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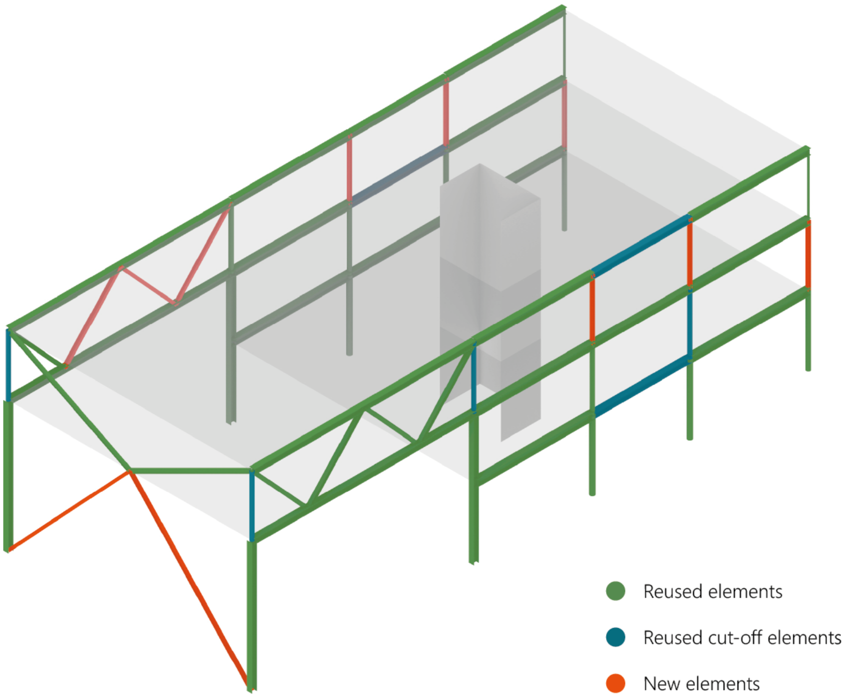

Integrating Reused Steel Elements in Structural Design

Structural Engineering and Building Technology

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Department of Architecture and Civil Engineering
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Cover picture: The Design Proposal and it's distribution of reused and new elements.

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Abstract

The building industry is one of the world's largest CO_2 emitters, the need to transition into a circular economy is becoming increasingly pressing. Steel is a long-lasting and dimensionally stable material and therefore suitable for reuse. However, reuse of steel is not yet implemented on a large scale in the building industry and inventories of available elements are still limited. This thesis showcase how structural engineers can work with reused steel, by the mapping of workflows and suggesting of an semi-automated design process.

The thesis is divided into four parts. In Part 1, a mapping of possible workflows is done through literature studies and informal interviews. In Part II, a digital workflow for integrating an inventory of reused elements into a structure is developed. This includes a parametric 3D model in Rhino/Grasshopper, structural analysis using FEM-Design, and a self-scripted tool in C# that performs Eurocode verification and matches reused elements to a structure using an A* optimization algorithm. The optimization objective is to minimise the embedded CO_2 equivalents (CO_2e) in the structure. In Part III, an iterative design process is carried out to test the digital workflow. Finally, Part IV presents reflections and discussions concerning the project.

For the design process, a fictitious office building is designed and matched with two different inventories of reused elements using the developed workflow. One inventory is based on the available elements from the steel supplier Stena Stål, the other is based on a building to be dismantled. For the design process, an iterative approach is implemented. Initially, several rough sketches are created followed by continuous evaluation, selection and developments leading to an increasingly refined design. The developments include defining and applying design principles to reduce the vulnerability to changes of the inventory. They also include smaller design changes, guided by the tool, to further decrease the environmental impact.

The result is a design proposal that exemplifies the potential of reused steel elements. The conclusion from the study is that structural engineers benefit from using automated workflows when designing with reused steel because the process is repetitive. Also, allowing reuse to influence design decisions can significantly increase the carbon savings of a project, as small design modifications can increase the reuse rate.

