) * W2req + np.array(ECIb
1300        [2]) * Waste2
1301
1302 impactresults2 = np.zeros((4,5)) ## Array
1303 impactresults2[0] = np.array(PPa[0]) * TotalNew1
1304 impactresults2[1] = np.array(PPa[0]) * TotalNew2
1305 impactresults2[2] = np.array(PPa[0]) * W1new + np.array(PPa[1]) * W1req + np.array(PPa
1306        [2]) * Waste1
1307 impactresults2[3] = np.array(PPb[0]) * W2new + np.array(PPb[1]) * W2req + np.array(PPb
1308        [2]) * Waste2
1309
1310 ## Dataframes
1311 imres = pd.DataFrame(impactresults, columns = ["A1-A3", "A4-A5", "B", "C", "D"])
1312 imres1 = np.ceil(imres)
1313 imress = pd.DataFrame(impactresults2, columns = ["A1-A3", "A4-A5", "B", "C", "D"])
1314 imress2 = np.ceil(imress)
1315
1316 ## Write output excel file
1317 path = Designname + ".xlsx"
1318 with pd.ExcelWriter(path) as writer:
1319     GHcolumns.to_excel(writer, "GHcolumns", index = False)
1320     GHbeams.to_excel(writer, "GHbeams", index = False)
1321     BD2.to_excel(writer, "BeamModel2", index = False)
1322     BL2.to_excel(writer, "BeamLengthModel2", index = False)
1323     CD1.to_excel(writer, "ColumnModel1", index = False)
1324     CL1.to_excel(writer, "ColumnLengthModel1", index = False)
1325     GHparams.to_excel(writer, "params", index = False)
1326     costs.to_excel(writer, "costs", index = False)
1327     imres1.to_excel(writer, "impactECI", index = False)
1328     imress2.to_excel(writer, "impactPP", index = False)
1329
1330 ## Print output to visualize/show in the tool
1331 print(np.round(TotalNew1/1000, 2), np.round(TotalNew2/1000, 2), np.round(W1new/1000, 2),
1332       np.round(W2new/1000, 2), np.round(W1req/1000, 2), np.round(W2req/1000, 2), np.round(
1333       Waste1/1000, 2), np.round(Waste2/1000, 2), np.sum(costresult[0]), np.sum(costresult
1334       [1]), np.sum(costresult[2]), np.sum(costresult[3]), np.round(Impact1, 2), np.round(
1335       Impact2,2), np.round(Impact3,2), np.round(Impact4,2), np.round(Impact5,2), np.round(
1336       Impact6,2), np.round(Impact7,2), np.round(Impact8,2))

```

```
1328
1329 if __name__ == "__main__": ## Call TheCode function to active code.
1330     TheCode(argv[1], argv[2], argv[3], argv[4], argv[5])
```

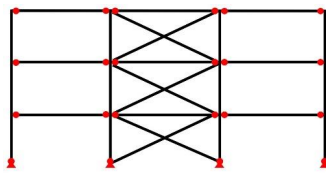

B

Appendix: Validation of structural analysis in python

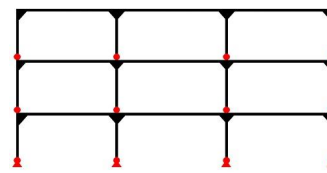
Verification of structural analysis

By Koen Aardoom

This document contains the verification of the structural analysis models used in the Steel-IT tool. It goes into the used methods and schematizations to determine the normal force, shear force and bending moments in the frames. The implemented code will be verified using matrix frame and hand calculations. The tool analyses two structural configurations:



Model 1



Model 2

This report consists of the following parts:

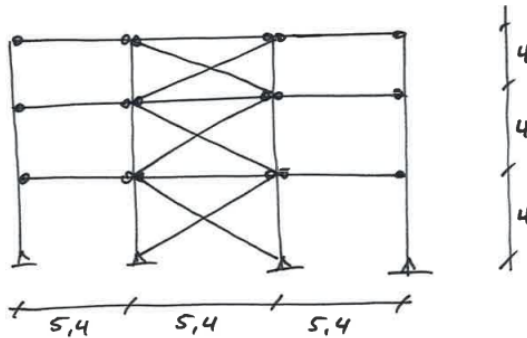
1. Model 1 verification
2. Model 2 verification
3. Stability model 1 and model 2 verification
4. Use of these results and resulting python code

If there are any question regarding the calculations or code, feel free to contact me.

Model 1 verification

The schematization of model 1 is shown below.

Model 1



Description:

Simply supported beams

Continuous columns

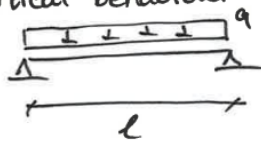
Windbraces to provide stability.

Hinge connection between columns and foundation

The simply supported beams make structural analysis quite simple. For both horizontal and vertical analysis, the leading calculation principles are shown below.

Used principles to describe load-bearing behaviour:

→ Vertical behaviour

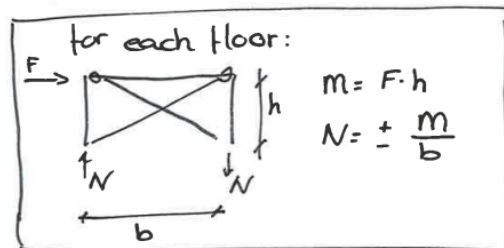
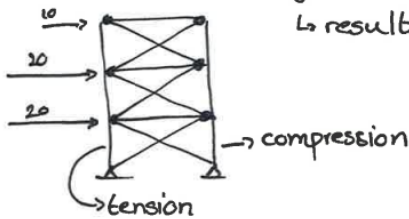


for each beam $M_{max} = \frac{1}{8}ql^2$
 $F_{column} = \frac{1}{2}ql$

→ Horizontal behaviour

• windbraces carry horizontal loads to foundation

↳ results in extra normal force in columns



To verify the calculation procedure, a case is elaborated by doing hand calculations and looking at results from the same load-case in Matrixframe. The results are compared with the code that will be implemented in the tool. The case that will be used to verify the calculations uses the following parameters:

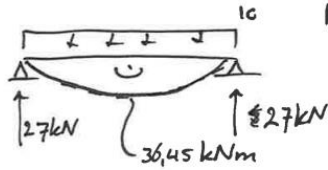
- $Q = 10 \text{ kN/m}$
- $F_{wind} = 10, 20, 20$
- Number of storeys = 3
- Storeyheight = 4 m.

- Number of beam spans per frame = 3
- Columns-to-column distance = 5.4 m.

Vertical load-bearing behaviour

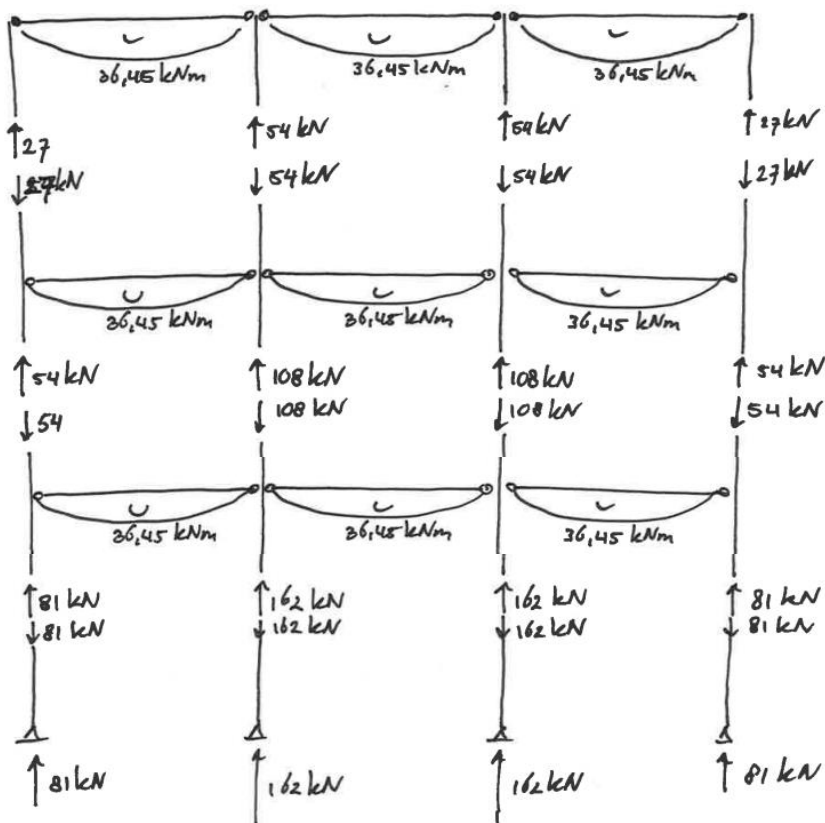
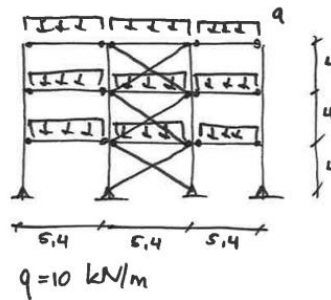
The hand calculation of the first model is shown below.

Vertical verification

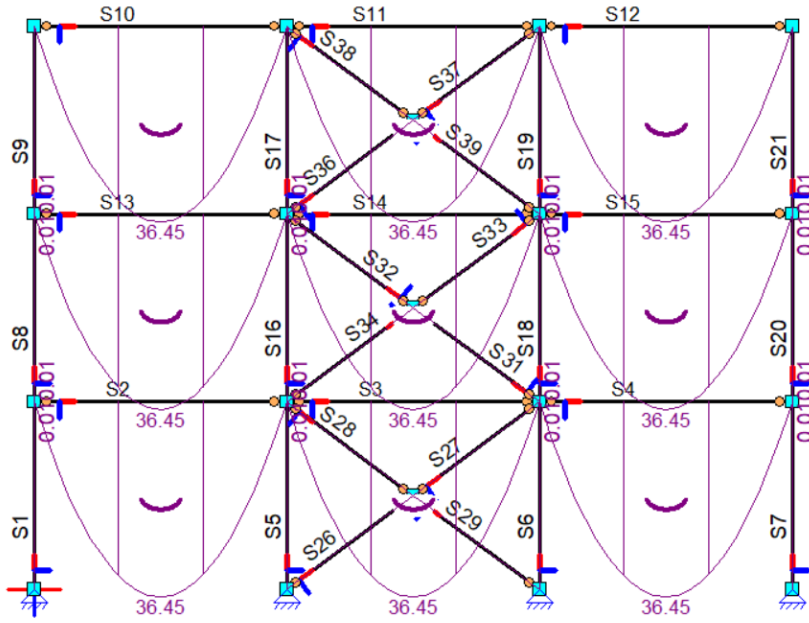
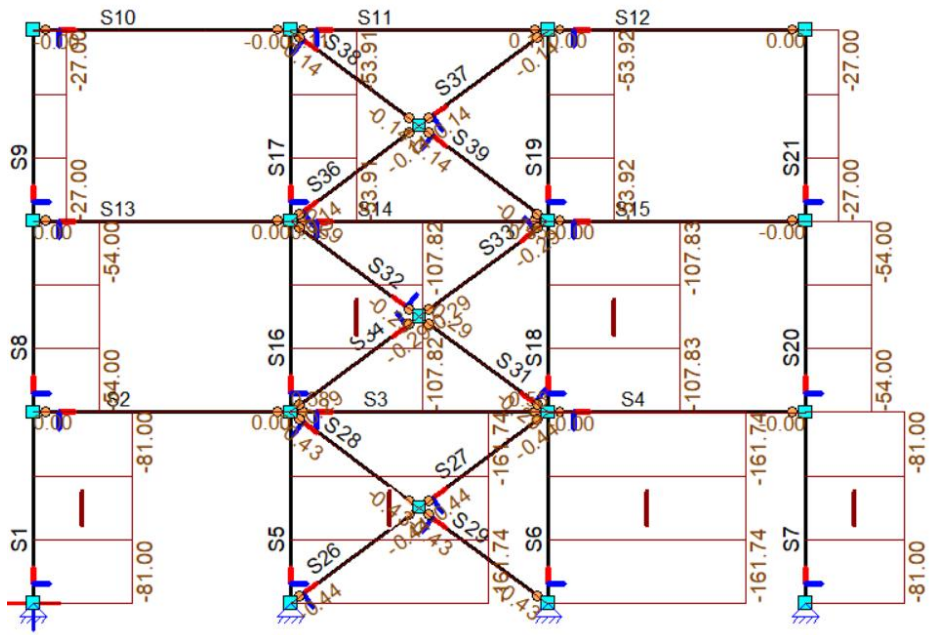


$$F_{col} = \frac{1}{2} \cdot 5.4 \cdot 10 = 27 \text{ kN}$$

$$M_{max} = \frac{1}{8} \cdot 10 \cdot 5.4^2 \cdot 8 = 36.45 \text{ kNm}$$



The results from a Matrixframe analysis of the same frame and loads are shown in the screenshots below.



The python code that will be used yields output for an identical frame and loading. For the columns, the following output is generated. The output consists of 3 arrays. The first are shearforces, then normal forces and lastly bending moments. The position of the columns in the array correspond to the front view of the structural scheme.

Columns output (V, N, M)

```
(array([[ 0.,  0.,  0.,  0.],
       [ 0.,  0.,  0.,  0.],
       [ 0.,  0.,  0.,  0.]],
      [[ 27.,  54.,  54.,  27.],
       [ 54., 108., 108.,  54.],
       [ 81., 162., 162.,  81.]],
      [[ 0.,  0.,  0.,  0.],
       [ 0.,  0.,  0.,  0.],
       [ 0.,  0.,  0.,  0.]])
```

As can be seen, the normal-forces correspond to the Matrixframe and hand-calculation results. The beams yield the following output (same datastructure as described above):

Beams output (V, N, M)

```
[[[27.  27.  27. ]
   [27.  27.  27. ]
   [27.  27.  27. ]],
 [[ 0.  0.  0. ]
   [ 0.  0.  0. ]
   [ 0.  0.  0. ]],
 [[36.45 36.45 36.45]
   [36.45 36.45 36.45]
   [36.45 36.45 36.45]]]
```

Also these numbers correspond to the output of the hand-calculations and Matrixframe analysis.

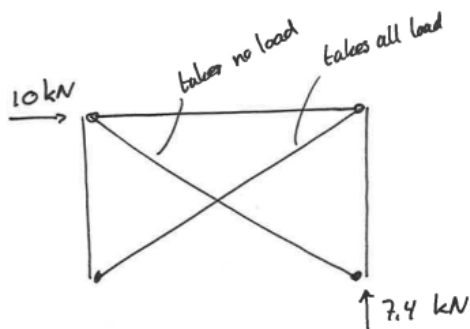
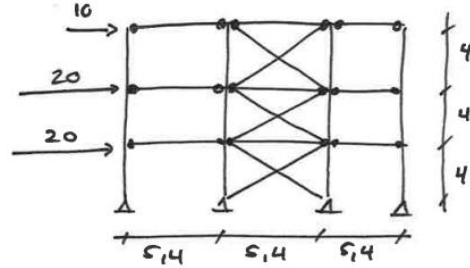
Horizontal load-bearing behaviour

The hand calculation of the first model is shown below.

Horizontal verification

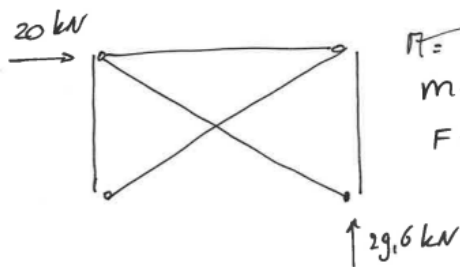
Assuming that the tension diagonal takes all load.

Compression force column governing and also applicable to tension column as wind can also be applied from the other direction



$$M = 10 \cdot 4 = 40 \text{ kNm}$$

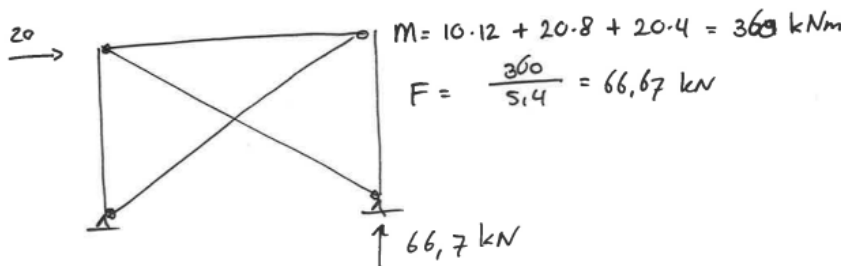
$$F = 40 / 5.4 = 7.4 \text{ kN}$$



$$M = (10 + 20) \cdot 4 =$$

$$M = 10 \cdot 8 + 20 \cdot 4 = 160 \text{ kNm}$$

$$F = \frac{160}{5.4} = 29.6 \text{ kN}$$

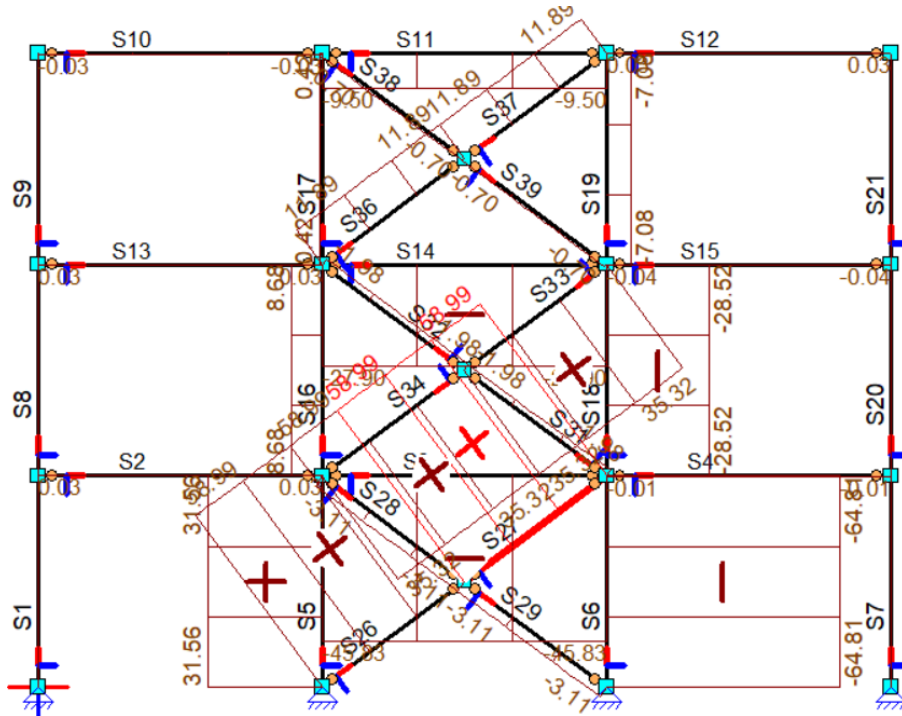


$$M = 10 \cdot 12 + 20 \cdot 8 + 20 \cdot 4 = 360 \text{ kNm}$$

$$F = \frac{360}{5.4} = 66.7 \text{ kN}$$

Only the compression forces are calculated as they are biggest and will contribute to the normal force from the vertical loading resulting in the governing load combination. The compression forces calculated are applicable to both columns (left and right of the bracings) as the wind can also come from the other side of the building.

The following figures shows the normal-forces in the columns from analysis of an identical frame and loads in Matrixframe.



The python code also determines the normal forces in the columns adjacent to the wind-bracings. The results for the columns are:

Columns output (V, N, M)