Keywords: steel reuse, research by design, CO_2 minimisation, sustainability, automated workflows.

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1
Introduction

With the ongoing climate crisis and rising costs of construction materials, the need for a transition into a circular economy has become more and more prominent. The building sector is one of the world's largest CO_2 emitters and stands for 37% of global gas emissions (United Nations Environment Programme and Yale Center for Ecosystems Architecture, 2023). The extraction of large amounts of raw materials needed to produce steel and concrete has a significant carbon footprint. While many companies within the building sector are starting to promote more sustainable solutions, the carbon emissions continue to rise and the $_2$ emissions from the building and construction sector reached an all-time high in 2022 (United Nations Environment Programme, 2022). To conquer the challenges, the UN highlights that more circular processes must be implemented to avoid waste, and building materials must be renewable and reusable (United Nations Environment Programme and Yale Center for Ecosystems Architecture, 2023).

What contributes the most to the embodied environmental impact of buildings and infrastructure is the load-bearing system (Brütting et al., 2019a). Therefore, reusing load-bearing elements, such as steel beams and columns, has the potential to improve sustainability in the building sector. Steel has a high potential for reuse, as it is long-lasting and dimensionally stable. Reusing these components yields significant savings in the environmental impact compared to using newly produced or recycled elements (The Steel Construction Institute, 2019), and studies have shown that reused steel has a 96% environmental impact saving compared to new steel with a 60% recycled content (Tingley et al., 2017).

The practical execution of dismounting, evaluating, designing and building with reused elements currently has many challenges that prevent large-scale implementation of steel reuse (Tingley et al., 2017). Nevertheless, several pilot projects worldwide have utilised a high percentage of reused elements. Additionally, new digital tools have emerged to help designers integrate reused elements within their designs.

This thesis explores the opportunities in which structural engineers can work with reused steel elements in a preliminary design process. This is done through a Research by Design method, where a structural system is designed using two different inventories of reused elements. Additionally, the thesis aims to develop design strategies that structural engineers can use to benefit the reuse of structural elements, taking both existing inventories and the possibility of a changing inventory into consideration. This is done by the development of a matching tool, that matches a preliminary design with reused elements and uses an optimisation algorithm to minimise the environmental impact.

1.1 Background

More than half of the steel that is produced today is used within the building sector. Steel has large potential when it comes to reuse, and the implementation of reuse would generate large savings in both CO_2 emissions and costs (Strand Nyhlin and Åfreds, 2022). Over the recent years, reuse has become a topic talked about on a large scale, and this does not exclude structural engineers. Plenty of research, pilot studies, and reports, e.g., Understanding and Overcoming the Barriers to Structural Steel Reuse (Tingley et al., 2017) and The Reuse of Load-bearing Components (Brütting et al., 2019a), have highlighted the benefits of reusing steel, as well as mapped the challenges.

The obstacles to the reuse of load-bearing steel elements often include economic concerns, the need for coordination and tight collaboration between multiple sectors, concerns about the testing of the elements, as well as a general scepticism and unwillingness to change. While the benefits and challenges of reuse are mapped, there is a general lack of research that summarises a workflow for how structural engineers can practically implement the reuse of load-bearing components in preliminary design. This includes knowledge about how to find and source an inventory of reused elements, general design principles to benefit the use of reused elements, and the implementation of computational tools to match reused elements to a design. To make reuse more accessible, there is a need for a large shift in mindset and a new design workflow that acts to benefit the potential of reused elements. This includes new guidelines for how to build with and consider reused elements in structural design.

1.2 Aim

This thesis explores and maps how structural engineers can work with the reuse of load-bearing steel elements in a preliminary design process. This is done by integrating stocks of reused structural steel elements into an iterative design process, and by establishing design principles to help benefit the reuse of steel. The aim of the thesis can thereby be summarised in the following points:

- Understand the role of the structural engineer when designing using reused structural steel elements.
- Understand the practical implications of designing a structural system using a limited and changing inventory of elements, and how one can design with reuse taken into consideration.
- Map a workflow for how to integrate reused elements into a design in the early stages of a project.