```
(array([ [ 0.      ,  0.      ,  0.      ,  0.      ],
        [ 0.      ,  0.      ,  0.      ,  0.      ],
        [ 0.      ,  0.      ,  0.      ,  0.      ]],
       [[ 7.40740741,  7.40740741,  0.      ,  0.      ],
        [29.62962963, 29.62962963,  0.      ,  0.      ],
        [66.66666667, 66.66666667,  0.      ,  0.      ]],
       [[ 0.      ,  0.      ,  0.      ,  0.      ],
        [ 0.      ,  0.      ,  0.      ,  0.      ],
        [ 0.      ,  0.      ,  0.      ,  0.      ]]),
      V,
      N,
      M)
```

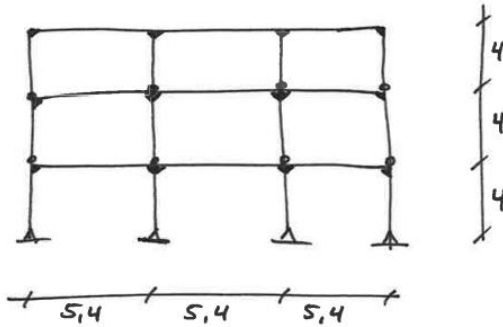
The output from the code complies with the hand-calculations. There is a small difference with the Matrixframe software. This is due to contribution of the windbraces which are not considered in the hand-calculations and code to keep it simple. The maximum difference in this case is 5% and on the conservative side which is regarded acceptable.

With this comparison, model 1 is verified.

Model 2 verification

The schematization of model 2 is shown below.

Model 2

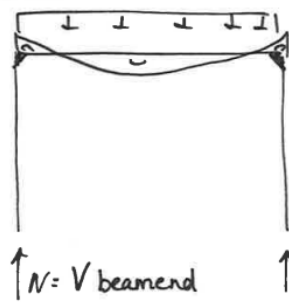


Description:

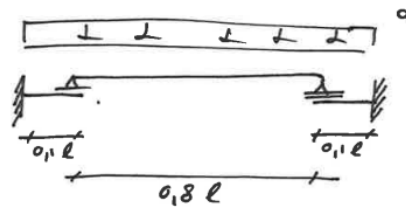
Continuous beams
Portals to provide stability
Hinge connection between columns and foundation

For both horizontal and vertical analysis, the leading calculation principles are shown below.

→ Vertical behaviour

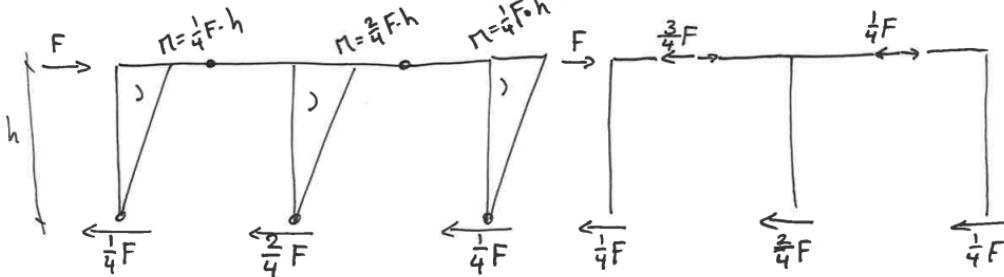


⇒



$$M = 0,05 \cdot l \cdot 0,19l + 0,1l \cdot 0,49l$$

→ Horizontal behaviour ⇒ introducing hinges at mid-span of beams



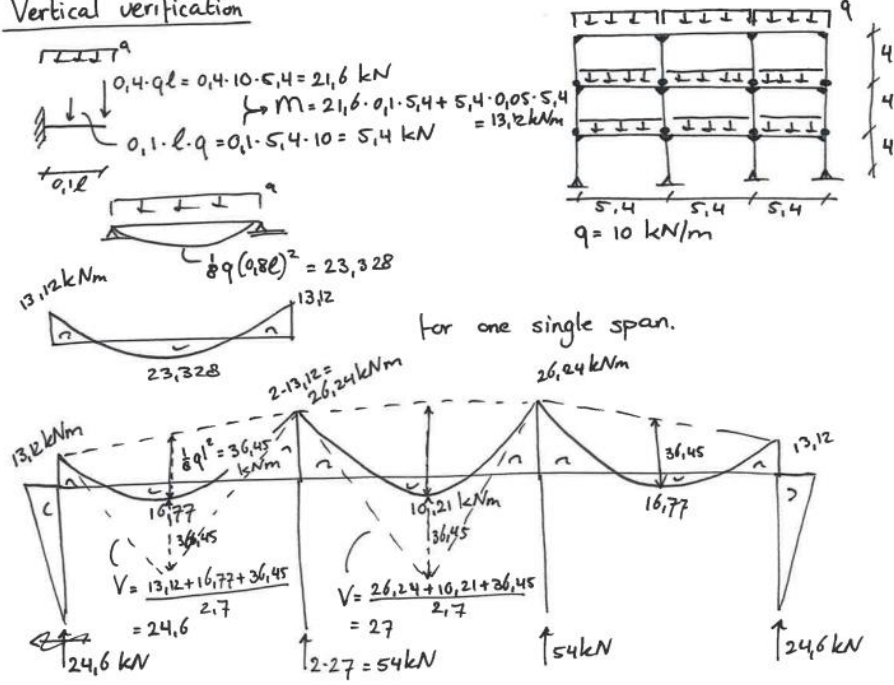
- Shear in beams from moment equilibrium around column foot
- Then use shearforce to determine moment in beams

The same verification is performed on model 2 using the same loads as for model 1.

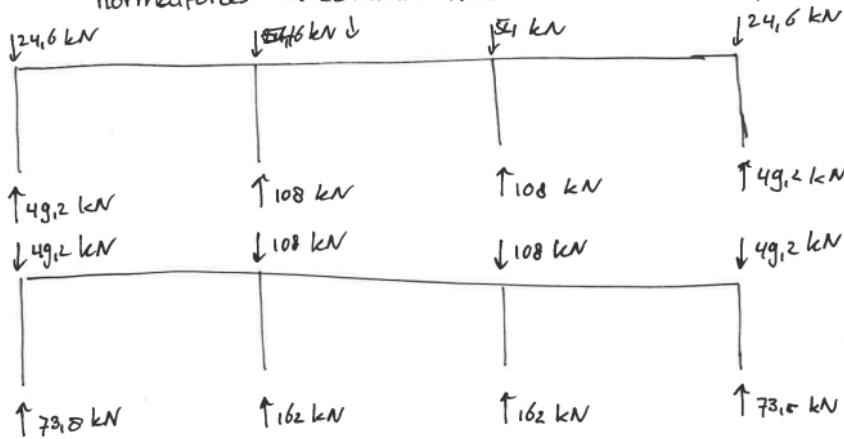
1. Vertical load-bearing behaviour

The hand calculation of the second model is shown below.

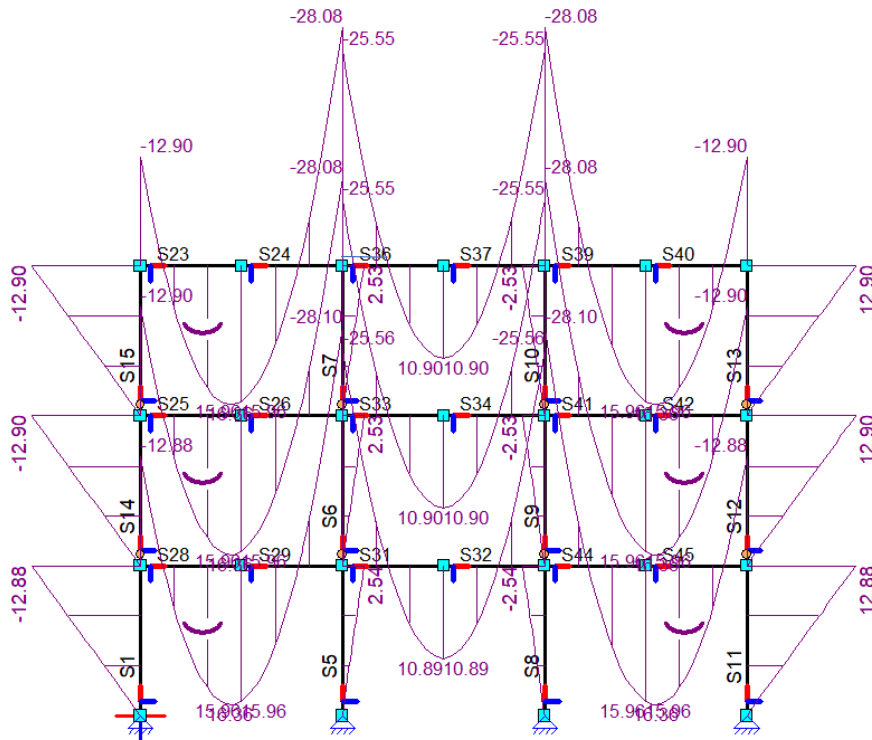
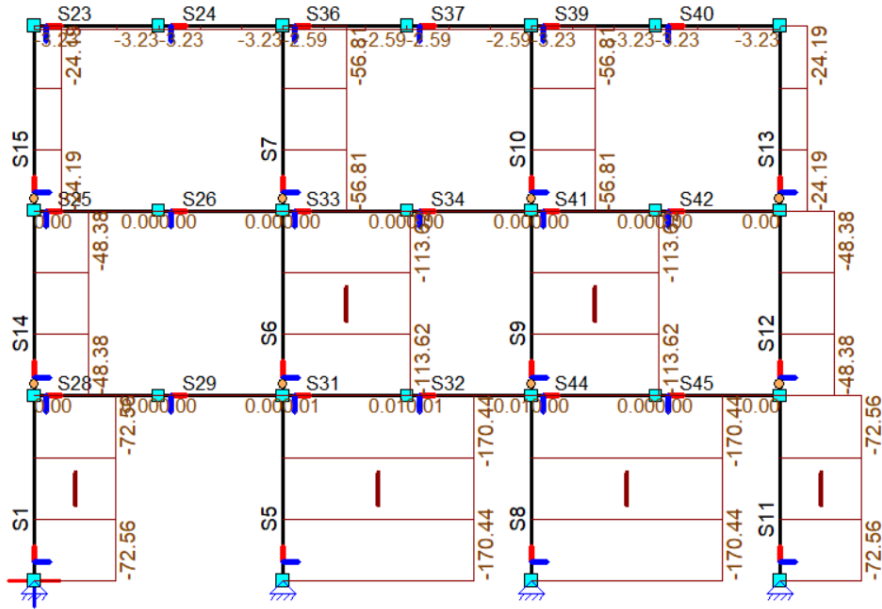
Vertical verification



moments are identical for each storey
 normal forces in columns need to be added up



The results from a Matrixframe analysis of the same frame and loads are shown in the screenshots below.



The python code that will be used yields output for an identical frame and loading. For the columns, the following output is generated. The output consists of 3 arrays. The first are shear forces, then normal forces and lastly bending moments. The position of the columns in the array correspond to the front view of the structural scheme.

Column output (V, N, M)

```
(array([[ [ 3.2805, 0. , 0. , 3.2805],
        [ 3.2805, 0. , 0. , 3.2805],
        [ 3.2805, 0. , 0. , 3.2805]]],
      [[ [ 24.57 , 54. , 54. , 24.57 ],
        [ 49.14 , 108. , 108. , 49.14 ],
        [ 73.71 , 162. , 162. , 73.71 ]]],
      [[ [ 13.122 , 0. , 0. , 13.122 ],
        [ 13.122 , 0. , 0. , 13.122 ],
        [ 13.122 , 0. , 0. , 13.122 ]]]),
```

V

N

M

The numbers are compliant with the hand calculations. A small difference in normal force and bending moment can be noticed. This is probably because the assumed inflection points at $0.1 * l$ from the supports are not completely correct. The difference between the used method in the code/hand calculations and Matrixframe is around 5%. This is acceptable in this early design stage.

Beam output (V, N, M)

```
[[ [27. 27. 27. ]
   [27. 27. 27. ]
   [27. 27. 27. ]],
 [[ 0. 0. 0. ]
   [ 0. 0. 0. ]
   [ 0. 0. 0. ]],
 [[26.244 26.244 26.244]
   [26.244 26.244 26.244]
   [26.244 26.244 26.244]]]
```

V

N

M

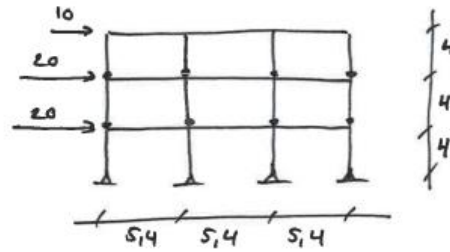
The moments in the beam are close to the Matrixframe results and suffice.

2. Horizontal load-bearing behaviour

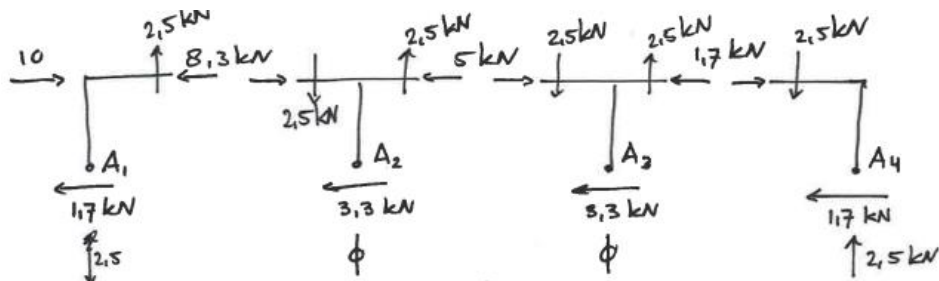
The hand calculation of the second model is shown below.

Horizontal verification

Introducing hinges at midspan



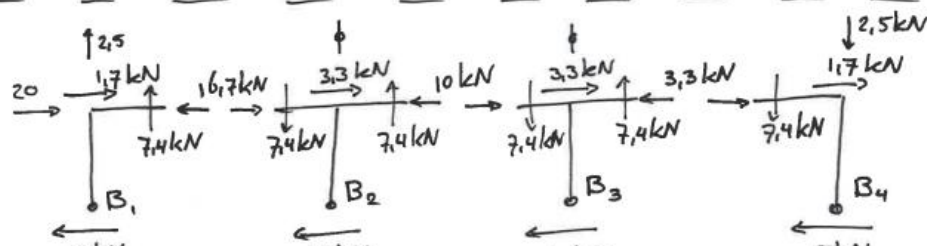
Starting point: distribute windforce over columns, edge mid columns get twice the load of shear edge columns



$$\begin{aligned} \sum M_{A1} &= 0 \\ -10 \cdot 4 + 8.3 \cdot 4 + \uparrow \cdot \frac{5.4}{2} &= 0 \\ \uparrow &= 2.5 \text{ kN} \end{aligned}$$

$$\begin{aligned} \sum M_{A2} &= 0 \\ -8.3 \cdot 4 + 5 \cdot 4 + 2.5 \cdot \frac{5.4}{2} + \uparrow \cdot \frac{5.4}{2} &= 0 \\ \uparrow &= 2.5 \text{ kN} \end{aligned}$$

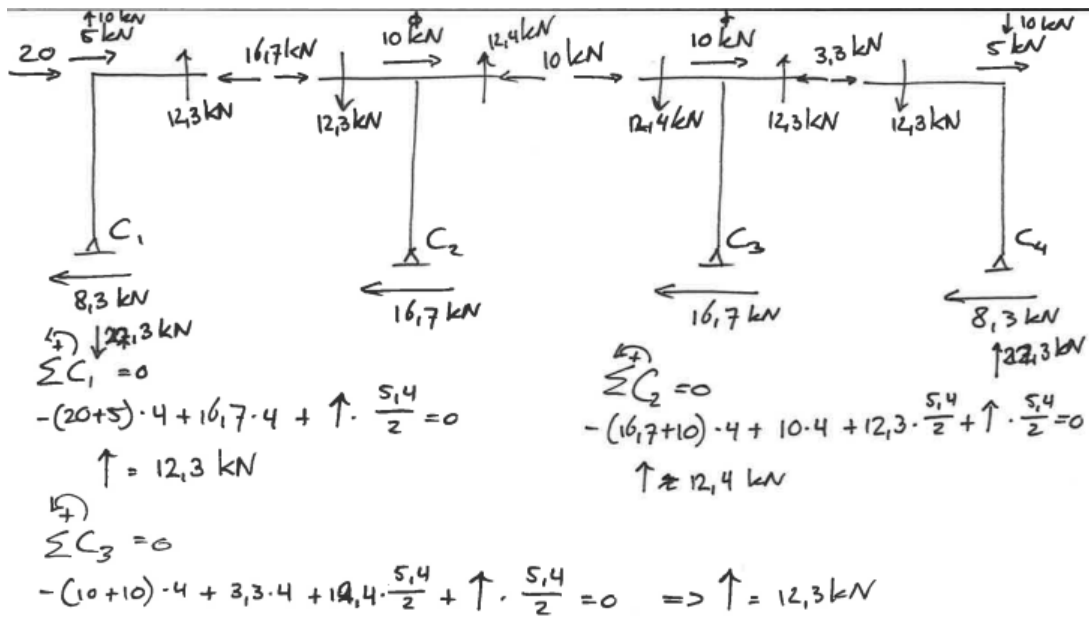
$$\begin{aligned} \sum M_{A3} &= 0 \\ -5 \cdot 4 + 1.7 \cdot 4 + 2.5 \cdot \frac{5.4}{2} + \uparrow \cdot \frac{5.4}{2} &= 0 \Rightarrow \uparrow = 2.5 \text{ kN} \end{aligned}$$



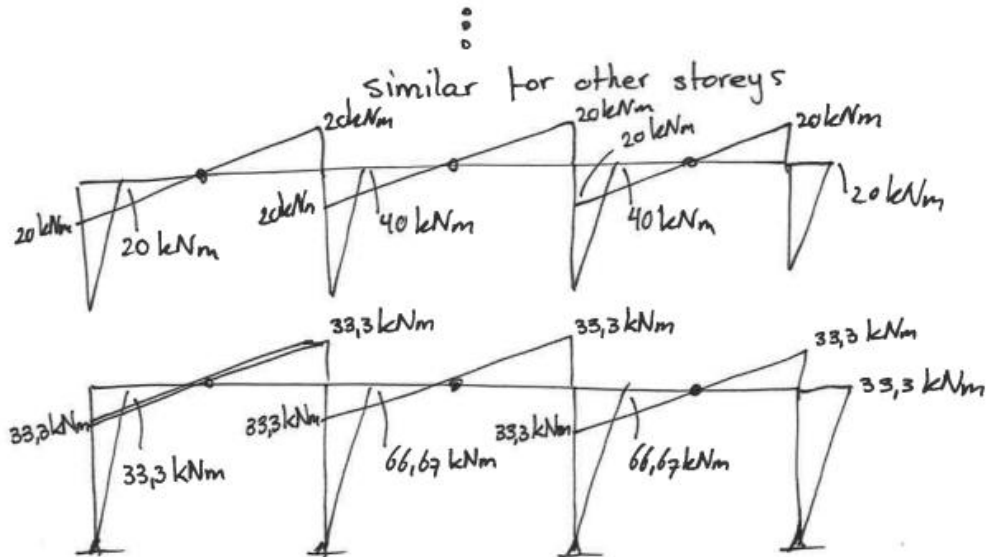
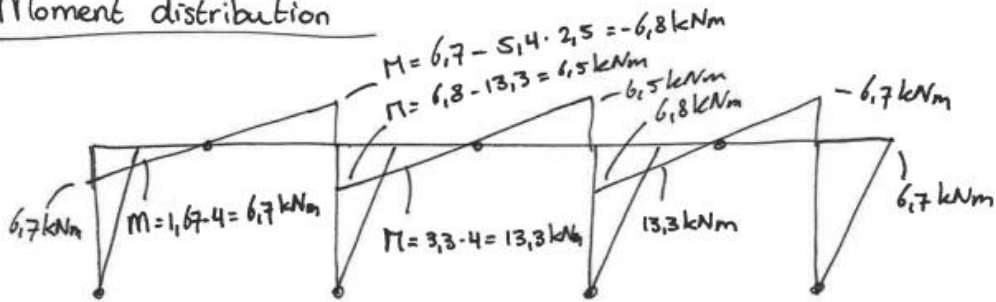
$$\begin{aligned} \sum B_1 &= 0 \\ -(20 + 1.7) \cdot 4 + 16.7 \cdot 4 + \uparrow \cdot \frac{5.4}{2} &= 0 \\ \uparrow &= 7.4 \text{ kN} \end{aligned}$$

$$\begin{aligned} \sum B_2 &= 0 \\ -(16.7 + 3.3) \cdot 4 + 10 \cdot 4 + 7.4 \cdot \frac{5.4}{2} + \uparrow \cdot \frac{5.4}{2} &= 0 \\ \uparrow &= 7.4 \text{ kN} \end{aligned}$$

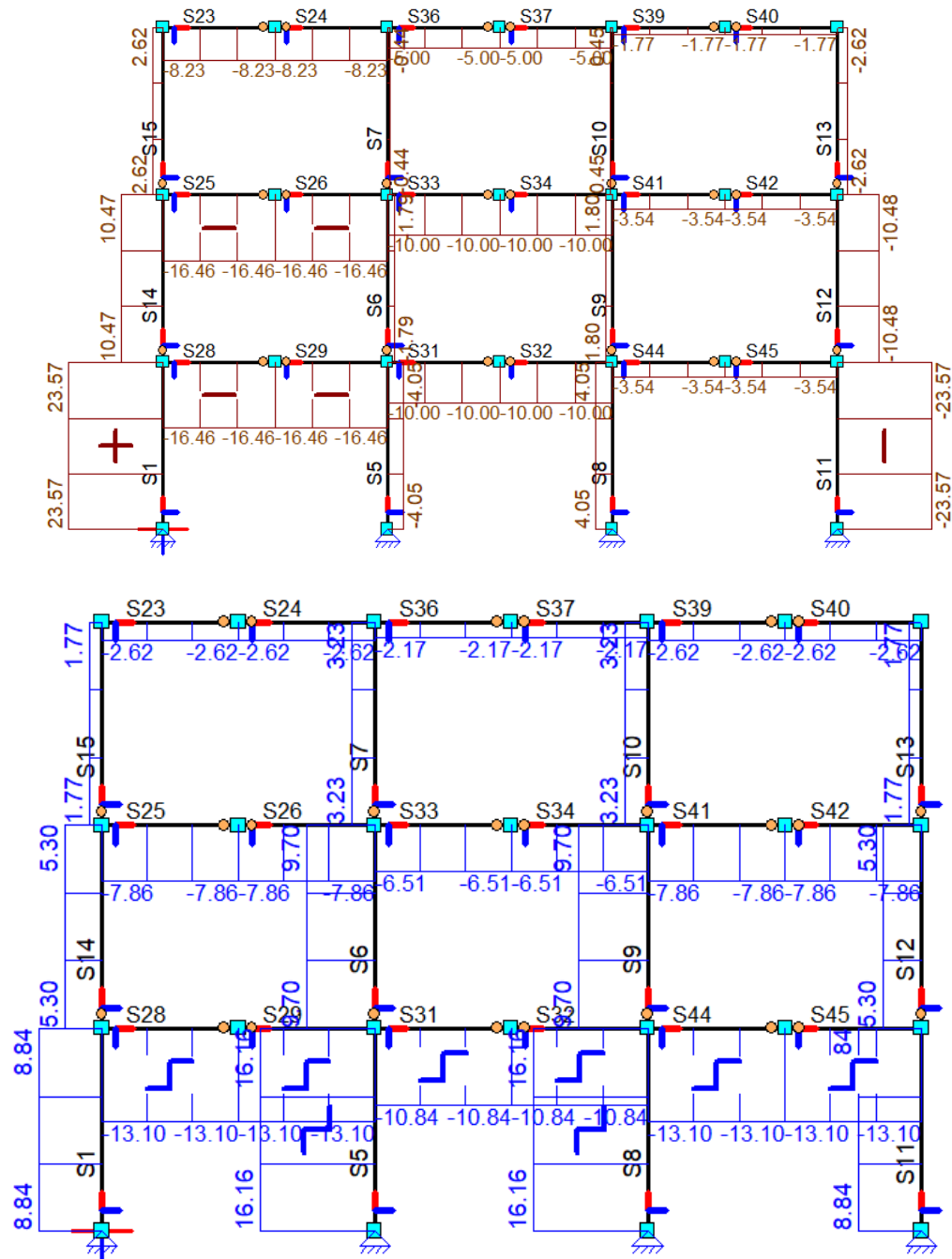
$$\begin{aligned} \sum B_3 &= 0 \\ -(10 + 3.3) \cdot 4 + 3.3 \cdot 4 + 7.4 \cdot \frac{5.4}{2} + \uparrow \cdot \frac{5.4}{2} &= 0 \Rightarrow \uparrow = 7.4 \text{ kN} \end{aligned}$$

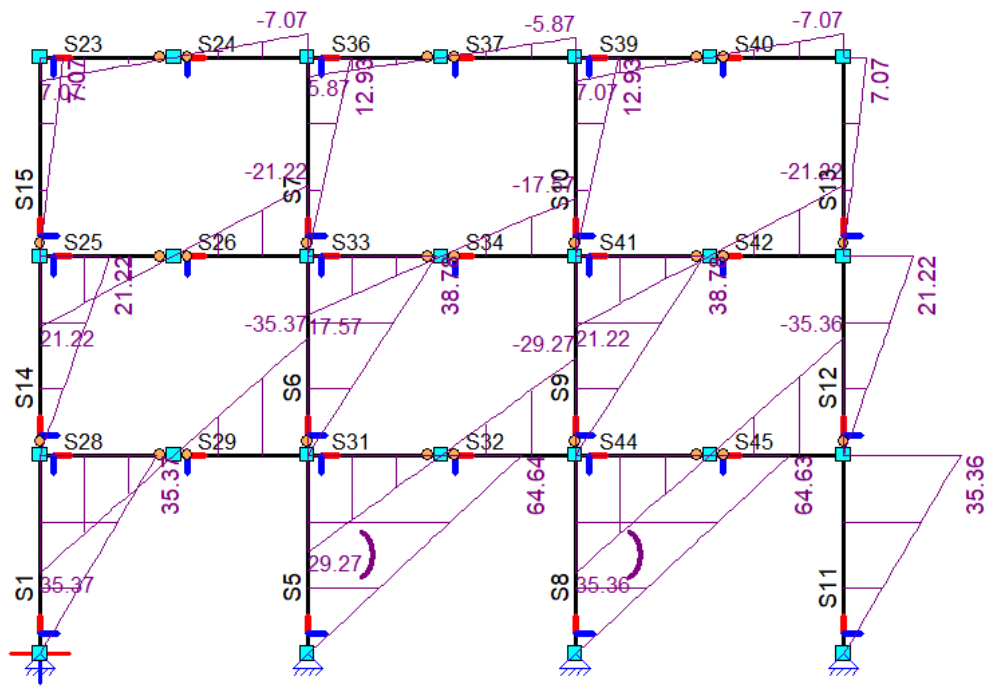


Moment distribution



The results from a Matrixframe analysis of the same frame and loads are shown in the screenshots below.





The python code does structural analysis based on the method used in the hand calculations. The output for the same case is shown below (columns, then beams).

Column output (V, N, M)

```
array([[ [ 1.66666667,  3.33333333,  3.33333333,  1.66666667],
        [ 5.          , 10.          , 10.          ,  5.          ],
        [ 8.33333333, 16.66666667, 16.66666667,  8.33333333]],
       [[ 2.4691358 , -0.          ,  0.          ,  2.4691358 ],
        [ 9.87654321,  0.          ,  0.          ,  9.87654321],
        [22.22222222,  0.          ,  0.          , 22.22222222]],
       [[ 6.66666667, 13.33333333, 13.33333333,  6.66666667],
        [20.          , 40.          , 40.          , 20.          ],
        [33.33333333, 66.66666667, 66.66666667, 33.33333333]]]),
```

V

N

M

Beam output (V, N, M)

```
array([[ [ 2.4691358 ,  2.4691358 ,  2.4691358 ],
        [ 7.40740741,  7.40740741,  7.40740741],
        [12.34567901, 12.34567901, 12.34567901]],
       [[ 8.33333333,  5.          ,  1.66666667],
        [16.66666667, 10.          ,  3.33333333],
        [16.66666667, 10.          ,  3.33333333]],
       [[ 6.66666667,  6.66666667,  6.66666667],
        [20.          , 20.          , 20.          ],
        [33.33333333, 33.33333333, 33.33333333]]]),
```

V

N

M


The results are in line with the hand calculations. There are some small differences as the used method uses an assumption for the distribution of the shear force among the columns. The biggest difference noticed in the normal forces, shear forces and bending moments are respectively 7%, 6% and 13%.

It should be noted that the forces resulting from the horizontal analysis are due to wind loads. In load combinations the resulting moments from vertical loading are added as well. When these two models are added up in the case above, the total difference between the model and Matrixframe is smaller.

Displacements (local and global deflection)

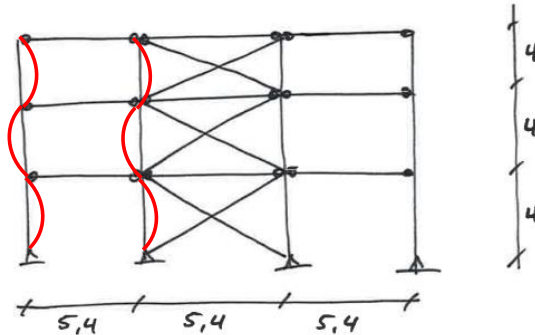
1. Model 1: windbraces

For the **local deformation** limits for the simply supported beams, forget-me-knots are used.

Belasting	Reactiekracht		Moment M_c	Hoekverdraaiing		Doorbuiging Y_c
	R_A	R_B		φ_A	φ_B	
	$\frac{q l}{2}$	$\frac{q l}{2}$	$\frac{q l^2}{8}$	$\frac{q l^3}{24 E I}$	$\frac{q l^3}{24 E I}$	$\frac{5 q l^4}{384 E I} = \frac{5 M l^2}{48 E I}$

By rewriting the last equation for sag ('doorbuiging') and substituting the $0.003 \cdot I$ limit, the minimum required I to fulfil this requirement can be determined. In this case, I_y is considered as the loads are applied in the 'strong' direction of the elements.

For column buckling, each donor element is evaluated on its Normal force resistance taking this stability phenomena into account according to the Eurocode. For model 1, the columns are continuous but the beams pivot around them and therefore the buckling length factor will be 1.0.



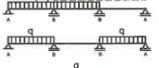
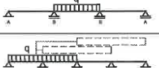




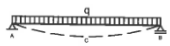
Global deflection for this model is dependent on the sections used in the wind braces. To limit the scope of this research, it is assumed that the braces are made from new steel sections later in the design process. It is not included in the structural analysis/tool.

2. Model 2: Portal frames

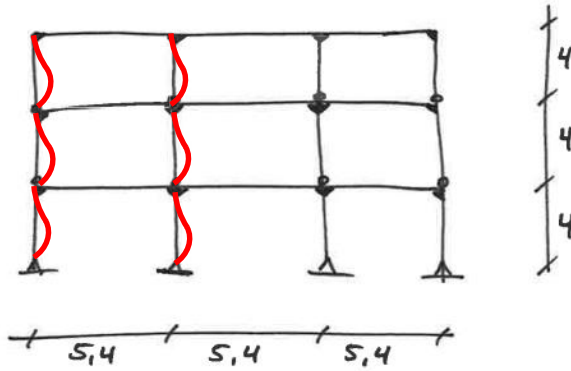
For **local deformation** of the beams, more cases need to be looked at. The beams are continuous and chess-board loads could be governing for deformation. Forget me knots are used just like in the previous model. Dependent on the number of spans, the correct forget-me-knot is selected.

Q-last met schaakbord belasting

Belasting	Reactiekracht Dwarskracht			Moment				Doorbuiging Y_{max}
	A	B	C	M_{11}	M_{12}	M_{21}	M_{22}	
	$R = 0,45 q \ell$	$1,2 q \ell$		$0,085 q \ell^2$	$0,125 q \ell^2$			$\frac{q \ell^4}{110 E I}$
	$V = 0,45 q \ell$	$0,65 q \ell$ $0,65 q \ell$						
	$R = 0,45 q \ell$	$1,2 q \ell$		$0,095 q \ell^2$	$0,115 q \ell^2$	$0,065 q \ell^2$		$\frac{q \ell^4}{101 E I}$
	$V = 0,45 q \ell$	$0,65 q \ell$ $0,60 q \ell$						
	$R = 0,45 q \ell$	$1,2 q \ell$	$1,1 q \ell$	$0,090 q \ell^2$	$0,115 q \ell^2$	$0,065 q \ell^2$	$0,100 q \ell^2$	$\frac{q \ell^4}{102 E I}$
	$V = 0,45 q \ell$	$0,65 q \ell$ $0,60 q \ell$	$0,55 q \ell$					

Belasting	Reactiekracht		Moment M_0	Hoekverdraaiing		Doorbuiging Y_0
	R_A	R_B		φ_A	φ_B	
	$\frac{q l}{2}$	$\frac{q l}{2}$	$\frac{q l^2}{8}$	$\frac{q l^3}{24 EI}$	$\frac{q l^3}{24 EI}$	$\frac{5 q l^4}{384 EI} = \frac{5 M l^2}{48 EI}$

For column buckling the same applies as in the previous model. The columns are not connected by a hinge and a rigid connection. The buckling length factor will be 0.7.



For **global deflection** the frame relies on the portals and thus the reclaimed elements. The portal method is used to determine the minimum required I to fulfil the global deformation criteria which are:

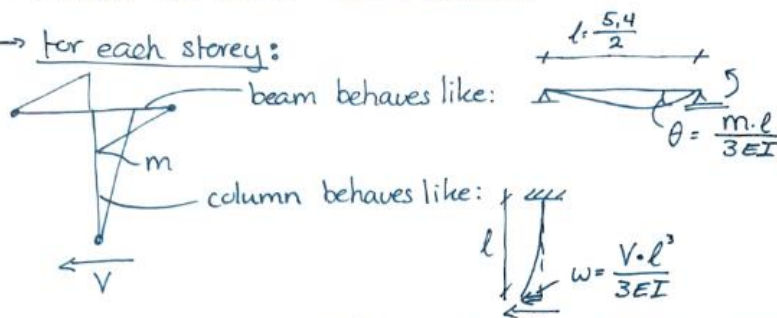
- Maximum total deflection at the top of the building $< 1/500 \cdot$ building height
- Maximum deflection at the top of each storey $< 1/300 \cdot$ storey height

A hand calculation of this methodology is shown below.

Minimum I portal method

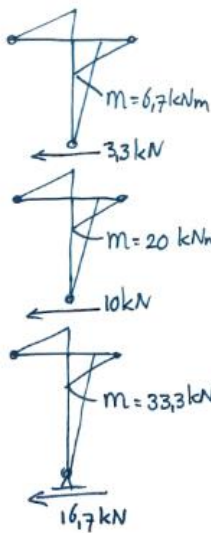
- Use results from the model 2 horizontal analysis (SLS combination)
- Consider the heaviest loaded column.

→ for each storey:



total deformation: $u = \frac{V \cdot l^3}{3EI} + \frac{m \cdot l^2}{3EI} \cdot l$

deformation limits:
 → per storey: $\frac{1}{300} \cdot 4000 = 13,3$
 → total: $\frac{1}{500} \cdot 12000 = 24$ mm



$$I_{\text{min, storey}} = \frac{3,3 \cdot 10^3 \cdot 4000^3}{3 \cdot 210 \cdot 10^3 \cdot (13,3)} + \frac{6,7 \cdot 10^6 \cdot \frac{5,4 \cdot 10^3}{2}}{3 \cdot 210 \cdot 10^3 \cdot (13,3)} \cdot 4000$$

$$= 33,8 \cdot 10^6 \text{ mm}^4$$

$$I_{\text{min, storey}} = \frac{10 \cdot 10^3 \cdot 4000^3}{3 \cdot 210 \cdot 10^3 \cdot (13,3)} + \frac{20 \cdot 10^6 \cdot \frac{5,4 \cdot 10^3}{2}}{3 \cdot 210 \cdot 10^3 \cdot (13,3)} \cdot 4000$$

$$= 102,2 \cdot 10^6 \text{ mm}^4$$

$$I_{\text{min, storey}} = \frac{16,7 \cdot 10^3 \cdot 4000^3}{3 \cdot 210 \cdot 10^3 \cdot (13,3)} + \frac{33,3 \cdot 10^6 \cdot \frac{5,4 \cdot 10^3}{2}}{3 \cdot 210 \cdot 10^3 \cdot (13,3)} \cdot 4000$$

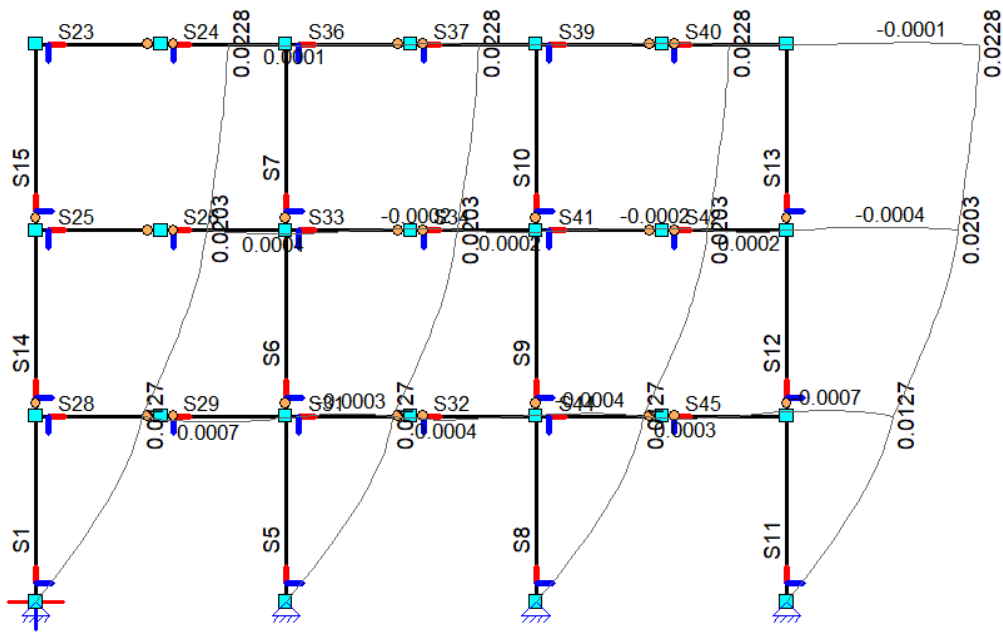
$$= 170,5 \cdot 10^6 \text{ mm}^4$$

$I_{\text{min, total}} \Rightarrow$ sum all components of floors with def limit = 24 mm instead of (13,3)

\Rightarrow Result $\Rightarrow \underline{\underline{I_{\text{min, total}} = 170,5 \cdot 10^6 \text{ mm}^4}}$

In the portal method, the internal columns and edge columns show a difference in the shear force they take up. The I's for the edge columns is determined by doing the same calculation but with the reduced shear force to get a more accurate estimates on the minimum require I in the structure.

When inserting the minimum required I for the total building into Matrixframe software, the following deformations can be visualized.



A difference of 5% between the limit 24mm and the deflection of the actual frame is noticed. This can be since the method used is an approximation. More detailed calculations need to be performed in finite element packages like Matrixframe. The calculated values are on the safe side and are accepted. The output from the python code complies with the hand calculations and are shown below.