1.3 Research questions

The objective is to answer the following questions:

1. What key tasks included in the reuse workflow directly affect the work of the structural engineer?
2. What could an inventory of reused steel elements look like and which uncertainties could be associated with such inventories?
3. What characterises an optimized structure in the context of reuse, and how can this be translated into an optimization objective?
4. How can an inventory of reused structural steel elements be used in a new structure in an optimized way and what tools can aid this process?
5. What design verifications according to Eurocode are directly affected by the fact that the elements are reused?
6. How can reuse influence the design of the structural system, and what qualities and compromises can this lead to?

1.4 Scope and Limitations

This thesis focuses on component reuse in the design of structural systems in buildings, where individual elements are placed in a new location with a new or the same function. Reuse of entire systems, where a whole building is dismounted and built up again in a new location, but with the same design, is out of the scope of the thesis. The thesis focuses on the reuse of steel and not the recycling of steel, meaning that the inventory elements will be used in their original state. They are not melted down and formed into new cross sections. However, new holes can be made and the elements can be cut or repainted to accommodate for their new usage.

The project will focus on early stage design, workflow development, structural verification, and the background of reusing steel elements. The design project will be carried out without a site-specific context. Coordination, logistics, LCA-calculations, and the economy of the final design are out of the scope of the thesis.

The thesis is written in a Swedish context using Eurocode and EKS 12 for verification and calculations. However, inspiration is taken from reference projects in Canada, England, the Netherlands, and Norway. The thesis is limited to performing member verification, excluding global analysis of the structure and connection design. Also, the thesis focuses on the reuse of steel elements only, and will not consider other elements in detail, such as slab and foundation design, when analysing the structure.

1.5 Outline of the report

The thesis is divided into four parts. Part I, presents the contextualisation of the thesis, while the main results are presented in part II, *The design workflow* and in part III, *The design process*. Part IV contains discussions and conclusions.

Part I – Contextualisation:
Chapters 3, 4 and 5 summarise literature, interviews, and a site visit that introduces theory, reference projects, and ways of working with steel reuse.

Part II – The design workflow:
Chapter 7 describes the software that is used during the thesis: Rhinoceros 3d, Grasshopper and FEM-Design.

Chapter 8 describes the inventories of reused elements that are integrated into the iterative design process.

Chapter 9 describes the assumed preconditions of the design task as well as the initial design sketch, which is referred to as the base design. It also describes the loads, load combinations, and FEM model which is used for analysing the structure.

Chapter 10 describes the matching tool by presenting the theory of the optimization algorithm that is used, and by explaining how it has been adapted to the reuse optimization problem.

Part III – The design process:
Chapter 11 presents several rough design sketches made by adjusting the base design model. It describes the matching results for the sketches and additionally introduces some design principles that benefit reuse.

Chapter 12 introduces some ranked criteria for evaluating the sketches which are used for selecting the two most promising ones. The chapter also describes some design changes and tool updates that are made as well as an updated matching result.

Chapter 13 describes the final design proposal and a physical model that was built to showcase the result.

Part IV – Reflections:
Finally, the discussion and the conclusions of the work are presented in Chapters 14 and Chapter 15, respectively.

2
Methodology

The methods used in this thesis are divided into several parts. For the contextualisation, literature studies, a site visit, and informal interviews have been made to get both a theoretical understanding of steel reuse, and of how it can be implemented in practice. The knowledge gained from the contextualisation was summarised and used to develop a digital design workflow. The workflow was then tested by implementing it on an fictive design.