```
[33.96825396825397,
 21.269841269841265,
 101.90476190476193,
 63.8095238095238,
 169.84126984126982,
 106.34920634920634,
 169.84126984126982,
 106.34920634920636]
```

Minimum I top storey (internal)
Minimum I top storey (edge)
Minimum I middle storey (internal)
Minimum I middle storey (edge)
Minimum I bottom storey (internal)
Minimum I bottom storey (edge)
Minimum I complete structure (internal)
Minimum I complete structure (edge)

With these results the minimal required I analysis is completed and validated.

The use of these results/python code

The data structure of the resulting python code makes it possible to add up the horizontal and vertical loading results to create load combinations. The following combinations are used to determine the maximum forces and moments for each building element:

ULS (determining max N, V, M)

$$1.2 * G + 1.5 * Q + 1.5 * \psi * \text{wind} (=0)$$

$$1.2 * G + 1.5 * F_{\text{wind}} + 1.5 * \psi * Q$$

$$1.35 * G + 1.5 * \psi * Q + 1.5 * \psi * \text{wind} (=0)$$

SLS (determining minimum I's)


$$1.0 * G + 1.0 * Q + 1.0 * \text{wind}$$

As mentioned, the dimensioning will happen by matching elements with that meet the minimum requirements for I, N and M from the above-described structural analysis. For beams, lateral torsional buckling is not considered as this problem can be solved by connecting the beams to the floor slabs. For lateral buckling of the columns, the normal force capacity is calculated for all donor elements including buckling around their weak axis.

Initial sway imperfections and second-order effects.

Initial sway imperfection can result in additional horizontal forces in the structure as the vertical loading has an eccentricity compared to the centre-line of the columns. The implication for the braced frame is limited, the extra horizontal forces are carried by the windbraces which are outside of the scope of this research. For the portal frame, the shear-force and bending-moment in the beams/columns do increase. The calculation below shows how to determine the final first-order bending moments which are relevant for the design.

Initial sway imperfections:



$$\phi = \frac{1}{200} \cdot \frac{2}{\sqrt{h}} \cdot \sqrt{0,5 \cdot \left(1 + \frac{1}{m}\right)} = \frac{1}{200} \cdot \frac{2}{\sqrt{12}} \cdot \sqrt{0,5 \cdot \left(1 + \frac{1}{4}\right)}$$

$$h = 4 \cdot 3 = 12 \text{ m}$$

$$m = 4$$

$$= 0,00228 \text{ rad}$$

results in additional shear:


$$H = N_{Ed} \cdot \phi \text{ [kN]}$$

1	$H = 0,00228 \cdot 154 = 0,35 \text{ kN}$
5	$H = 0,00228 \cdot 368 = 0,84 \text{ kN}$
7	$H = 0,00228 \cdot 590 = 1,34 \text{ kN}$

Scale moments according to $1 + \frac{H}{V}$ ratio:

$$\left(1 + \frac{0,35}{22,5}\right) \cdot 15490 = 91,4 \text{ kNm}$$

$$\left(1 + \frac{0,84}{34,4}\right) \cdot 137 = 140,4 \text{ kNm}$$

$$\left(1 + \frac{1,34}{39,2}\right) \cdot 156 = 161,3 \text{ kNm}$$


1^e orde momenten

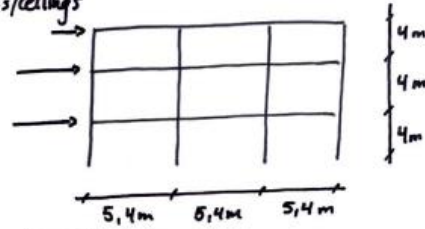
Second order effects are relevant for the second frame (portal) as well. The additional moment caused by deformation of the structure due to more eccentricity of the normal force is taken up by the portal frames. To determine the second-order factor that is used to multiply the design values for the bending-moments is calculated by evaluating the first and second order bending moments for the extreme load-combination for wind.

$$1,2 * G + 1,5 * F_{wind} + 1,5 * Q * \psi_0$$

The second-order moments are calculated by adding an additional rotation of the columns to the initial sway imperfections. The calculation on the next two pages shows a worked-example.

Second order analysis - Portal Frame

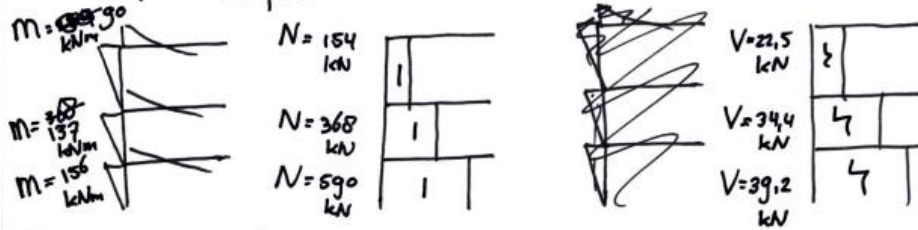
$G = \text{self-weight floor} + \text{self-weight finishes/installations/ceilings}$
 $= 2,8 + 1,8 = 4,6 \text{ kN/m}^2$
 $Q = 4 \text{ kN/m}^2 \text{ (including sep. walls)}$
 $Q_{\text{wind}} = 1,0 \text{ kN/m}^2$



Second-order effect due deformation under wind-loading.

\hookrightarrow load combination: $1,2G + 1,5F_{\text{wind}} + 1,5 \cdot Q \cdot \psi_0$
 $+ H_{\text{load}} \text{ due initial sway imperfections.}$
 \hookrightarrow floor $\psi_0 = 0,5$
 roof $\psi_0 = 0$

Results from script:



Initial sway imperfections:



$$\phi = \frac{1}{200} \cdot \frac{2}{\sqrt{h}} \cdot \sqrt{0,5 \cdot \left(1 + \frac{1}{m}\right)} = \frac{1}{200} \cdot \frac{2}{\sqrt{12}} \cdot \sqrt{0,5 \cdot \left(1 + \frac{1}{4}\right)}$$

$$= 0,00228 \text{ rad}$$

$h = 4 \cdot 3 = 12 \text{ m}$
 $m = 4$

results in additional shear:

$$H = N_{\text{ed}} \cdot \phi \text{ [kN]}$$

1	$H = 0,00228 \cdot 154 = 0,35 \text{ kN}$
1	$H = 0,00228 \cdot 368 = 0,84 \text{ kN}$
1	$H = 0,00228 \cdot 590 = 1,34 \text{ kN}$

Scale moments according to $1 + \frac{H}{V}$ ratio:

$$\left(1 + \frac{0,35}{22,5}\right) \cdot 90 = 91,4 \text{ kNm}$$

$$\left(1 + \frac{0,84}{34,4}\right) \cdot 137 = 140,4 \text{ kNm}$$

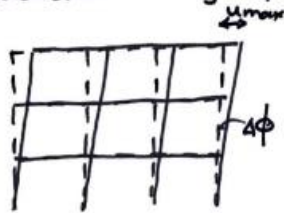
$$\left(1 + \frac{1,34}{39,2}\right) \cdot 156 = 161,3 \text{ kNm}$$



L^e orde momenten

2^e ordre effects

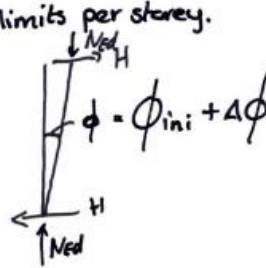
→ additional sway imperfections due to building deformation.



using deformation limits per storey.

$$U_{max} = \frac{1}{300} \cdot h.$$

$$\Delta\phi = \frac{1}{300}$$



$$\phi = 0,00228 + \frac{1}{300} = 0,00561 \text{ rad.}$$

4	$H = 0,00561 \cdot 154 = 0,864 \text{ kN}$
4	$H = 0,00561 \cdot 368 = 2,064 \text{ kN}$
4	$H = 0,00561 \cdot 590 = 3,310 \text{ kN}$

Scale moments

$$\left(1 + \frac{0,864}{22,5}\right) \cdot 90 = 93,5 \text{ kNm}$$

$$\left(1 + \frac{2,064}{34,4}\right) \cdot 137 = 145,2 \text{ kNm}$$

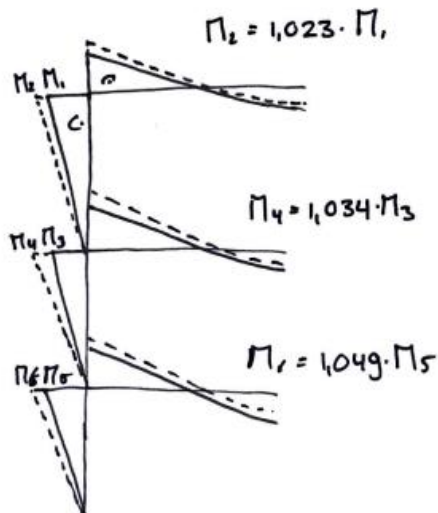
$$\left(1 + \frac{3,310}{39,2}\right) \cdot 156 = 169,2 \text{ kNm}$$

2nd order factors per storey

$$\frac{93,5}{91,4} = 1,023 \quad 2,3\%$$

$$\frac{145,2}{140,4} = 1,034 \quad 3,4\%$$

$$\frac{169,2}{161,5} = 1,049 \quad 4,9\%$$



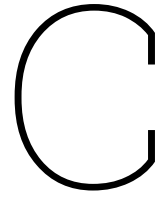
Conclusions and discussion

By adopting the analytical methods described in this document, the force and moment distributions in the frames can be calculated quite precisely. The table below gives an overview of the differences between the Matrixframe calculations and the results of the described methods.

	Method	N	V	M	δ
Braced frame	Vertical	<1%	0%	0%	-
	Horizontal	5%	0%	0%	-
Portal frame	Vertical	5%	2%	2%	-
	Horizontal	6%	6%	13%	-
	Global displacement	-	-	-	5%

Difference between Matrixframe and analytical methods used in the python code.

The difference is bigger for the horizontal method for the second model. It should be noted that in a load-combination with horizontal wind force and vertical loading, the vertical loading will be bigger than the horizontal loading and the combined difference between the Matrixframe results and analytical method will be smaller. The difference is regarded as sufficient for the early design stage this tool is used in.



Appendix: Costing-model scenarios

This appendix includes different scenarios that were compared to make the decisions for the costing model in this thesis. The different parts of this appendix are:

Appendix 1: Material testing scenarios

Appendix 2: Storage scenarios

Appendix B1: material testing

Material testing is performed using the prescribed procedures in the NTA: NEN-8713. This means that:

- Test-groups need to be identified.
- Recalculation of the structure is necessary.
- For each test-group, one tensile test needs to be performed.
- If the materials in the test-group need to be welded, one chemical composition test needs to be performed.

Each test-group consists of elements with an identical cross-section. Nebest has provided the following description of work to do material property research:

- To do an inventory, set up a test plan and take out samples for 20 test-groups, one day of fieldwork is needed with 2 persons. This translates to 2500 euro including some reporting.
- To perform in-situ chemical composition checks on the elements and additional worker is needed on the day in the field. This translates to 3200 including some reporting.
- Each tensile test costs 150 euro.

Testing will only be conducted on materials that are from an existing structure. Contact with HP staal, a reclaimed steel trader, suggest that they use the lower bound method to determine the material properties. This can be translated to costs using two different scenarios.

Scenario 1: Testing the total set of reclaimed elements that become available.

This would imply that upon deconstruction the whole set of reclaimed elements are tested. All elements can then be used in a new building. Although this might not happen in the building that is designed, the rest of the market can utilize the elements. The costs of testing would be spread over all the elements. The costs of testing are then determined using the following equation:

$$C_{testing} = \frac{\#_{tg}}{20} * \epsilon_{field,day} + \#_{tg} * \epsilon_{tensile-test}$$

$\#_{tg}$	Number of test-groups in the database of reclaimed steel elements
$\epsilon_{field,day}$	Costs of a field-day → 2500 or 3200, dependent on required tests
$\epsilon_{tensile-test}$	Costs of a tensile test → 150

For attributing the costs to the elements two options are available:

Scenario 1a: The costs are spread over all the elements in the database, not only the ones which are used in the building project. For each element:

$$C_{testing,element} = \frac{C_{testing}}{\#_{elem,donorbuilding}}$$

$$C_{testing,project} = \sum C_{testing,element}$$

In this case, the client does not pay all the testing costs. The testing will need to be performed by a third party. This is likely to be the deconstruction contractor or a reclaimed steel trader. They are then looking to sell the rest of the stock to cover for these costs and make a profit.

Scenario 1b: The total costs are attributed to the project.

$$C_{testing,project} = C_{testing}$$

In this case the client will perform all the testing. In this way more flexibility in the useable stock is created. This approach seems quite unlikely as the client will look to keep costs to a minimum and thus only test test-groups that contain elements that are going to be used in the new building.

Scenario 2: Testing the elements that will be used in the new building.

As an alternative to scenario 1b, the client only tests the elements that are going to be used in the building. This will result in a lower number of test-groups, work and thus costs overall. In this method, not all elements from the donor building receive a declaration of performance. The costs of testing can be determined for the whole project when it is known which elements will be used in the design.

$$C_{testing} = \frac{\#_{tg,project}}{20} * \epsilon_{field,day} + \#_{tg,project} * \epsilon_{tensile-tes}$$

$\#_{tg,project}$	Number of test-groups of the used elements in the building design
-------------------	---

Again, two options are available for crediting the costs to the elements.

Scenario 2a: The costs are spread over all elements in the test-group. This means that all elements that are in the test-group bear the costs of receiving a material certificate. Even the ones that do not get used in the building.

$$C_{testing,element} = \frac{C_{testing}}{L_{total,tgs}} \times L_{element}$$

$$C_{testing,project} = \sum C_{testing,element}$$

The elements which are not used but have a material certificate (DoP), need to be sold on to make up for the costs that are made. The market for reclaimed steel is quite small so this seems unlikely to happen.

Scenario 2b: The costs are spread over the elements from the test-groups that get used in the building itself. The elements in the test-groups that are not used in the project are still eligible for a material passport.

$$C_{testing,project} = C_{testing}$$

In this scenario the risk of not earning the costs back are covered by attributing all the costs to the project to begin with.

Comparison

In a case where 20%, 50% and 80% of the test-groups in the donor database are reused, the following costs for testing are credited to the project (40 test groups, 400 elements). The assumption is made that the elements that are used are equally spread over the test-groups.

	Total costs	20%	50%	80%
Scenario 1a	11000	2200	5500	8800
Scenario 1b	11000	11000	11000	11000
Scenario 2a	2200-5500-8800	440	2750	7040
Scenario 2b	2200-5500-8800	2200	5500	8800

Total costs vs credited costs for each scenario under the above stated assumptions.

In scenario 1a, not all testing costs are paid for by the client. The residual testing costs are taken up by the deconstruction contractor or reclaimed steel trader. They can earn these costs back by selling on the rest of the donor steel stock. Scenario 1b is unlikely to happen as mentioned earlier. The client will seek to reduce costs. Unnecessary test will not be performed.

Scenario 2a, where unused elements from the project are sold on is not realistic yet as the market for these elements remains quite small. Scenario 2b is more realistic in this case. The advantages and disadvantages of the most realistic scenarios, 1a and 2b, are summarised in the table below.

	Scenario 1a	Scenario 2b
Advantages	The costs of testing can be spread over all the elements.	You pay what you use. To tensile tests are performed on test-groups that won't get utilized in the building.
	The elements that are not used now have material certificates and can be used in other buildings.	
	If there are changes in the design, elements from the stockpile can be used without researching their material properties.	
Disadvantages	If remaining elements are not used in a different project, the costs can remain unpaid for.	The testing costs for the project will be higher as the left-over elements with a declaration of performance are not sold on.

Advantages and disadvantages to scenarios 1a and 2b.

Conclusion

It is seen that scenario 1a and 2b do generate similar results. This will not always be the case as the used elements will not always be spread equally over the test groups. If they are not, scenario 2b will result in a more representative cost as the test-groups are regarded separately.

Scenario 2b seems more likely in today's practices and is dominant in completed projects like Biopartner 5. This scenario will be implemented in the costing model for SteelIT. It is likely that in the future, a market will develop for tested, reclaimed steel elements as they can be treated like new. Conducting material verification and supplying the elements with a declaration of performance adds value. Therefore, scenario 1a is likely to develop as reclaimed steel gets utilized in more projects. The effect of this way of costing will be investigated in the sensitivity analysis.

D

Appendix: Case study SteelIT

This appendix contains the list of elements, database and output that is viewed in the tool for the case study in section D. Table D.1 gives an overview of the four designs that are evaluated in the tool.

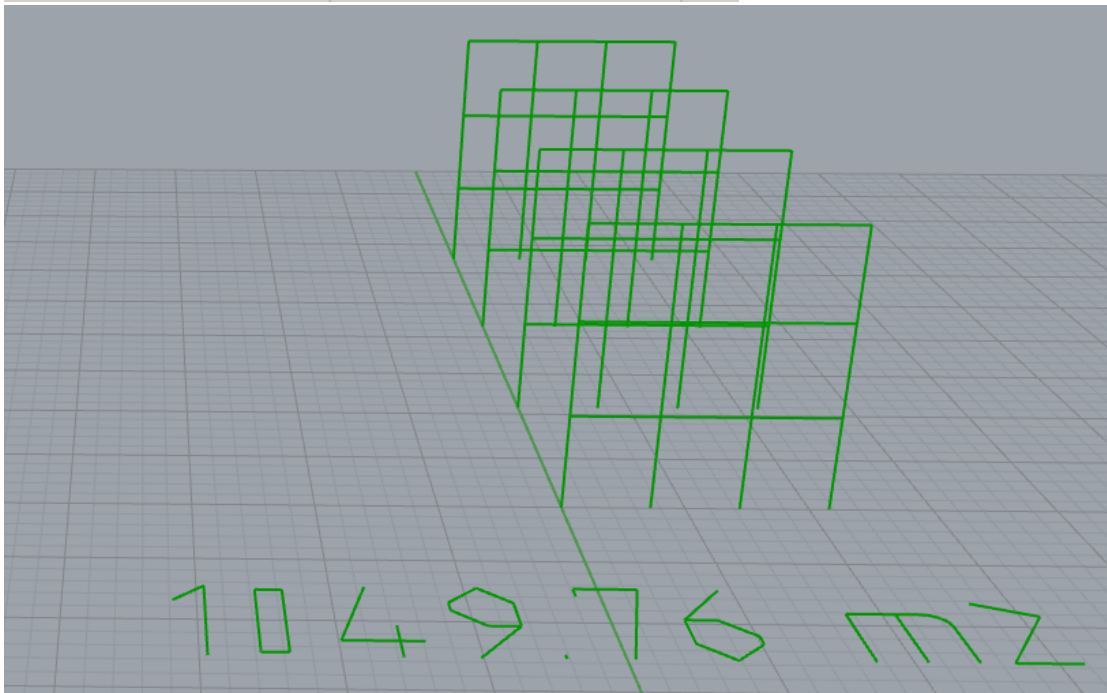
	floor span [m]	column-distance [m]	h_{floor} [m]	floor spans	column spans	W_{mult}
Case1	10.8	3.6	3.7	3	3	1.5
Case2	7.2	5.4	3.5	3	3	1.5
Case3	5.4	7.2	3.5	3	3	1.5
Case4	10.8	5.4	3.7	3	2	1.5

Table D.1: The design parameters for each design iteration.

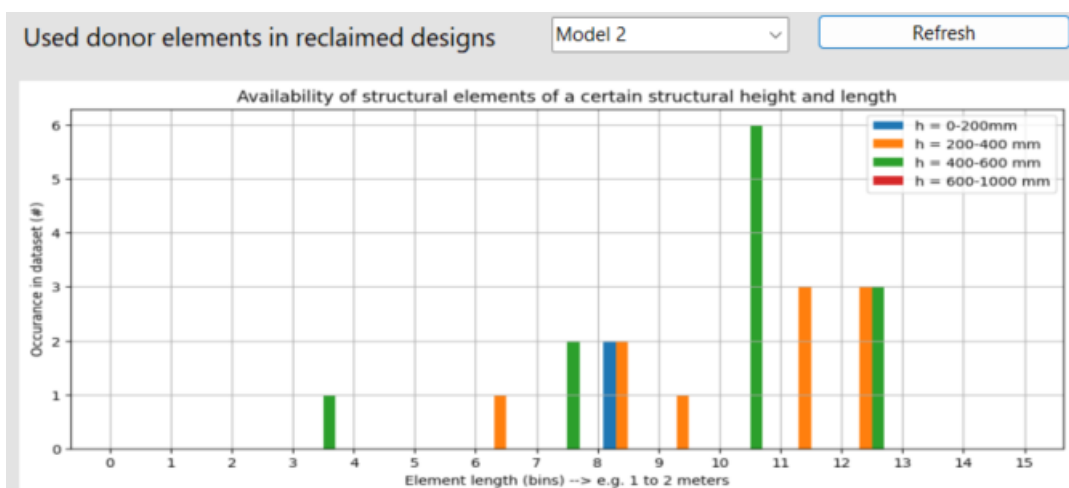
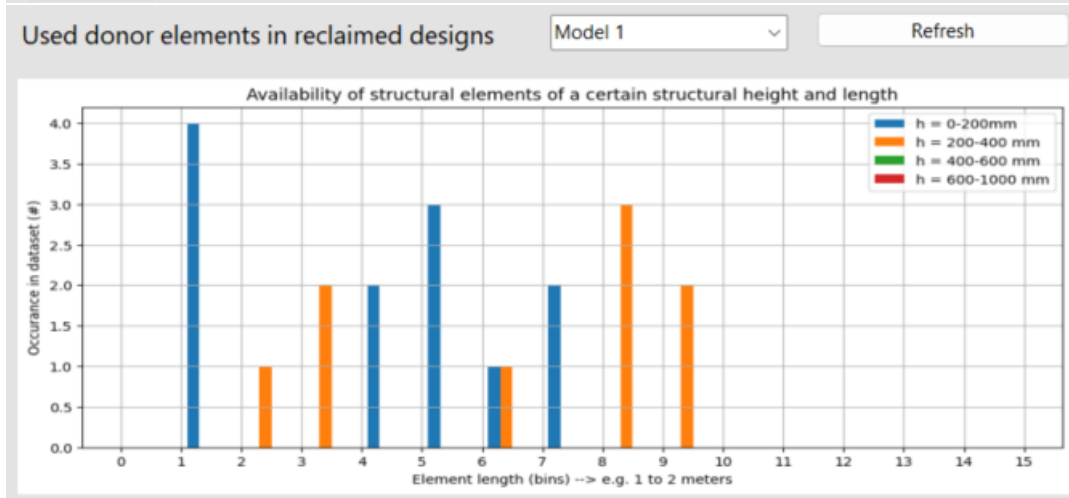
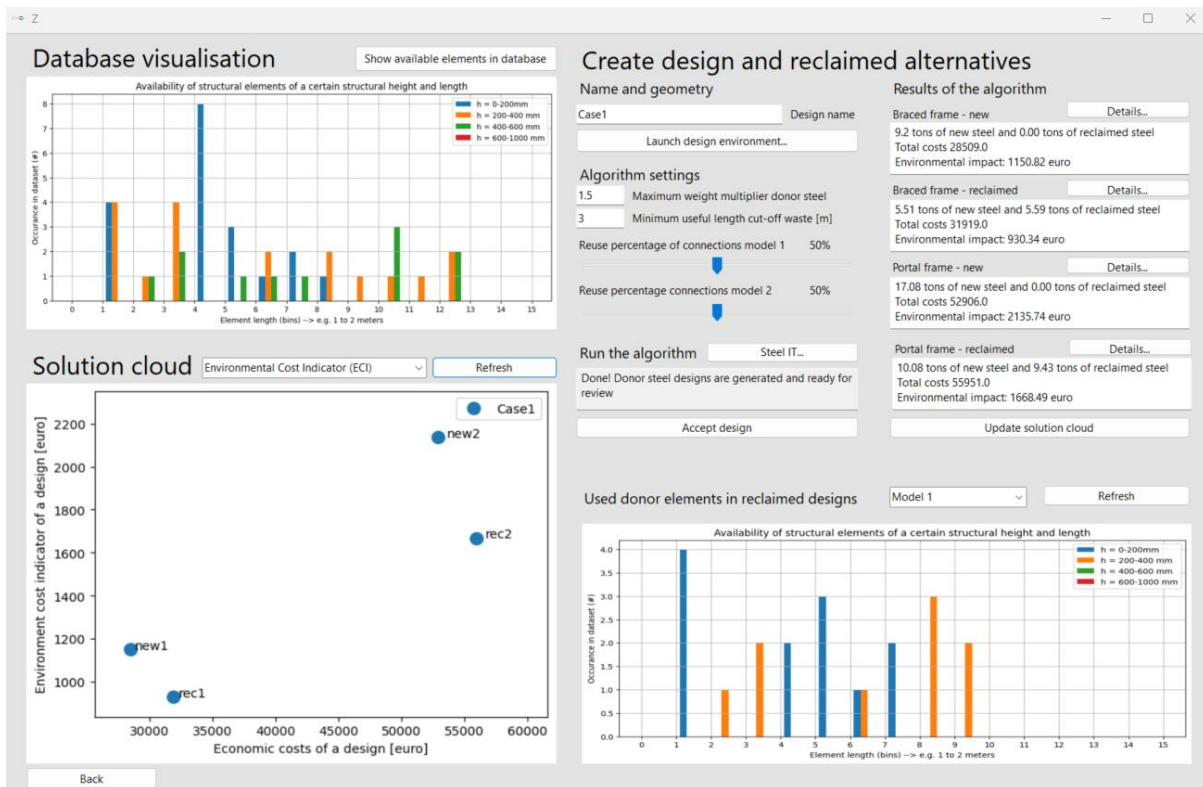
Case 1 – output

The design parameters used and resulting geometry:

Amount of column spans	3
Amount of storeys	3
Amount of floor spans	3
floorheight	3.5
Column-to-column distance	3.6 meters
Floor span in meters	10.8 meters
Type of floor	Heavy floor (VBI slab)
Structural height of floor:	260
Save design	



Tool output and stock use:

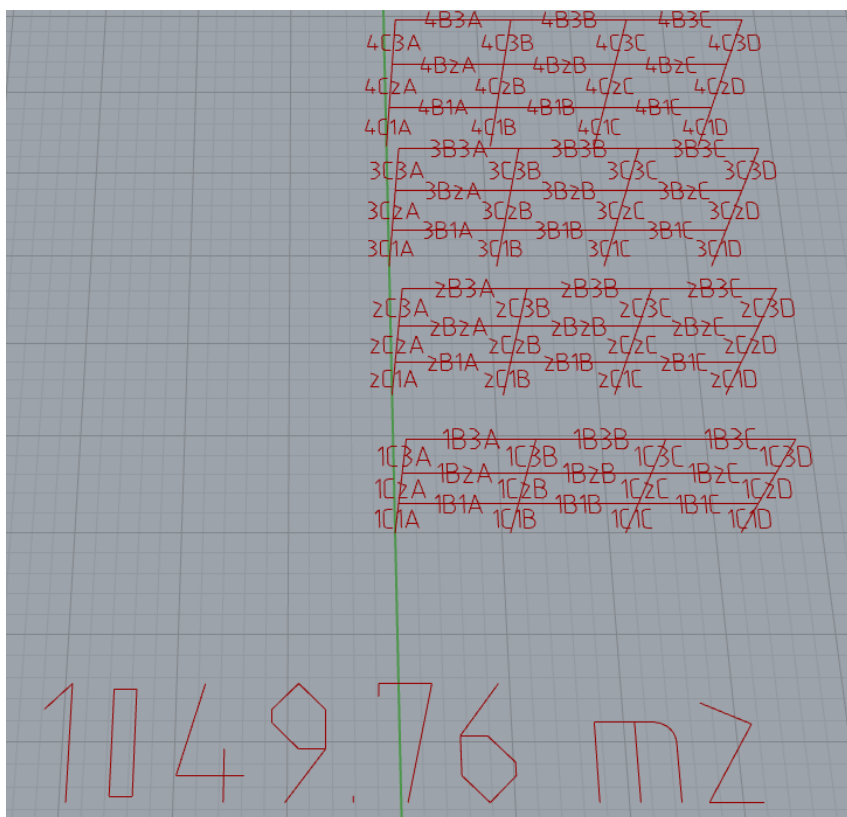


Case 2 – output

The design parameters used and resulting geometry:

The screenshot shows a software interface with the following parameters and controls:

- Amount of column spans: 3
- Amount of storeys: 3
- Amount of floor spans: 3
- floorheight: 3.4
- Column-to-column distance: 5.4 meters
- Floor span in meters: 7.2 meters
- Type of floor: Heavy floor (VBI slab)
- Structural height of floor: 200
- Save design button



Tool output and stock use:

Database visualisation

Show available elements in database

Availability of structural elements of a certain structural height and length

Element length (bins)	h = 0-200mm	h = 200-400 mm	h = 400-600 mm	h = 600-1000 mm
1	4	4	0	0
2	0	0	1	1
3	0	4	2	0
4	8	0	0	0
5	3	0	0	0
6	1	2	1	0
7	2	2	1	0
8	1	2	0	0
9	0	1	0	0
10	0	0	3	0
11	0	1	0	0
12	0	0	2	0
13	0	0	2	0

Create design and reclaimed alternatives

Name and geometry

Case2 Design name

Launch design environment...

Algorithm settings

1.5 Maximum weight multiplier donor steel

3 Minimum useful length cut-off waste [m]

Reuse percentage of connections model 1 50%

Reuse percentage connections model 2 50%

Run the algorithm Steel IT...

Done! Donor steel designs are generated and ready for review

Accept design

Results of the algorithm

Braced frame - new

12.03 tons of new steel and 0.00 tons of reclaimed steel
Total costs 37274.0
Environmental impact: 1504.63 euro

Braced frame - reclaimed

11.12 tons of new steel and 1.64 tons of reclaimed steel
Total costs 43018.0
Environmental impact: 1461.27 euro

Portal frame - new

17.18 tons of new steel and 0.00 tons of reclaimed steel
Total costs 53233.0
Environmental impact: 2148.91 euro

Portal frame - reclaimed

9.97 tons of new steel and 10.45 tons of reclaimed steel
Total costs 56820.0
Environmental impact: 1699.57 euro

Update solution cloud

Solution cloud

Environmental Cost Indicator (ECI) Refresh

Environment cost indicator of a design [euro]

Economic costs of a design [euro]

Back

Used donor elements in reclaimed designs

Model 1 Refresh

Availability of structural elements of a certain structural height and length

Element length (bins)	h = 0-200mm	h = 200-400 mm	h = 400-600 mm	h = 600-1000 mm
1	4.0	0	0	0
2	0	1.0	0	0
3	0	0	0	0
4	0	0	0	0
5	1.0	0	0	0
6	1.0	1.0	0	0
7	2.0	0	0	0

Used donor elements in reclaimed designs

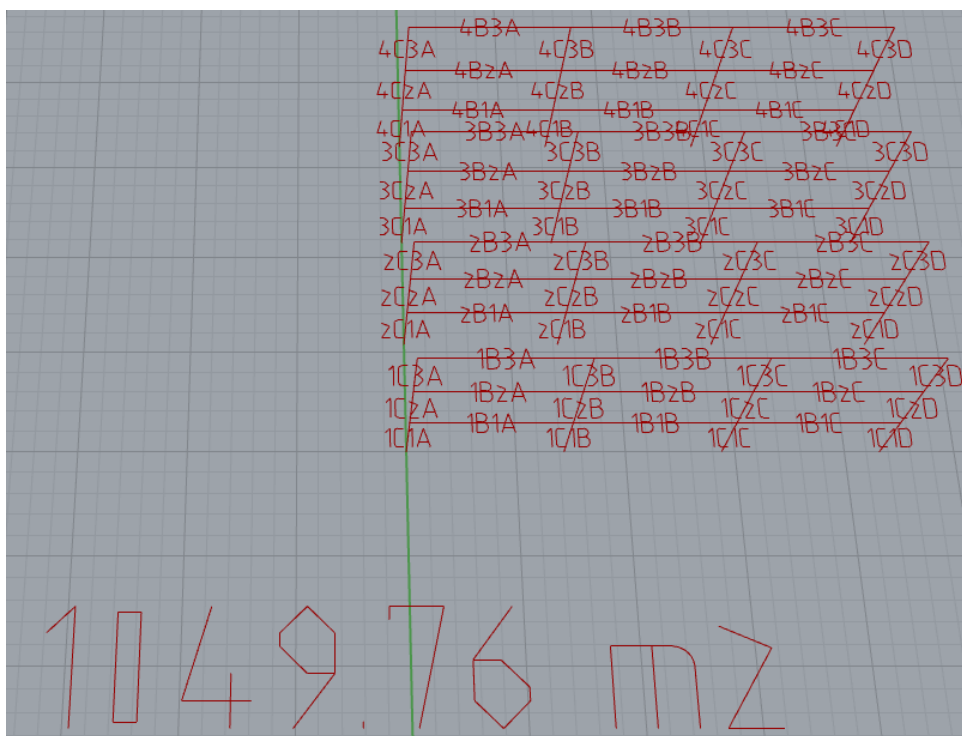
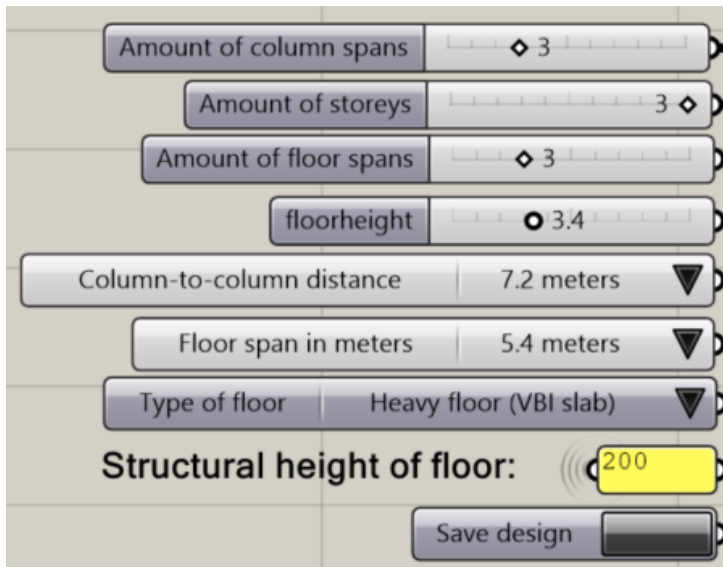
Model 2 Refresh

Availability of structural elements of a certain structural height and length

Element length (bins)	h = 0-200mm	h = 200-400 mm	h = 400-600 mm	h = 600-1000 mm
5	1.0	0	0	0
6	0	1.0	0	0
7	1.0	0	0	0
8	2.0	3.0	0	0
9	0	2.0	0	0
10	0	0	7.0	0
11	0	3.0	0	0
12	0	3.0	0	0

Case 3 – output

The design parameters used and resulting geometry:



Tool output and stock use:

Database visualisation

Show available elements in database

Availability of structural elements of a certain structural height and length

Element length (bins)	h = 0-200mm	h = 200-400 mm	h = 400-600 mm	h = 600-1000 mm
1	4	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	8	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0
12	0	0	0	0
13	0	0	0	0
14	0	0	0	0
15	0	0	0	0

Create design and reclaimed alternatives

Name and geometry

Case4 Design name

Launch design environment...

Algorithm settings

1.5 Maximum weight multiplier donor steel

3 Minimum useful length cut-off waste [m]

Reuse percentage of connections model 1 50%

Reuse percentage connections model 2 50%

Run the algorithm Steel IT...

Done! Donor steel designs are generated and ready for review

Accept design

Results of the algorithm

Braced frame - new Details...

11.57 tons of new steel and 0.00 tons of reclaimed steel
Total costs 35843.0
Environmental impact: 1446.93 euro

Braced frame - reclaimed Details...

8.52 tons of new steel and 4.34 tons of reclaimed steel
Total costs 40040.0
Environmental impact: 1252.21 euro

Portal frame - new Details...

17.86 tons of new steel and 0.00 tons of reclaimed steel
Total costs 55313.0
Environmental impact: 2232.87 euro

Portal frame - reclaimed Details...

10.72 tons of new steel and 14.25 tons of reclaimed steel
Total costs 60981.0
Environmental impact: 1953.65 euro

Update solution cloud

Solution cloud

Environmental Cost Indicator (ECI) Refresh

Environment cost indicator of a design [euro]

Economic costs of a design [euro]

Case1 Case2 Case3 Case4

new1 new2 rec1 rec2

Back

Used donor elements in reclaimed designs

Model 1 Refresh

Availability of structural elements of a certain structural height and length

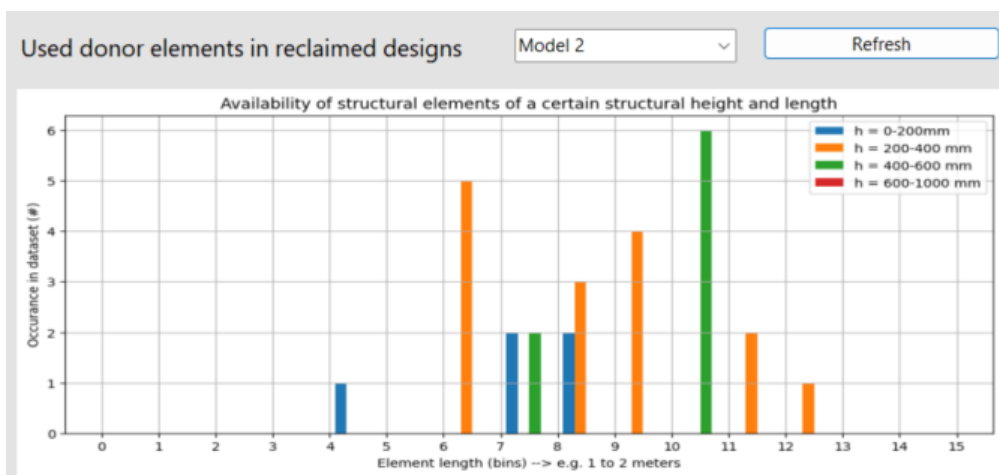
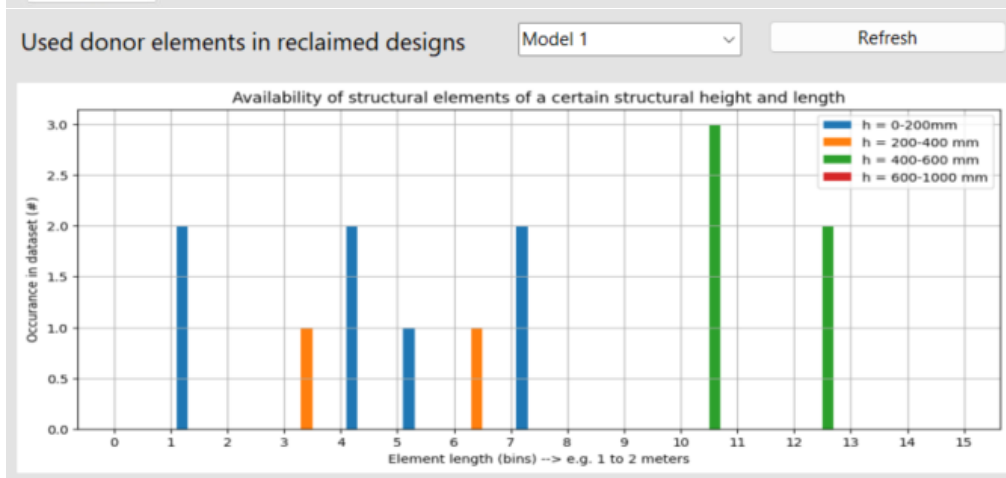
Element length (bins)	h = 0-200mm	h = 200-400 mm	h = 400-600 mm	h = 600-1000 mm
1	2	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0
12	0	0	0	0
13	0	0	0	0
14	0	0	0	0
15	0	0	0	0

Used donor elements in reclaimed designs

Model 2 Refresh

Availability of structural elements of a certain structural height and length

Element length (bins)	h = 0-200mm	h = 200-400 mm	h = 400-600 mm	h = 600-1000 mm
4	1	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0
12	0	0	0	0
13	0	0	0	0
14	0	0	0	0
15	0	0	0	0



Case 4- output

The design parameters used and resulting geometry:

Amount of column spans

Amount of storeys

Amount of floor spans

floorheight

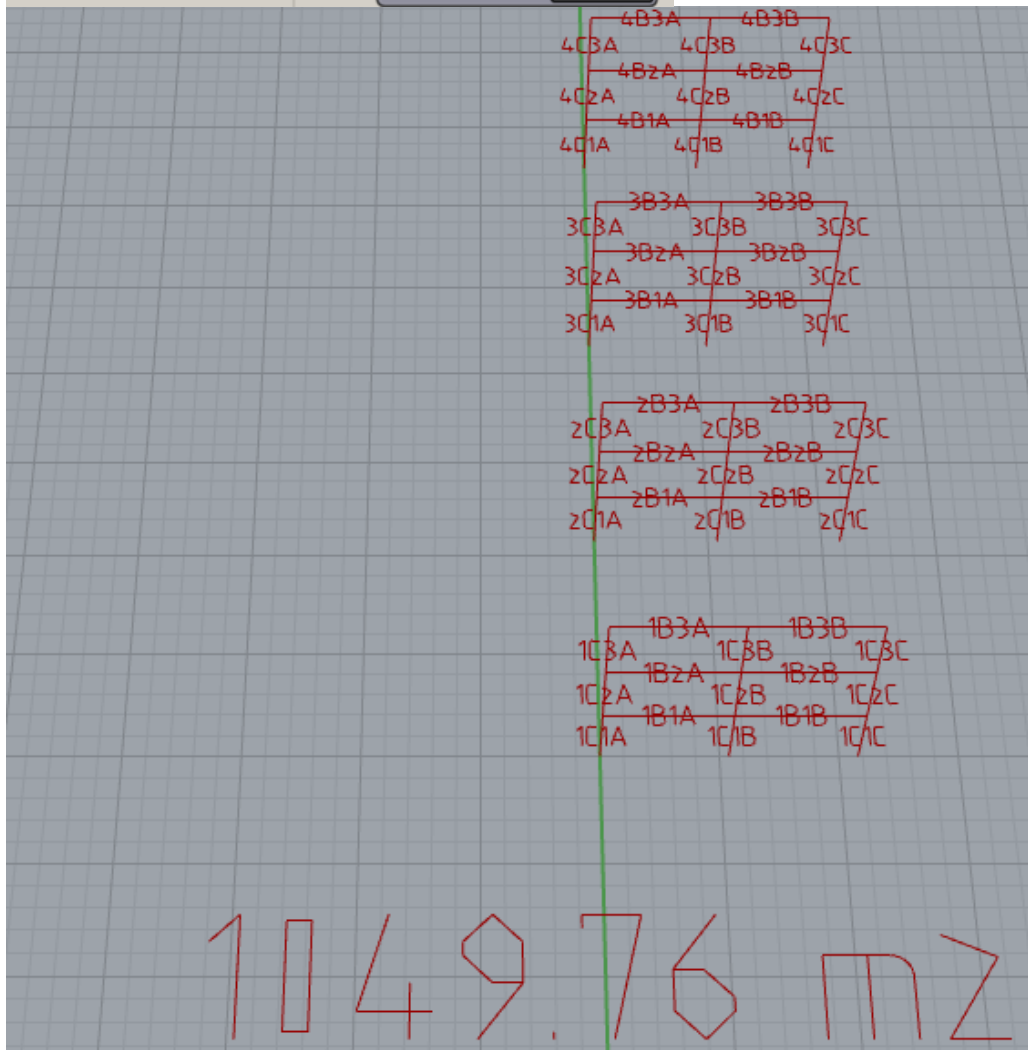
Column-to-column distance 5.4 meters

Floor span in meters 10.8 meters

Type of floor Heavy floor (VBI slab)

Structural height of floor:

Save design



Tool output and stock use:

Database visualisation

Show available elements in database

Create design and reclaimed alternatives

Name and geometry

Case4 Design name

Algorithm settings

1.5 Maximum weight multiplier donor steel

3 Minimum useful length cut-off waste [m]

Reuse percentage of connections model 1 50%

Reuse percentage connections model 2 50%

Run the algorithm

Done! Donor steel designs are generated and ready for review

Used donor elements in reclaimed designs

Solution cloud

Environmental Cost Indicator (ECI)

Used donor elements in reclaimed designs

Model 1

Used donor elements in reclaimed designs

Model 2

E

Appendix: Sensitivity analysis and scenario exploration

In chapter 10, multiple analyses are performed. This appendix contains all the databases, designs and analysis methods that are used. The following section will be included in this appendix.

1. Analysis database and office design.
2. Analysis flooring system.
3. Analysis model constraints.
4. Analysis cost model parameters.

1. Analysis database and office design

The influence of the database and design have been analysed by generating results for 25 combinations of design and database. For this purpose, 5 databases and 5 design have been created. Using the code below, all combinations between database and design have been evaluated.

```
## D1 = Brede Buurtschool
## D2 = Differ
## D3 = Schiphol
## D4 = Schmidt Zeevis
## D5 = Pathe Maastricht

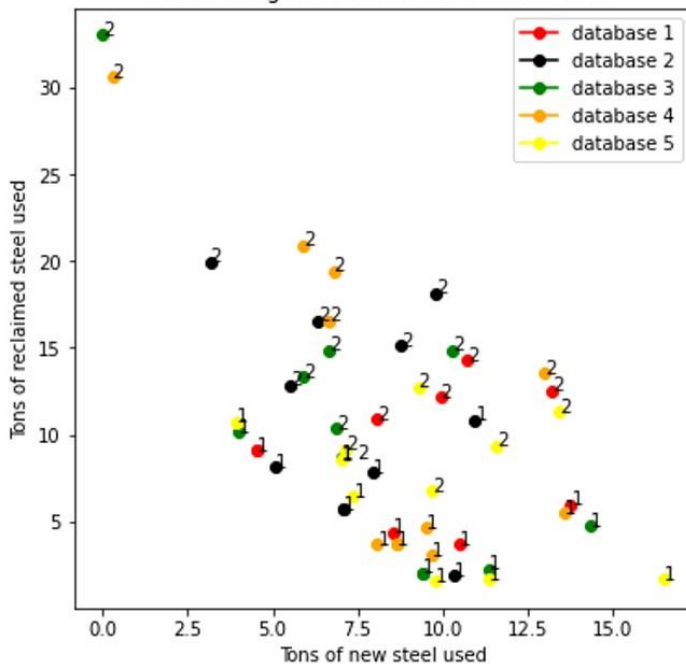
## List of database names to use in analysis.
excels = ["D1", "D2", "D3", "D4", "D5"]