2.1 Literature studies

The literature was mainly found by recommendations from the interviewees and through browsing the Chalmers Digital Library (Chalmers Digital Library, nd) using keywords such as 'steel reuse' and 'stock constrained optimization'. It consists of a variety of reports, books, articles, and master thesis essays. A majority of the literature is from the years 2019–2023 as the topic of steel reuse is still relatively new. Literature was searched for during September-October 2023.

2.2 Interviews

All interviews were made in a conversation format, where questions specific to the person who was interviewed were prepared in advance. Few people have worked with steel reuse in practice. Therefore, the experiences of the interviewees were vital to gain insight and develop the design workflow. The questions asked were often targeted towards the projects that each person had worked with. However, some general questions were also discussed, like the future of steel reuse, and what challenges they have encountered in their work.

2.3 Site visit

During October 2023, a site visit to Oslo, Norway, was made to look at Kristian Augusts gate 13, a project that has reused large amounts of steel elements. The purpose of the site visit was to get an idea of how reused elements can be implemented into design. The building was researched in beforehand, and during the visit many photographs were taken.

2.4 Design

The results of the thesis are mainly presented in Part II *The design workflow* and Part III *The design process*. A combination of existing software and a self-scripted matching tool was developed to be used for integrating an inventory of reused elements into a base design. The main part of the matching tool is an optimization algorithm to minimise the amount of embedded CO_2e in the structure.

To test the workflow, a design process was performed where the matching tool was used to design a fictitious office building using two different inventories. The process was iterative, meaning that several rough design sketches were created initially, followed by continuous evaluations, selections, and developments leading to an increase in the design resolution and a final design proposal. It is a method rooted in architectural design and is more holistic than many traditional engineering methods, where the main focus is usually put on mathematical models (Sehlström et al., 2021). Most research concerning reuse has a narrow scopes and focuses on one aspect at a time, there is also a gap between how to summarise existing theory and how to apply it practically. Therefor, this method aims to cover a larger complexity and lead to more holistic reflections.

The design process was divided into three different phases following conceptual design methods developed for the *Matter Space Structure* architecture studio at Chalmers University of Technology: *The intuitive phase*, *The intentional phase*, and *The evaluation phase* (Sehlström et al., 2021). The result was a final design proposal which was presented by a physical scale model. The design workflow development and the design process are described in greater detail in Section 2.4.1 and Section 2.4.2, respectively. An overview of how the design workflow has been integrated with the iterative design process is presented in Figure 2.1.

2.4.1 The design workflow

The purpose of the design workflow was to develop a method for matching inventories of reused elements to design sketches. This is to find out how the reused elements can be used in an efficient way within the structures and to evaluate how many of their elements can be replaced by reused elements. To do this, a parameterised centre line model of a base design was created in Rhino/Grasshopper (Rhinoceros3D, 2023) and used to create a FEM model using the FEM-Design API (Strusoft, 2023). After performing a FEM analysis, the FEM-Design auto design function was used. This function finds the cross section with the highest acceptable utilisation rate, among some predefined alternative sections. This was done to get an idea of which new elements are required if no suitable reused elements are found.

The sectional forces of the elements, their lengths, and their environmental impact calculated based on the auto designed cross sections were extracted from Grasshopper and FEM-Design. Also, information about the cross sections, material grades and lengths of the reused elements in the inventory was compiled in Excel lists. This was then used as input for the matching tool which performs Eurocode verification and uses an A* search algorithm to minimise the total amount of embedded CO_2e of the structure.