## List of designfile names to use in analysis
names = ["design1", "design2", "design3", "design4", "design5"]

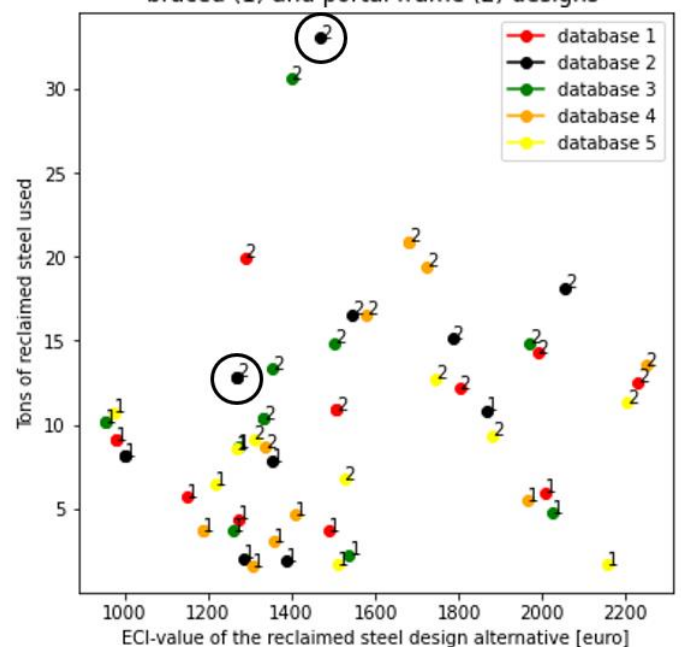
## List of names to give to the generated designs
designfiles = ["GHuitvoer1", "GHuitvoer2", "GHuitvoer3", "GHuitvoer4", "GHuitvoer5"]
res = [] ## Array to save results
for i in range(len(excels)):
    for j in range(len(designfiles)):
        ##Run the code for each combination and save results to "res" array
        res.append(np.array(TheCodeV2.TheCode(1.5, 3, names[i], excels[i],
                                                50, 50, 1.8, 0.50,150, 1.20, 20,
                                                0.1625, 235, designfiles[j])))
```

The following graphs are produced with the results.

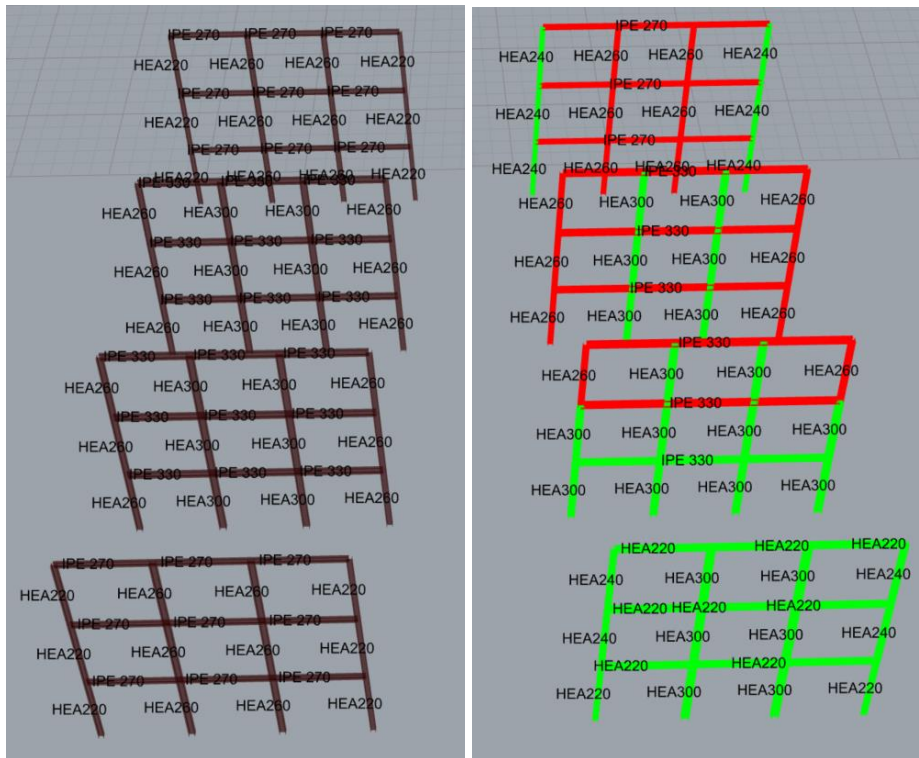
Tons of new and reclaimed steel used in model 1 and 2 for 25 design and database combinations



Tons of reclaimed steel used against ECI-value for braced (1) and portal frame (2) designs



Top circled solution (black circle)



Combined weight: 20.23 tons (7.69 new steel, 12.54 reclaimed steel)

Costs Breakdown

6924	Cost price new steel
6807	Cost price reclaimed steel
1925	Costs of material testing
0	Storage costs
1924	Cost of sandblasting and painting
11402	Fabrication costs
15372	Assembly costs
2947	Engineering costs
47301	Total without risk
7095	Risk
54396	Total costs including risk

Close

Environmental impact breakdown

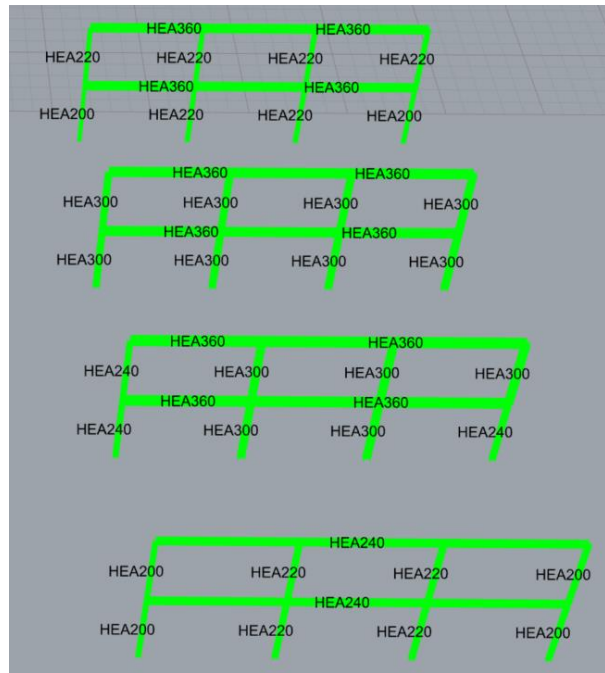
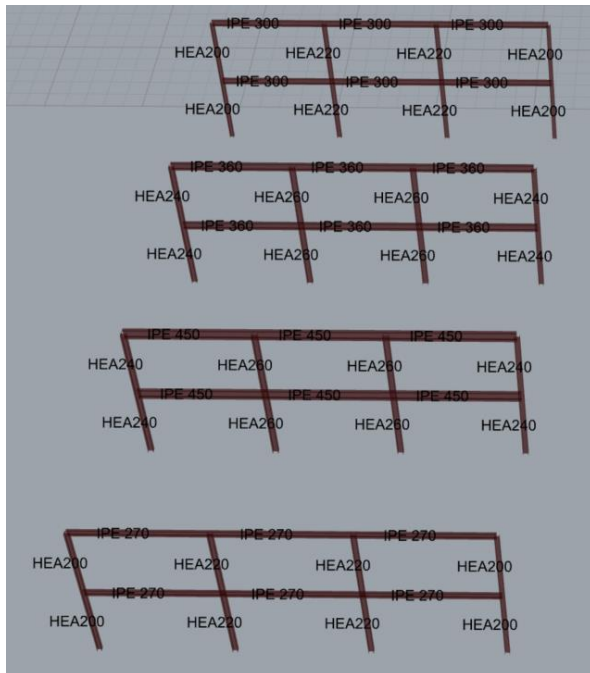
Environmental cost indicator [euro]

1226	A1 - A3: Production and Manufacturing
189	A4 - A5: Construction
0	B: Use phase
297	C: End-of-life
-203	D: Benefits and loads beyond service life
1509	Total

Paris proof indicator [kg CO2-eq]

11207	A1 - A3: Production and Manufacturing
1582	A4 - A5: Construction
12789	Total

Bottom circles solution (black circle)



Combined weight: 33.01 tons (0 new steel, 33.01 reclaimed steel)

Costs Breakdown

0	Cost price new steel
16963	Cost price reclaimed steel
2109	Costs of material testing
0	Storage costs
0	Cost of sandblasting and painting
7859	Fabrication costs
11788	Assembly costs
2260	Engineering costs
40979	Total without risk
6147	Risk
47126	Total costs including risk

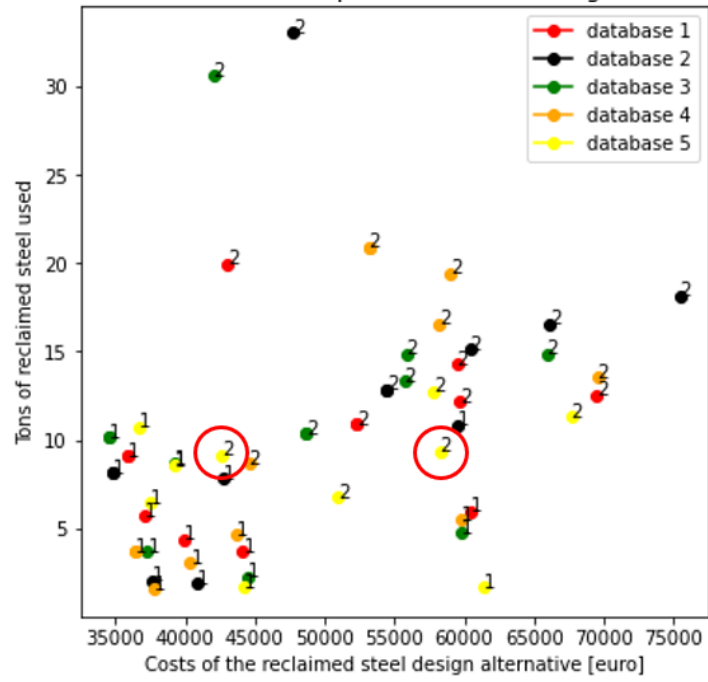
Environmental impact breakdown

Environmental cost indicator [euro]	
710	A1 - A3: Production and Manufacturing
308	A4 - A5: Construction
0	B: Use phase
479	C: End-of-life
-72	D: Benefits and loads beyond service life
1425	Total

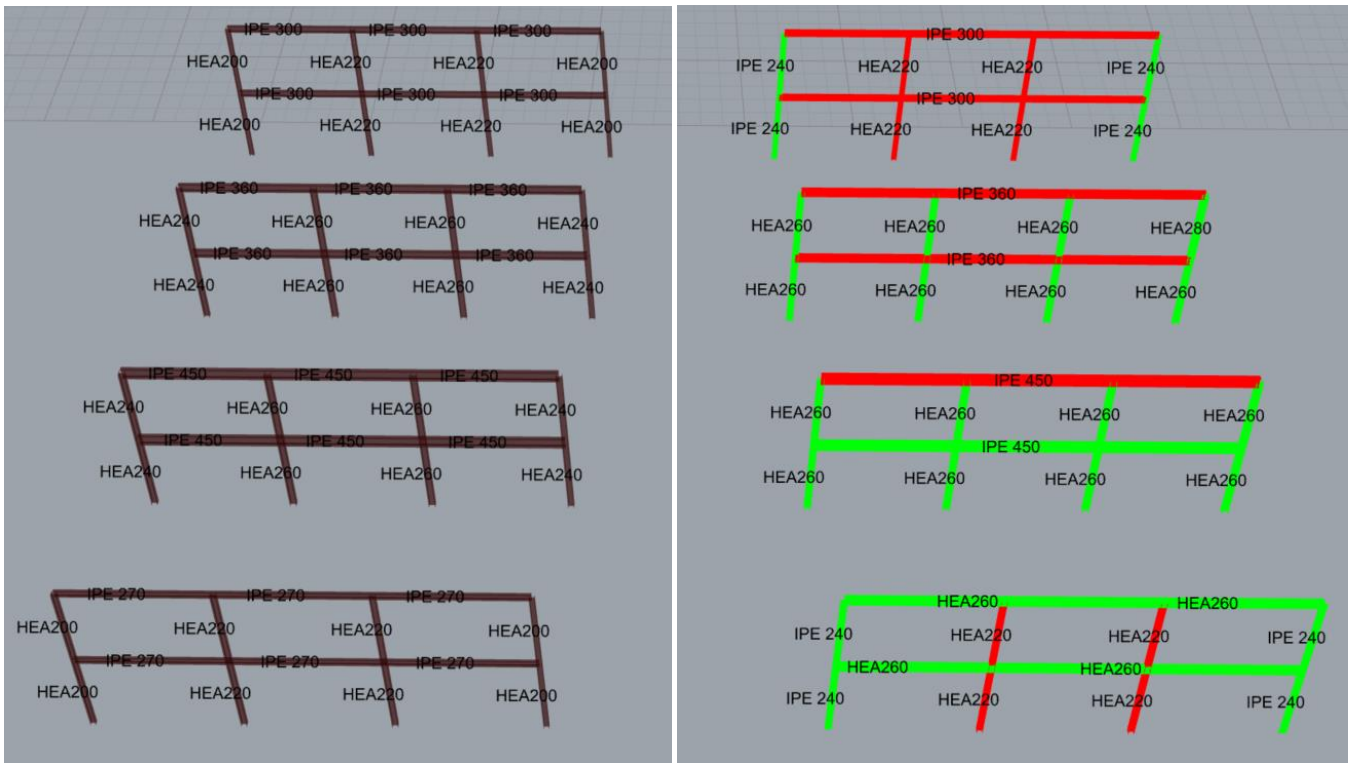
Paris proof indicator [kg CO2-eq]

6628	A1 - A3: Production and Manufacturing
2582	A4 - A5: Construction
9210	Total

Tons of reclaimed steel used against total costs for braced (1) and portal frame (2) designs



Left circled solution (red circle)



Combined weight: 16.28 tons (7.15 new steel, 9.13 reclaimed steel)

Costs Breakdown

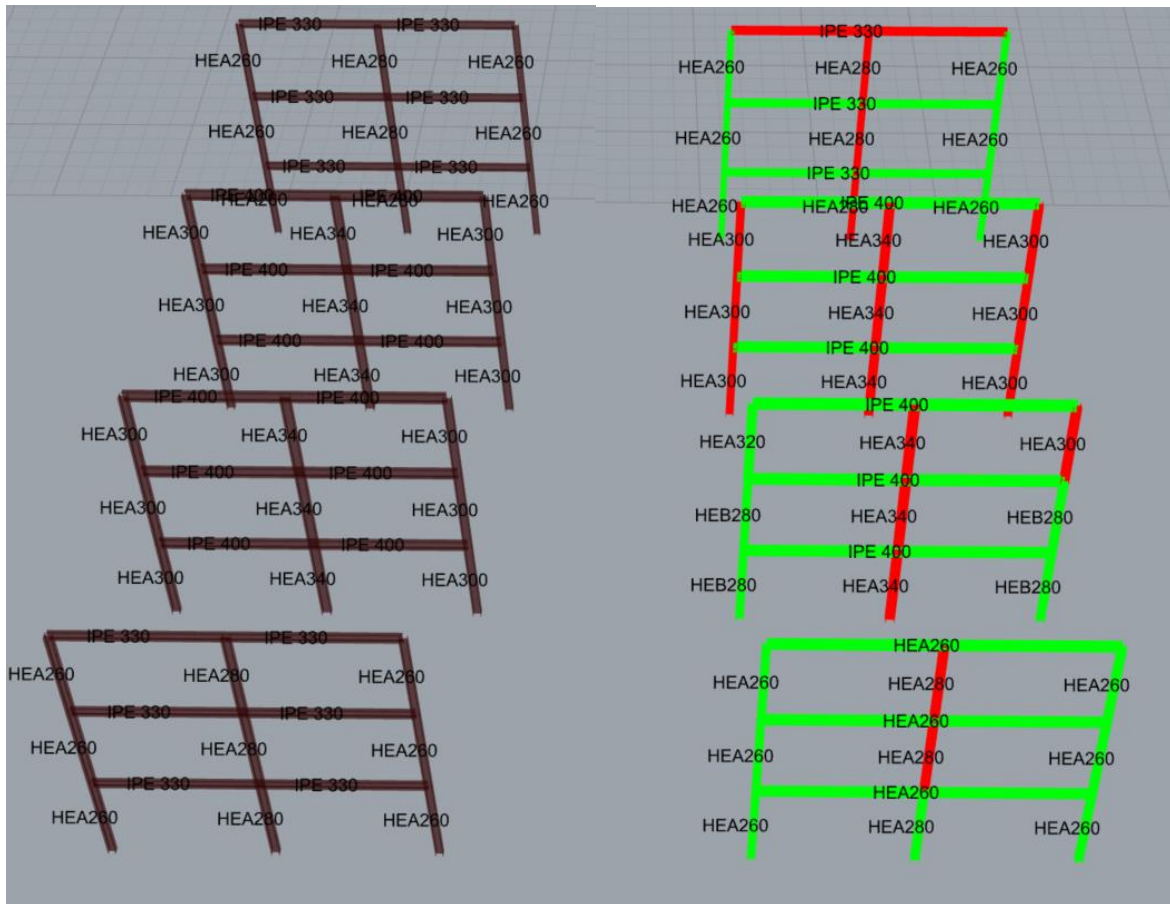
6432	Cost price new steel
4643	Cost price reclaimed steel
1984	Costs of material testing
0	Storage costs
1787	Cost of sandblasting and painting
8931	Fabrication costs
11788	Assembly costs
2260	Engineering costs
37825	Total without risk
5674	Risk
43499	Total costs including risk

Environmental impact breakdown

Environmental cost indicator [euro]	
1085	A1 - A3: Production and Manufacturing
152	A4 - A5: Construction
0	B: Use phase
234	C: End-of-life
-183	D: Benefits and loads beyond service life
1288	Total

Paris proof indicator [kg CO ₂ -eq]	
9826	A1 - A3: Production and Manufacturing
1273	A4 - A5: Construction
11099	Total

Right circles solution (red circle)



Combined weight: 20.93 tons (11.59 new steel, 9.34 reclaimed steel)

Costs Breakdown

10430	Cost price new steel
4827	Cost price reclaimed steel
1488	Costs of material testing
0	Storage costs
2898	Cost of sandblasting and painting
12452	Fabrication costs
16071	Assembly costs
3081	Engineering costs
51247	Total without risk
7687	Risk
58934	Total costs including risk

Environmental impact breakdown

Environmental cost indicator [euro]

1642	A1 - A3: Production and Manufacturing
195	A4 - A5: Construction
0	B: Use phase
302	C: End-of-life
-285	D: Benefits and loads beyond service life
1854	Total

Paris proof indicator [kg CO₂-eq]

14860	A1 - A3: Production and Manufacturing
1637	A4 - A5: Construction
16497	Total

Database 1: Brede Buurtschool



Type	Length	Type	Length	Type	Length	Type	Length
HE140A	28.3	HE240A	11.95	HE320B	1.32	IPE330	9.78
HE160A	1.8	HE240A	12	HE320B	1.4	IPE330	28.49
HE160A	1.83	HE200B	4.2	HE320B	3.01	IPE500	0.17
HE160A	1.83	HE200B	4.2	HE320B	3.01	IPE500	0.2
HE160A	1.83	HE200B	4.2	HE340B	6.39	IPE500	2.92
HE160A	7.53	HE200B	4.35	HE340B	10.22	IPE500	3.43
HE180A	6.62	HE200B	4.72	HE400B	12.2	IPE500	3.84
HE200A	5.87	HE200B	4.72	HE900B	17.64	IPE500	5.27
HE200A	7.58	HE200B	4.8	HE900B	17.64	IPE500	6.15
HE240A	0.594	HE200B	4.8	HE900B	17.64	IPE500	7.5
HE240A	1.31	HE200B	5.27	HE900B	17.66	IPE500	10.3
HE240A	1.4	HE200B	5.51	HE900B	17.66	IPE500	10.3
HE240A	2.68	HE200B	8.85	IPE270	6.24	IPE500	10.3
HE240A	3.01	HE200B	19.2	IPE330	8.74	IPE500	12.31
HE240A	3.01	HE320B	0.597	IPE330	8.74	IPE550	12.26

Properties.

Fy: 235 MPa

Tonnage: 50.4 ton

Total length elements: 445 m.

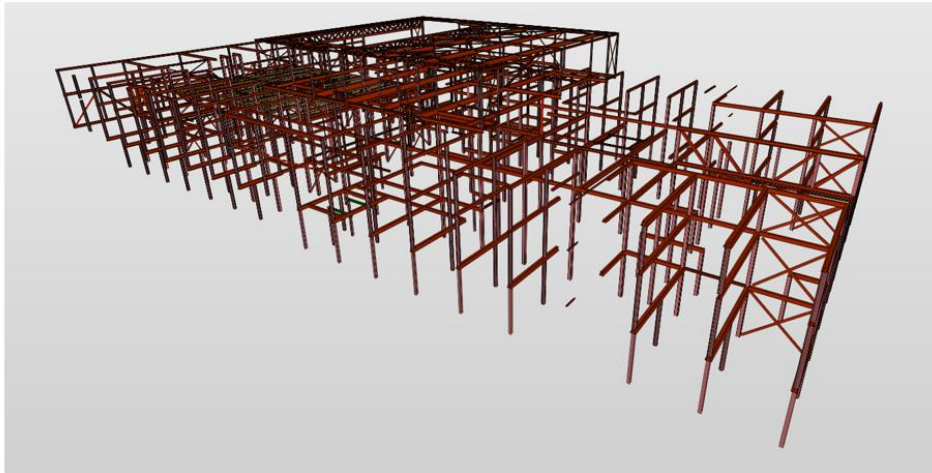
Average weight elements: 90.8 kg/m

Number of elements: 60

average length elements: 8.0 m.

average W elements: 2204 * 10⁶ mm⁴

Database 2: Differ



Type	Length	Type	Length	Type	Length	Type	Length
HE200A	5.1	HEA160	5.1	HEA240	2.81	HEA360	11.69
HE200A	5.1	HEA160	5.17	HEA240	2.83	HEA360	11.69
HE200A	5.2	HEA160	5.17	HEA240	2.83	HEA360	11.69
HE200A	5.2	HEA160	5.17	HEA240	13.31	HEA360	11.69
HE200A	7.02	HEA160	5.17	HEA240	23.7	HEA360	11.69
HE200A	8.65	HEA160	5.17	HEA240	24.2	HEA360	11.69
HE200A	8.65	HEA160	6.93	HEA260	3.11	HEA360	11.69
HEB200	3.25	HEA160	6.93	HEA300	2.79	HEA400	7.65
HEB200	3.56	HEA180	6.81	HEA300	15.9	HEA400	7.65
HEB200	3.56	HEA180	6.87	HEA300	34.2	HEA400	9.45
HEB500	11.73	HEA200	5.14	HEA300	34.2	HEA400	9.52
HEB500	8.76	HEA200	5.14	HEA360	4.13	HEA450	5.1
HEA160	3	HEA220	4.17	HEA360	4.13	HEA450	5.16
HEA160	3	HEA220	4.17	HEA360	7.36	HEA450	6.9
HEA160	3.47	HEA220	4.24	HEA360	7.36	HEA450	6.9
HEA160	4.3	HEA220	4.24	HEA360	9.74	HEA450	6.9
HEA160	4.32	HEA220	7.24	HEA360	11.54	HEA450	13.35
HEA160	5.1	HEA220	7.37	HEA360	11.69	HEA450	14.42
HEA160	5.1	HEA220	7.37	HEA360	11.69		
HEA160	5.1	HEA220	8.69	HEA360	11.69		

Properties

Fy: 235 MPa

Tonnage: 54.7 tons

Number of elements: 78

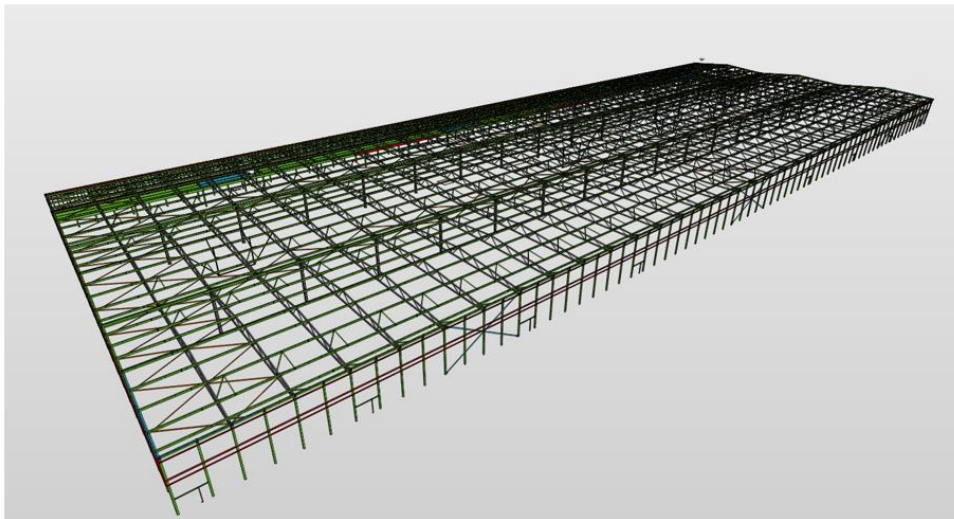
Total length elements: 640 m.

average length elements: 8.2

Average weight elements: 76.3 kg/m

average W elements: $1303 * 10^6 \text{ mm}^4$

Database 3: Schiphol hanger



Type	Length	Type	Length	Type	Length	Type	Length
HEA260	7.44	HEA160	4.07	HEA280	10.25	HEA360	9.97
HEA260	7.44	HEA160	4.07	HEA280	10.25	HEA360	9.97
HEA260	7.44	HEA160	4.07	HEA280	10.25	HEA360	9.97
HEA260	8.47	HEA200	4.87	HEA280	10.25	HEA360	9.97
HEA260	8.47	HEA200	4.87	HEA280	10.25	HEA360	9.97
HEA260	8.47	HEA200	4.87	HEA280	10.25	HEA360	9.97
HEA260	8.47	HEA200	4.87	HEA280	10.47	HEA360	9.97
HEA260	8.47	HEA200	4.87	HEA280	10.47	HEA360	9.97
HEA260	8.47	HEA200	5.07	HEA280	10.47	HEA500	9.4
HEA500	6.76	HEA200	5.51	HEA280	10.47	HEA500	9.4
IPE220	7.44	HEA220	3.96	HEA280	10.47	HEA500	9.4
IPE330	7.44	HEA240	10.07	HEA300	3.13	HEA500	9.97
IPE330	7.44	HEA240	10.07	HEA300	5.36	HEA500	9.97
IPE330	7.44	HEA280	4.87	HEA300	9.4		
IPE330	7.44	HEA280	4.87	HEA300	9.87		
IPE330	7.44	HEA280	4.87	HEA300	9.97		
IPE330	7.44	HEA280	4.87	HEA300	9.97		
IPE330	7.44	HEA280	4.87	HEA360	9.84		
IPE330	10.61	HEA280	4.88	HEA360	9.97		
IPE330	10.61	HEA280	6.5	HEA360	9.97		

Properties

Fy: 235 MPa

Tonnage: 48.8 tons

Number of elements: 73

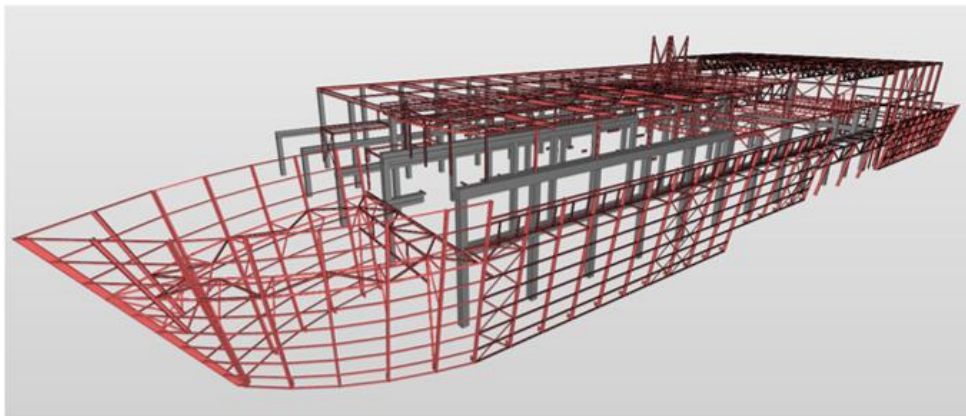
Total length elements: 586 m.

average length elements: 8.0

Average weight elements: 78.8 kg/m

average W elements: 1349 * 10⁶ mm⁴

Database 4: Schmidt Zeevis office



Type	Length	Type	Length	Type	Length	Type	Length
HEA200	3.42	IPE240	3.64	IPE400	8.76	HEA300	14.62
HEA200	5.54	IPE240	3.69	IPE400	15.6	HEA320	14.62
HEA200	6.32	IPE270	2.13	IPE400	15.6	HEA320	14.62
HEA200	6.32	IPE270	2.13	IPE400	15.6	HEB180	3.46
HEA260	6.29	IPE270	2.13	HEA260	14.82	HEB180	3.46
HEA260	6.32	IPE270	2.13	HEA260	14.82	HEB180	3.46
HEA300	10.49	IPE270	2.33	HEA260	14.82	HEB180	3.46
IPE120	4.72	IPE300	2.54	HEA280	14.82	HEB180	3.46
IPE120	6.21	IPE300	3.53	HEA280	14.82	HEB180	3.46
IPE120	7.1	IPE300	4.17	HEA280	14.82		
IPE120	8.02	IPE300	4.81	HEA280	14.82		
IPE240	2.5	IPE300	5.45	HEA300	14.62		

Properties

Fy: 235 MPa

Tonnage: 22.3 tons

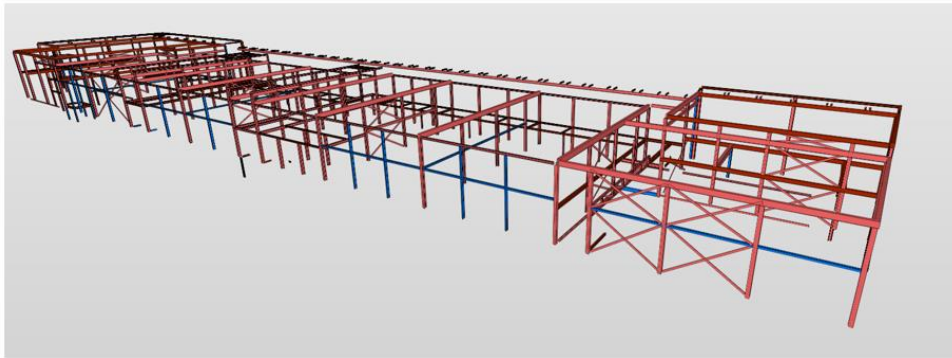
Number of elements: 45

Total length elements: 350 m.

average length elements: 8.0

Average weight elements: 52.7 kg/m average W elements: $738 * 10^6 \text{ mm}^4$

Database 5: Pathe Maastricht



Type	Length	Type	Length	Type	Length	Type	Length
HEA160	2.73	HEA260	11.76	IPE240	10.21	HEA260	7.39
HEA160	3.22	HEA260	13.06	IPE240	10.21	HEA260	7.39
HEA160	3.22	HEA260	13.06	IPE240	10.21	HEA260	7.39
HEA160	3.35	HEA280	3.82	IPE300	2.21	HEA260	7.39
HEA160	4.21	HEA320	3.81	IPE300	3.01	HEB140	3.67
HEA160	4.57	HEA550	7.58	IPE300	3.01	HEB140	3.67
HEA160	4.57	HEB120	3.59	IPE300	3.01	HEB140	3.67
HEA160	6.9	HEB220	2.85	IPE300	3.01	HEB140	3.67
HEA160	10.2	HEB260	5.33	HEA140	4.78	HEB280	7.76
HEA160	10.22	IPE180	10.26	HEA260	3.5	HEB280	7.76
HEA180	13.41	IPE180	10.27	HEA260	3.5	IPE240	6.64
HEA200	3.01	IPE180	10.27	HEA260	3.5	IPE240	6.64
HEA200	3.07	IPE180	10.28	HEA260	6.05	IPE240	6.64
HEA200	3.74	IPE180	10.49	HEA260	6.27	IPE240	6.64
HEA200	12.41	IPE180	13.29	HEA260	6.27	IPE240	6.64
HEA220	5.74	IPE180	13.32	HEA260	6.64		
HEA260	5.74	IPE240	10.21	HEA260	7.39		

Properties

Fy: 235 MPa

Tonnage: 20.5 tons

Number of elements: 66

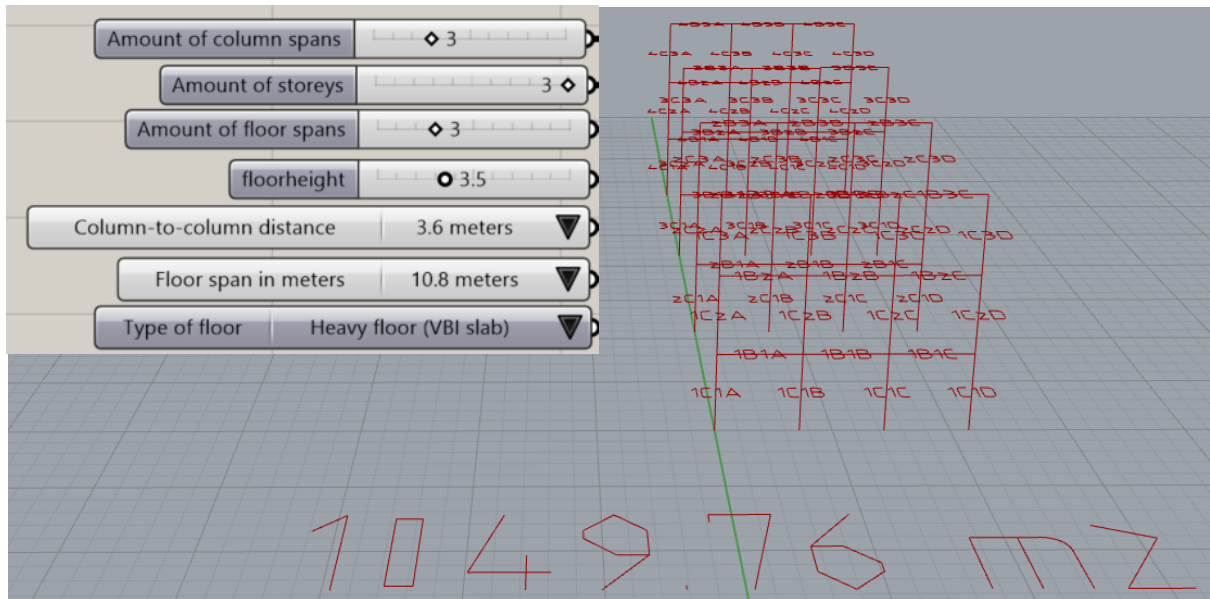
Total length elements: 439

average length elements: 6.7 m.

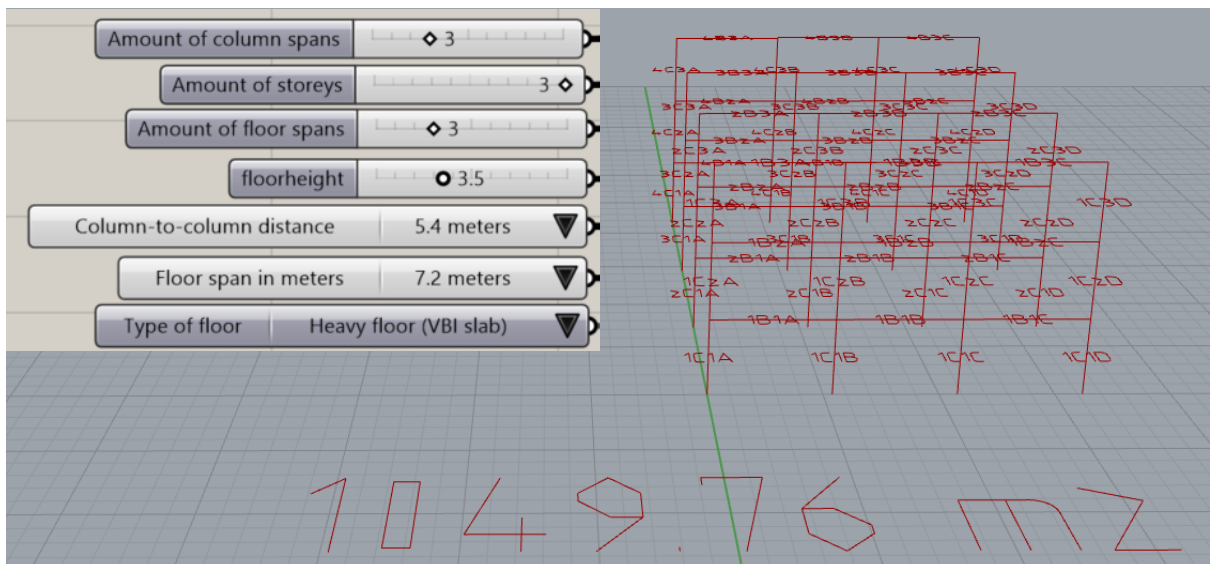
Average weight elements: 50.0 kg/m

average W elements: $625 * 10^6 \text{ mm}^4$

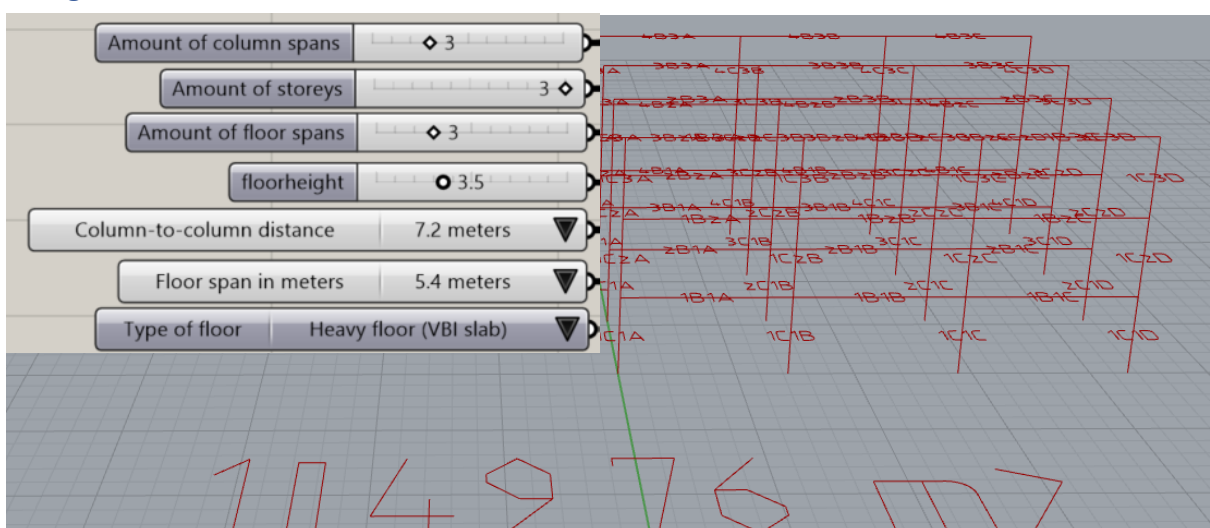
Design 1



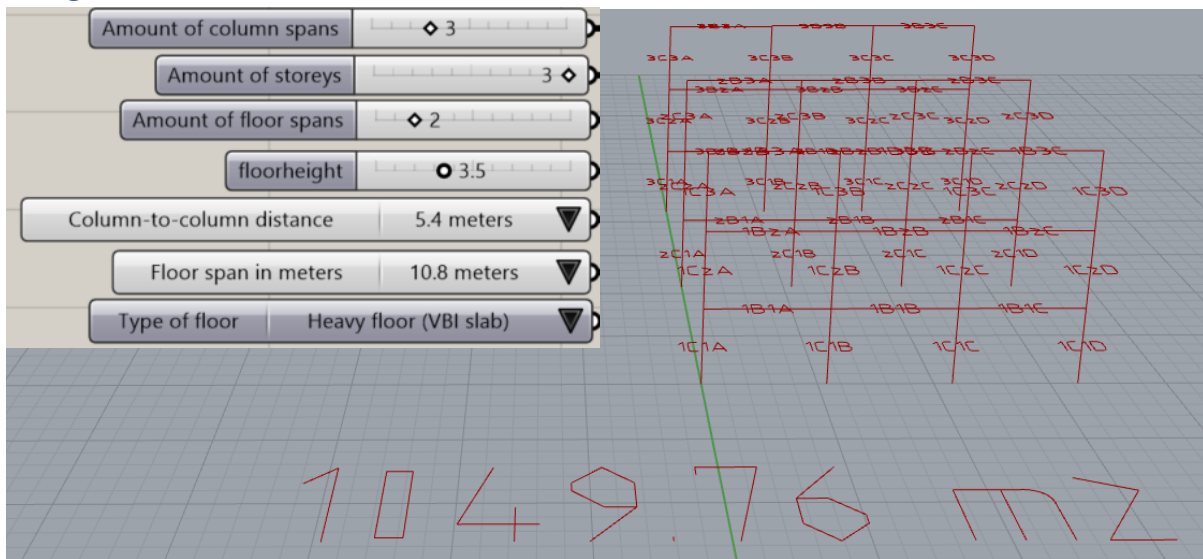
Design 2



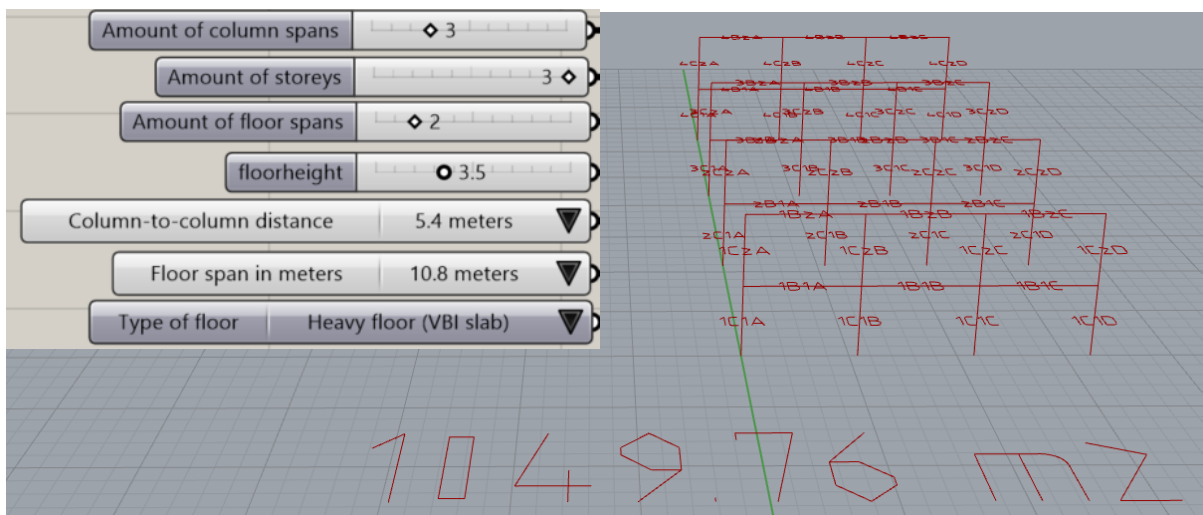
Design 3



Design 4



Design 5



2. Analysis flooring system

To analyse the effect of the choice of flooring system on costs and environmental impact, code has been created to evaluate the same database and office design combinations as the first analysis in this appendix. Each database and design combination is evaluated with the concrete hollow-core slab and the more lightweight wooden hollow core slab. The difference in costs and environmental impact between the two model runs is calculated and visualized in two boxplots. This code is shown below.

```
## List of all the database filenames
excels = ["D1", "D2", "D3", "D4", "D5"]

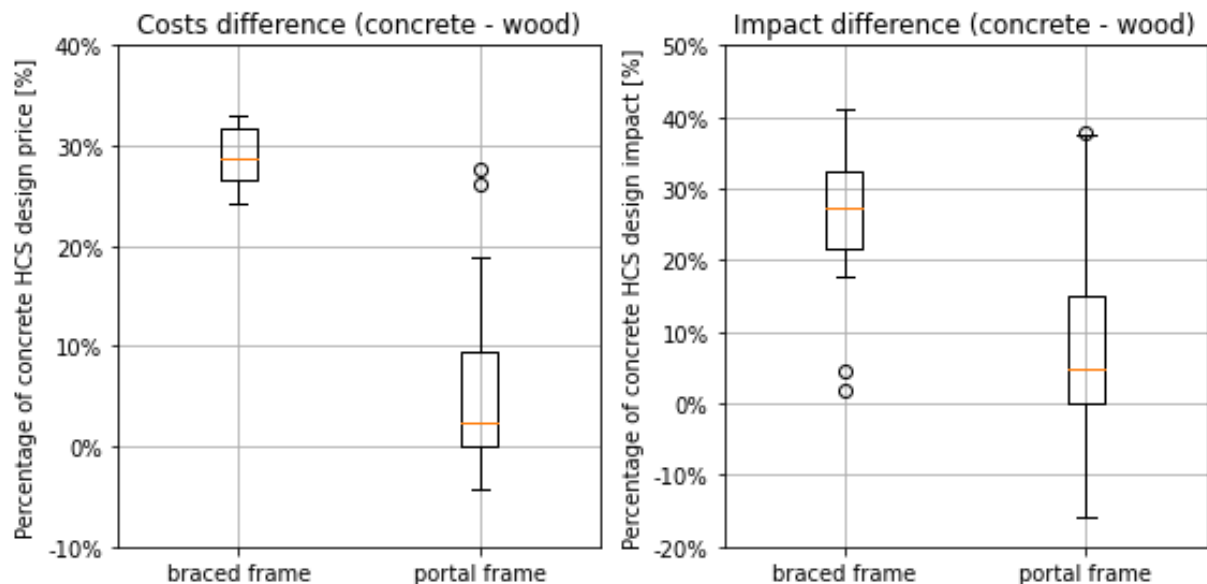
## List of design names
names = ["design1", "design2", "design3", "design4", "design5"]

## List of all the design filenames
designfiles = ["GHuitvoer1", "GHuitvoer2", "GHuitvoer3", "GHuitvoer4", "GHuitvoer5"]

res = [] ## Array to save the results of the analysis
ns = [1,3] ## 1 == wooden floor, 3 == concrete floor

for i in range(len(excels)): ## Loop through all databases
    for j in range(len(designfiles)): ## Loop through all design files
        for n in ns: ## Run wooden en concrete floor
            ## Run code
            res.append(np.array(TheCodeV2.TheCode(1.5, 3, names[i], excels[i],
                                                    50, 50, 1.8, 0.50,150, 1.20, 20,
                                                    0.1625, 235, designfiles[j], n)))
```

Graphs after processing:



3. Analysis model constraints

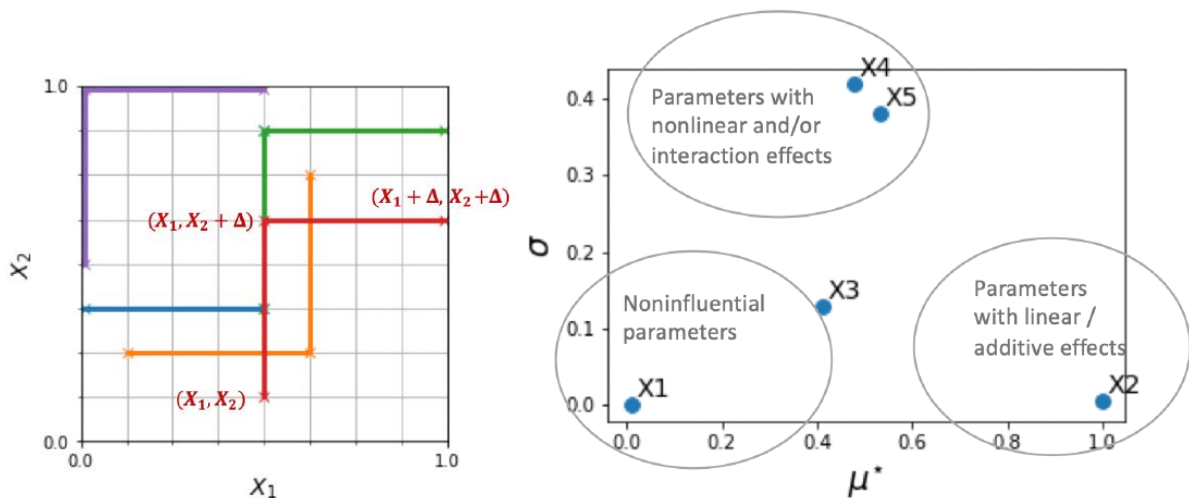
In this analysis the sensitivity of the model constraints is investigated. Elementary effect analysis is used to determine the influence of changing the weight multiplication factor (Wmult), the useful cut-off waste length and the yield strength of the donor steel.

Elementary Effect Analysis

Elementary effect analysis is performed by performing model evaluation while changing the model parameters and reporting the influence of these changes. The procedures consist of the following steps¹.

1. Define the realistic ranges of uncertainty in the model parameters in question.
2. Normalize these parameters to a scale of 0% to 100% (of change within the range).
3. For each parameter, select a value at random.
4. Evaluate the model and save the outcome.
5. Change one of the parameters randomly.
6. Evaluate the model and save the outcome.
7. Evaluate the derivative by looking at the difference between the outcome in step 4 and 6.
8. Go back to step 5 and repeat until all parameters have been changed once.

This procedure can be repeated n times. The mean of the derivatives across the n experiments is called the elementary effect. This mean elementary effect is denoted as μ^* . The result of the analysis is a graph with the mean elementary effect on the x-axis and standard deviation of this elementary effect on the y-axis (σ). An example for an arbitrary case is shown in the figures¹ below.



The graph on the left shows the solution space that is explored with procedure. Each time the experiment is conducted, a new starting point is used. The elementary effect method is known to be a quick analysis tool to determine the influence and linearity of parameters in a model in respect to the outcome. On the right, the resulting graph is shown. The higher the parameter scores on the x-axis, the more influence it has on the outcome of the model. The higher the parameter scores on the y-axis, the more non-linear the derivative is across the solution space. This indicates non-linearity and/or dependency.

- $\sigma / \mu^* \leq 0.1$: linear behaviour.

¹ Information and figures Morris Method:

https://gsa-module.readthedocs.io/en/stable/implementation/morris_screening_method.html

- $\sigma / \mu^* \leq 0.5$: monotonic
- $\sigma / \mu^* \geq 0.5$: almost monotonic
- $\sigma / \mu^* \geq 1.0$: non-linear behaviour and or higher dependency

It should be noted that the results are absolute, and the analysis does not provide details on non-linear behaviour or dependencies. The results can be used to identify influential parameters of interest.

Elementary effect analysis model constraints

To perform the EE-analysis, the following ranges have been identified for the model constraints.

Parameter	Range
Weight multiplication factor [-]	[1.0, 2.0]
Useful length cut-off waste [m]	[1.0, 4.0]
Yield Strength [MPa]	[200, 460]

Table 10.2: Ranges for the parameters of interest that influence the assignment algorithm.

To standardize these parameters from their ranges to a 0-100% range, the following equation is used.

$$x' = \frac{x - c}{d - c}(b - a) + a$$

Where the data region (range of the parameter in the table) is denoted as [c, d] and the other domain (0-100% range) is $x' = [a, b]$. The following python code was used. Both the effect on costs and environmental impact is analysed. Database D1 and D4 in combination with design 1 are used for this analysis.