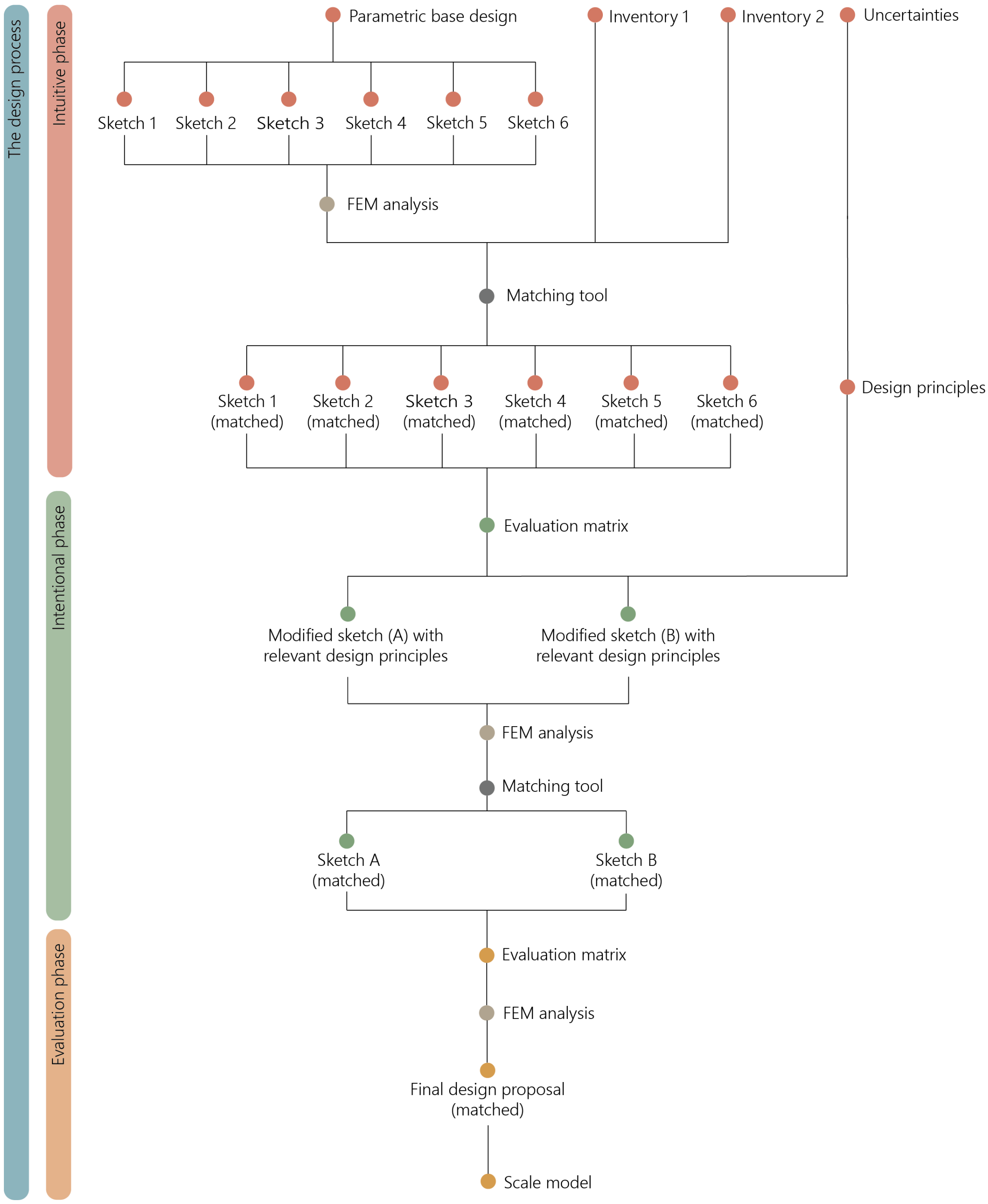

Figure 2.1: Design process overview.

2.4.2 The design process

During the design process, two different inventories were used. One was taken from Stena Stål's existing inventory of reused steel elements. The other was estimated based on a fictive donor building, a temporary mounting hall. Uncertainties regarding the inventories are also considered, since the availability of inventory elements might change from the preliminary design stage to the construction stage. The starting point for the design was a base structure of an office building with a large hall on the ground floor. The design includes both a truss system in the hall, as well as a beam-column system in the office areas.