```
r=15  ## The number of experiments performed

## Arrays to save the elementary effects
res1 = []
res2 = []
res3 = []
res4 = []

for i in range(r):
    pbase = []  ## Array to save starting values of the parameters in the experiment
    pits = []   ## Array to save the final (changed) values after the experiment

    ## Randomly choosing the base and changed value for each parameter
    for n in params2:
        bp = np.random.choice([0, 20, 40, 60, 80, 100],2, replace = False)
        pbase.append(bp[0])
        pits.append(bp[1])

    ## Determining the change in the parameters (base compared to final)
    dif = np.array(pbase) - np.array(pits)

    ## Evaluation using the base parameter values
    base = TheCodeV2.TheCode(Convert(Wmult, pbase[0]), Convert(Uf, pbase[1]),
                              "ontwerpq", "Database", 50, 50, 1.8, 0.50, 150,
                              1.20, 20, 0.20, Convert(fy, pbase[2]))

    ## Collecting the required model output
    Cn1, Cn2, Cr1, Cr2 = base[8], base[9], base[10], base[11]
    Ir1, Ir2 = base[14], base[15]
    id1 = Cr1
    id2 = Cr2
    id3 = Ir1
    id4 = Ir2
```

```

args = pbase
ids = [0, 1, 2]
np.random.shuffle(ids)      ## Randomly pick order of changing the parameters

## Array to save elementary effect per parameter for the experiment
itres = np.zeros(len(ids))
itres2 = np.zeros(len(ids))
itres3 = np.zeros(len(ids))
itres4 = np.zeros(len(ids))

for j in range(len(pbase)):
    idswap = ids[j]          ## Get id of changed parameter
    args[idswap] = pits[idswap] ## Change the parameter

    ## Evaluate the model using with the changed parameter
    perm = TheCodeV2.TheCode(Convert(Wmult, pbase[0]), Convert(Uf, pbase[1]),
                              "ontwerpl", "Database", 50, 50, 1.8, 0.50, 150,
                              1.20, 20, 0.20, Convert(fy, pbase[2]))

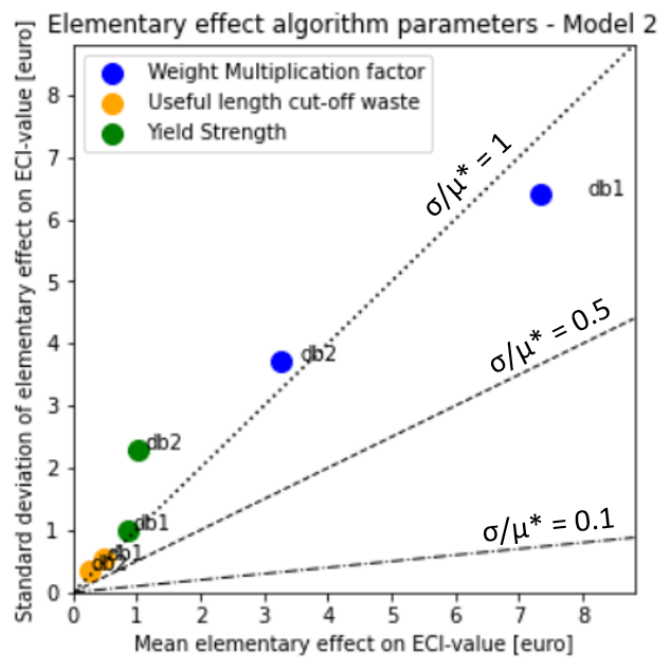
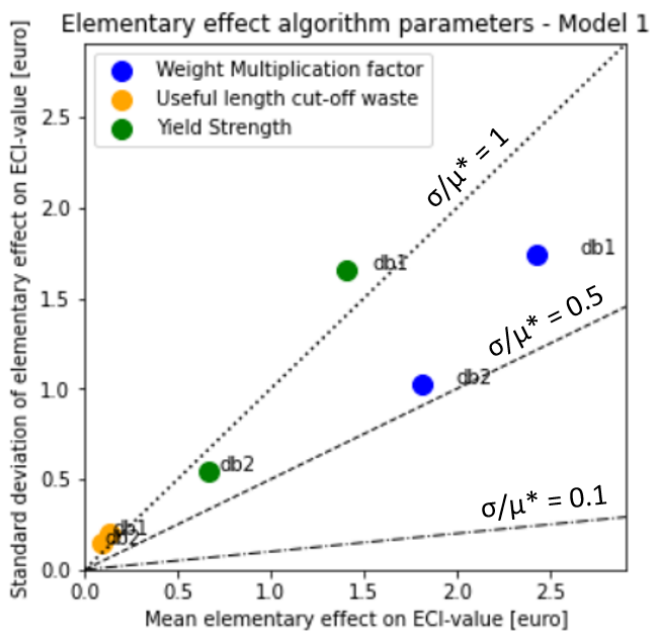
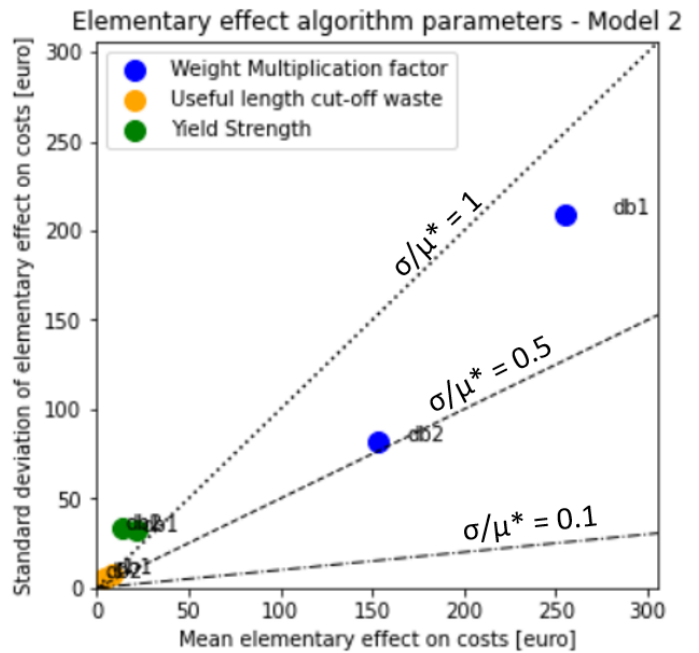
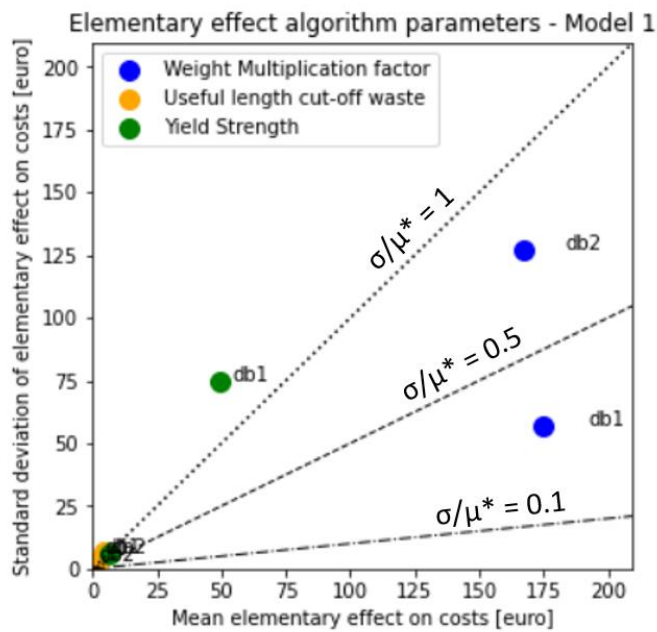
    ## Collecting the required model output
    Cn1n, Cn2n, Cr1n, Cr2n = perm[8], perm[9], perm[10], perm[11]
    Ir1n, Ir2n = perm[14], perm[15]
    id1n = Cr1n
    id2n = Cr2n
    id3n = Ir1n
    id4n = Ir2n

    ## Calculate the derivates
    itres[idswap] = (id1 - id1n) / dif[idswap]
    itres2[idswap] = (id2 - id2n) / dif[idswap]
    itres3[idswap] = (id3 - id3n) / dif[idswap]
    itres4[idswap] = (id4 - id4n) / dif[idswap]
    id1 = id1n
    id2 = id2n
    id3 = id3n
    id4 = id4n

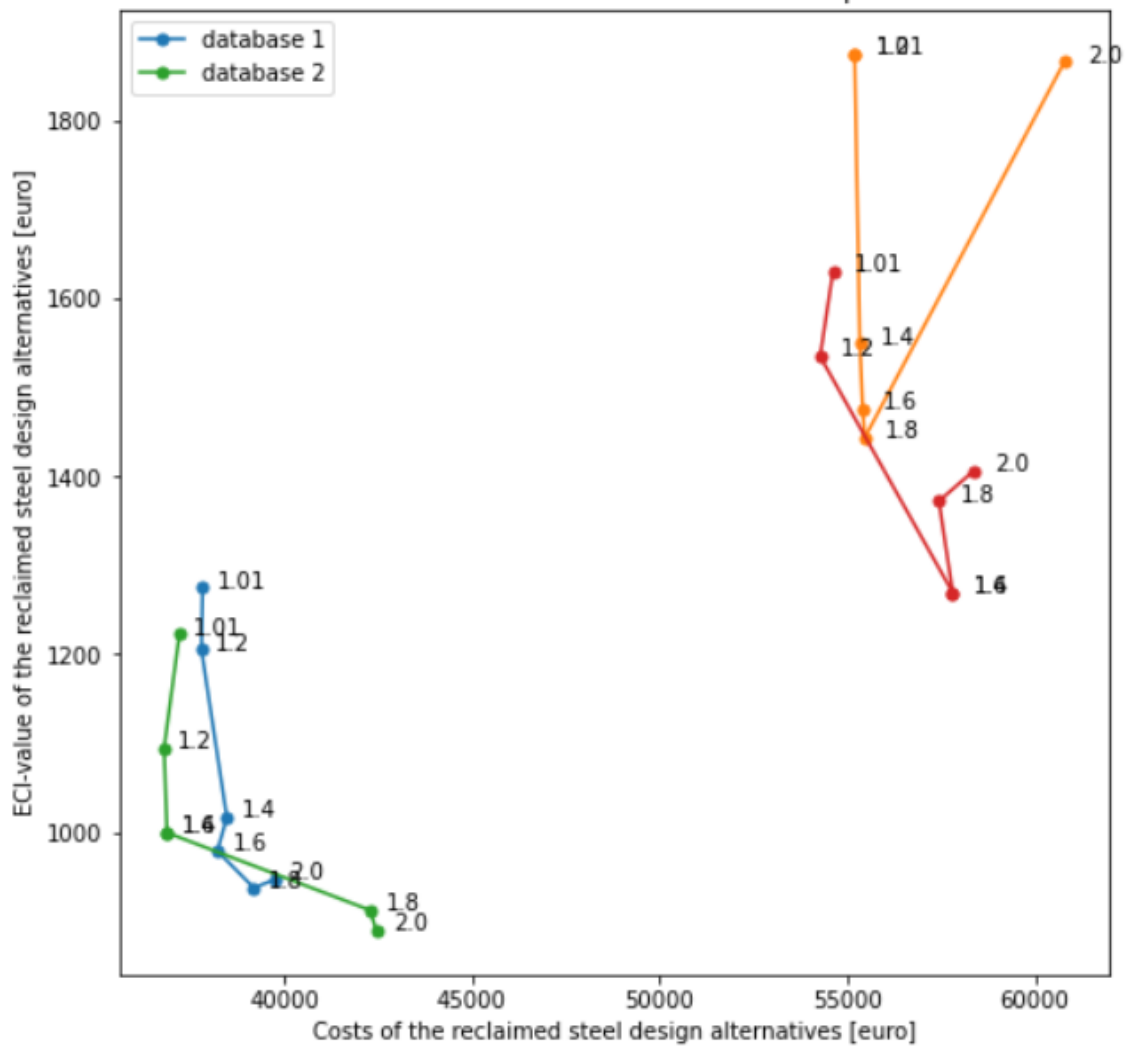
## Save the elementary effects per experiment
res1.append(itres)
res2.append(itres2)
res3.append(itres3)
res4.append(itres4)

```

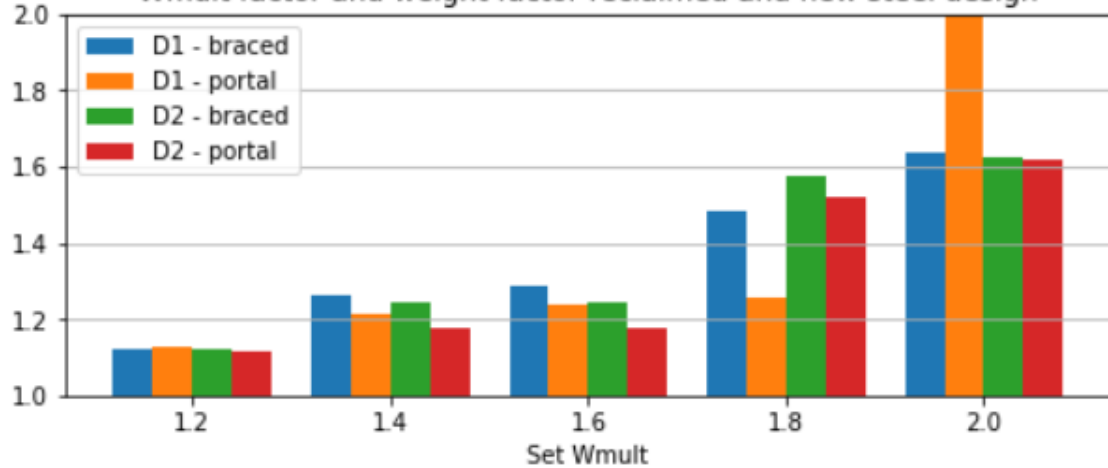
This results in the following graphs.



Influence of Wmult on the costs and impact.



Wmult factor and weight factor reclaimed and new steel design



Fy analysis

To further investigate the influence of the yield strength of the donor steel, all database and design combinations from the first analysis in this appendix are evaluated for 3 different yield strengths. The code and resulting graphs are shown below.

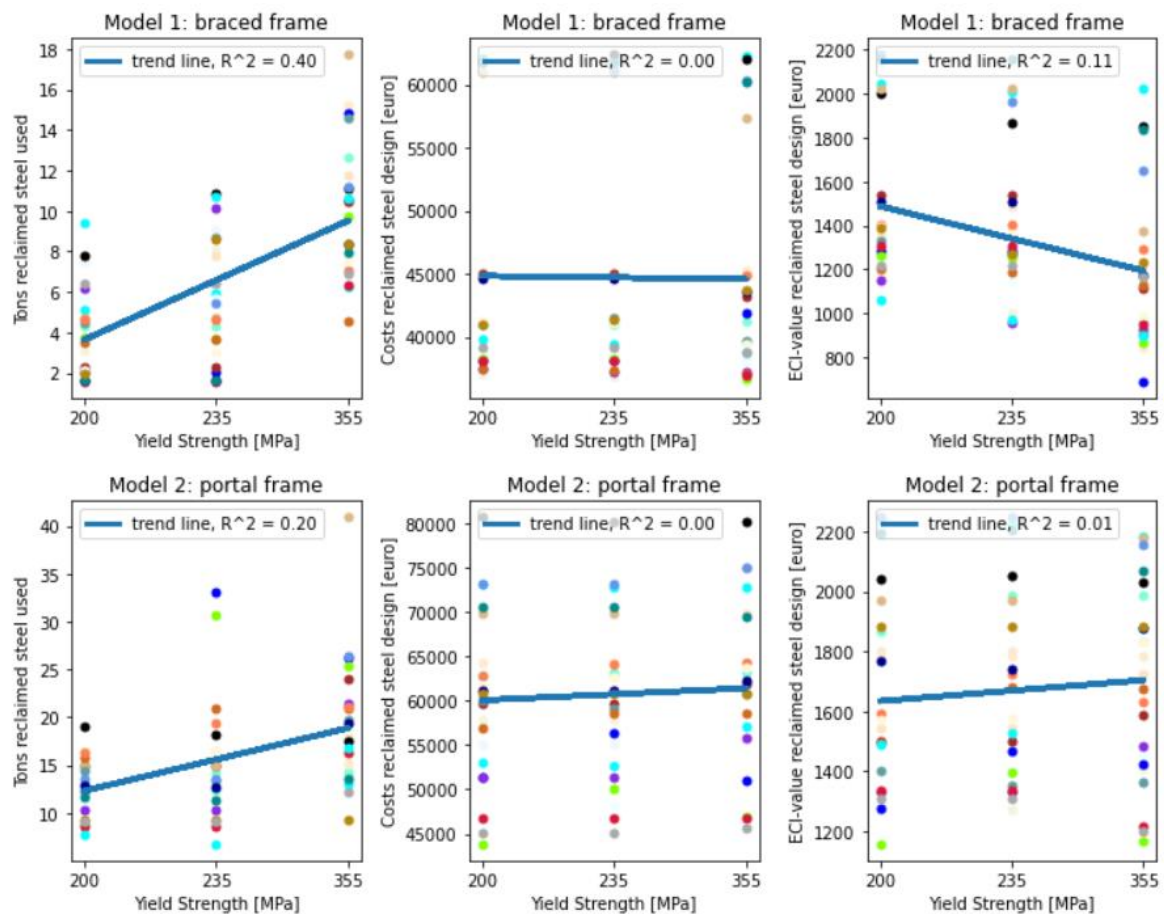
```
## List of all the database filenames
excels = ["D1", "D2", "D3", "D4", "D5"]

## List of design names for generated designs
names = ["design1", "design2", "design3", "design4", "design5"]

## List of all the design filenames
designfiles = ["GHuitvoer1", "GHuitvoer2", "GHuitvoer3", "GHuitvoer4", "GHuitvoer5"]

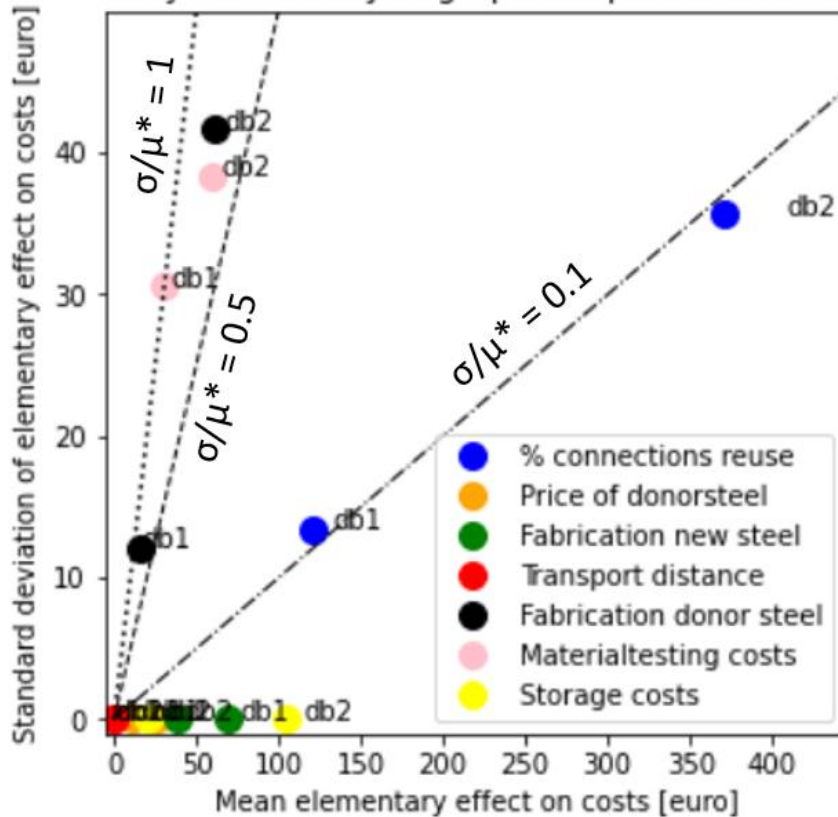
## List of yield strengths to evaluate
ys = [200, 235, 355]
res5 = [] ## Array to save results

for i in range(len(excels)):
    for j in range(len(designfiles)):
        for n in range(len(ys)):
            ## Run code for each database - design - yieldstrength combination
            res5.append(np.array(TheCodeV2.TheCode(1.5, 3, names[i], excels[i],
                                                    50, 50, 1.8, 0.50, 150, 1.20, 20,
                                                    0.1625, ys[n], designfiles[j])))
```

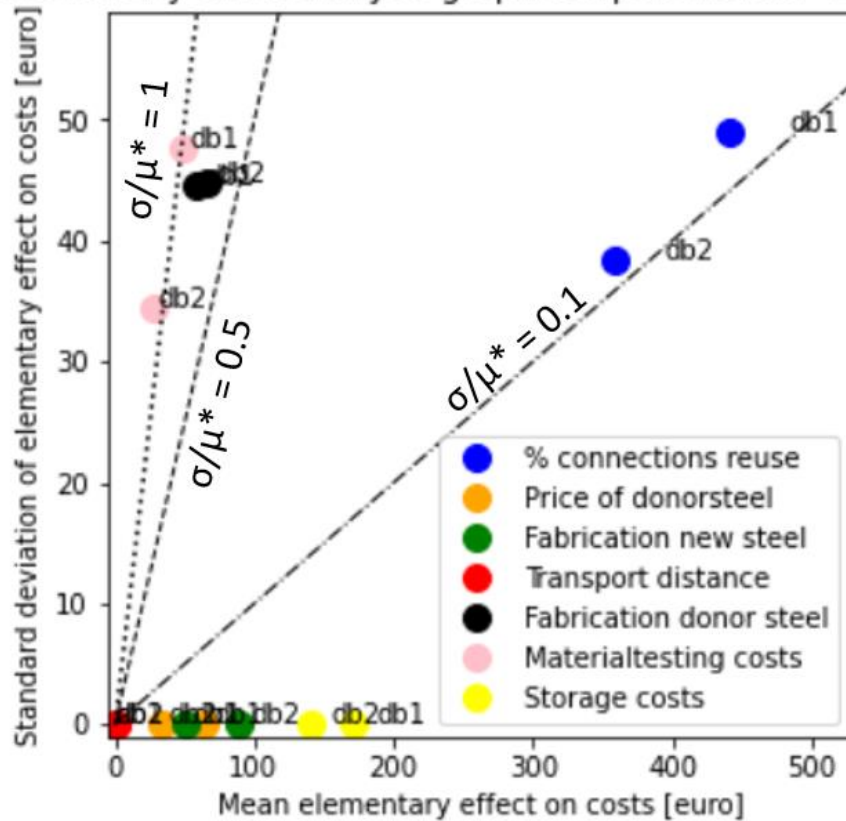


The results are visualized with python.

Elementary effect analysis graph costparameters - Model 1



Elementary effect analysis graph costparameters - Model 2



These graphs have also been changed to boxplots to improve readability.