Several design proposals were sketched, analysed, matched, and evaluated using an evaluation matrix. In the end, one final design proposal was chosen and visually represented in a physical model. The purpose of this was to compare different design alternatives using several criteria related to reuse. Another purpose was to investigate whether it is possible to achieve better and better matching results throughout the design process.

2.4.2.1 Intuitive phase

Initially, six different design sketches were created by modifying the base design. Parameters such as span lengths, building dimensions, truss geometry and column height were changed between the different sketches, which is described in greater detail in Section 11.1. As the name of the design phase suggests, the sketches were produced fast and intuitively. Each design sketch was analysed using FEM-Design and matched to the inventories using the matching tool. This is to get an idea of how many elements could be replaced by reused elements from the inventories. This data was extracted and calculations of the CO_2e were summarised in tables. Additionally, the uncertainties concerning the availability of elements were accounted for by formulating design principles for reducing a structure's vulnerability to changes in elements. These principles were based on literature studies, reference projects, and interviews.

2.4.2.2 Intentional phase

The design sketches produced from the two inventories during the intuitive phase were evaluated using an evaluation matrix. This is a way of compiling results from evaluations using several criteria which are ranked according to their importance. The two best sketches were chosen for further development, and analysed to find in which ways they could be improved further. The initial sketches were also allowed to be combined to create an even better design. Design changes were made to achieve as large savings of CO_2e as possible. The designs were also altered by the implementation of the design principles defined during the intuitive phase. The altered designs were once again analysed in FEM-Design and plugged into the matching tool.

2.4.2.3 Evaluation phase

The evaluation phase started by comparing the two designs developed in the intentional phase using an updated evaluation matrix. The design with the best result was chosen as the final design proposal. This design was analysed in greater detail to document all the used elements, cut-off parts that can be used again, and scrap pieces that the matching generated. A final FEM analysis was performed for the updated cross sections, and they were then verified using FEM-Design. The decisions, challenges and solutions found during the design were used as a base for the discussion and conclusion of the thesis.

Part I

Contextualisation

3
Literature studies

The contextualisation of this thesis is largely based on literature studies made to better understand the challenges and possibilities when working with reused steel elements. Reuse is becoming more and more talked about throughout the years and although there are still few practical examples, there is a wide amount of theory concerning steel reuse. The theory presented in this chapter concerns how the material properties of steel are affected by reuse, barriers that exist for reuse to be implemented on a larger scale, and alternative workflows for integrating reused steel elements in the design of structural systems.

3.1 Properties of reused steel

When working with reused steel it is important to know which steel components are appropriate to reuse and how the material properties are affected by the fact that a component is reused. This is treated in the following sections.

3.1.1 Steel components most appropriate for reuse

Several aspects determine whether a steel component is appropriate for reuse. If the component has been exposed to fatigue, seismic loading or fire it should not be reused (Brown et al., 2019). Even though elements are not exposed to the above mentioned loads, their quality still needs to be tested to ensure that they are safe to reuse. The existing guide for testing and quality assurance, which is explained in greater detail in Section 3.1.3, is limited to hot-rolled and cold-formed sections. Built-up sections and thin plate profiles are excluded from the guide, meaning that the process of reusing those would be more complex and with more uncertainties. Screws and bolts are not appropriate for reuse (Husson and Lagerqvist, 2021).

3.1.2 Regulations and CE marking

In the Swedish National Annex of Eurocode, *Boverkets Konstruktionsregler EKS 12*, it is stated that 'Materials of load-bearing structures, including soil and rock, must have known, appropriate and documented properties of aspects relevant for how they are used' (Boverket, 2021). CE marking, which stands for Conformité Européenne, is a system to ensure that a product fulfils the relevant requirements for health, environment, and safety specified by the EU (Svenska Institutet för Standarder, nd). A common way to prove that a building product fulfils the requirements in EKS

12 is to ensure that the product is CE marked. To achieve a CE marking, there are certain activities that need to be performed to ensure that the performance, functionality and technical documentation of a building product is of good enough quality. One of these activities is a production inspection and since this can not be performed for reused elements, they can not be CE marked according to the harmonising standards for new elements (Hansson et al., 2021).

However, a CE marking is not the only way to ensure that the building product has ‘known, appropriate and documented properties’ and according to Boverket it is usually not necessary to have a reused element CE marked (Boverket, 2023a). Another way of evaluating the material properties that is stated in EKS 12 is to perform testing (Boverket, 2021) to evaluate properties such as structural strength, stiffness, changes in geometry, etc. (Boverket, 2023c).

3.1.3 Testing and quality assurance

It is necessary to test the elements considered for reuse, to get good estimations of their load-carrying capacity and suitability for reuse. The tests can be divided into two categories: *destructive testing* and *non-destructive testing*. Generally, the elements are sorted into testing groups, where the elements in each group are from the same place, have the same origin, are the same age and have been used the same way. If the origin of certain elements is unknown, each individual element is considered to be a test group. The main factors that determine how much testing these groups have to go through are the age of the elements and the amount of available documentation about them (Husson and Lagerqvist, 2021).

A common non-destructive test is hardness testing according to Vickers using a Ultrasonic Contact Impedance (UCI) meter. As there is a correlation between the hardness of the material and its ultimate strength, this test is performed to either confirm or estimate the material grade of the element. The hardness of an element should be based on the mean value of three different tests along the element (Husson and Lagerqvist, 2021). If one beam differs by more than 10% from the average value of the group, it has to be removed from the inventory (Brown et al., 2019).

There may also be a need for non-destructive chemical analysis of the elements (Husson and Lagerqvist, 2021). Usually, it is enough to cut off 10–20 cm of the element to do this test, and that often happens naturally during deconstruction (Hansson et al., 2021). The samples are proposed to be taken from the beams with the highest and lowest hardness from the hardness testing and should be made for at least 20% of the test group. The purpose of the analysis is to evaluate the presence of the chemical substances C, Cr, Cu, Mn, Ni, P, Si and S to determine the homogeneity of the material and to set a carbon equivalent value, which is important for assessing whether the material is suitable for welding or not (Husson and Lagerqvist, 2021).

The destructive tests should be made by a non-partial part and should consist of tensile tests, impact strength tests, as well and destructive testing of the chemical composition. Both the destructive and non-destructive tests should be thoroughly documented and compiled together with the documents that show the traceability of the element (if such documentation exists) when a beam is sold (Husson and Lagerqvist, 2021).

Mekaniska Verkstädernas Riksförbund (MVR) has published the Swedish guidelines for what tests and how much testing the elements should go through, which depends on the tractability and age. In 1971, a production standard for a material equivalent to S355 was released and before that other production standards for materials equivalent to other steel grades which are commonly used today already existed (SBI Stålbyggnadsinstitutet, 2022). Therefore, it can be assumed that steel products made after 1971 will have fulfilled the same production requirements as the material that is sold today. Thus, the testing process becomes different depending on whether the steel element was produced before or after 1971. The testing can be divided into four procedures which are presented below (Husson and Lagerqvist, 2021).

- **Procedure A:** The elements are produced after 1971 with a known origin, fully traceable elements and available material certificates.
  - No demand for destructive testing nor non-destructive chemical analysis. The testing can be limited to a non-destructive hardness test that verifies the material properties stated on the material certificate.
- **Procedure B:** The elements are produced after 1971 with a known origin but the elements are not fully traceable.
  - Non-destructive hardness tests, as well as a non-destructive chemical analysis should be performed. In addition to this, destructive tests on a randomly selected element within the control group should be done.
- **Procedure C:** The elements are produced before 1971 with a known origin.
  - Non-destructive hardness tests, as well as a non-destructive chemical analysis should be performed. In addition to this, destructive tests on at least three randomly selected beams within the control group should be done. The characteristic values for ultimate- and yield strength should be determined based on a statistical analysis of the destructive testing results.
- **Procedure D:** The elements are produced before 1971 with an unknown origin.
  - Non-destructive tests should be done to estimate the steel grade and a non-destructive chemical analysis should be performed. In addition to this, destructive tests on each element should be done. The characteristic values for ultimate- and yield strength should be determined based on the destructive testing.

3.1.4 Practical considerations

In general, it is recommended that all existing coatings on elements suitable for reuse should be removed. The exception is when a building is dismantled and rebuilt on a new site but with the same original form. Also, existing fire protections should not be relied upon since fire protections are unique to the original use and building type, and since fire protection is very sensitive to moisture (Brown et al., 2019). Fire protection paint can be hard to remove, and therefore these elements are often seen as unsuitable for reuse. Corrosion protection on beams produced before the 1960s should be handled with caution as it may contain lead (Hansson et al., 2021). Holes in the beams from old attachments and bolted connections do not always need to be cut off if the design and geometric requirements are fulfilled. However, it is important to note that new connections should be made with a safe distance of 100 mm from the existing holes. It is possible to reuse existing connections, although this needs to be done carefully, especially when it concerns welds (Brown et al., 2019).

3.1.5 Structural verification

The testing of the reused elements is made to verify that they can be equated to new elements. Therefore, the ways of calculating and verifying reused elements are very similar to the calculations done on a system of new steel elements. Nevertheless, some adjustments should be made while working with reused elements. Hollow sections can be cold-formed or hot-finished, and since this is not always documented for reused elements, hollow sections should conservatory be assumed to be cold-formed. Also, plastic global analysis is not recommended when working with reuse since it requires a high level of ductility which can't always be guaranteed for reused steel (Brown et al., 2019).

In buckling verification, it is important to take imperfections into account. The checks of dimensions and straightness tolerances ensure that the same buckling curve can be used regardless of whether an element is reused or not. However, for a reused element, there will inevitably be some uncertainties concerning additional imperfections, such as torsional imperfections, since the testing procedures are likely to be less reliable in this aspect than those undertaken for new steel. This can lead to a reduced resistance due to an increase in second-order effects and therefore, it is recommended to use a modified value of γ_{M1} for the buckling verification where $\gamma_{\mathrm{M1,mod}}$=1,15. This adjustment does not have to be done if the reused element can be considered equal to a new one, which may be the case if the element was produced for a project that was cancelled, and never used (Brown et al., 2019).

Existing bolt holes need to be considered as well, if the holes reduce the cross sectional area by more than 15%, the net cross sectional properties should be used in member verification (Brown et al., 2019).

Since greater flexibility may be required concerning the choice of cross sections when working with reused elements there is a risk of having to use sections much larger than necessary. The steel supplier Stena Stål and MVR have expressed that as a guideline it is sustainable to reuse an element which is up to 50% over-dimensioned. If the element is more than 70% over-dimensioned it is more sustainable to leave the element for another project or to recycle it, and instead use a new element for the specific design application (SBI Stålbyggnadsinstitutet, 2022).

3.2 Barriers for reusing steel

In general, a lot need to be done to facilitate the reuse of steel. A common barrier is that there is no general market for reused steel products, which gives the impression of reuse being equal to much work and high risk. Scrap steel has an economic value, and there is an established method of recycling steel in the industry (Gorgolewski et al., 2008) which further increases the resistance to reuse. The study *Options to make steel reuse more profitable* investigates case studies that aimed to reuse steel and evaluate why some of the projects were unsuccessful. One project did not happen since the price of the scrap steel was too high, and so the demolition contractor did not find reuse to be profitable. Another project developed a plan for reuse, however, the suggestion was rejected on the basis of costs (Dunant et al., 2018). Other barriers which are often mentioned are a lack of client demand, lack of supply chain coordination, limited traceability of elements, knowledge gaps, uncertainties regarding availability of elements and inertia of the building sector to change (Tingley et al., 2017).

White Architects suggest that more open documentation at the sourcing stages may help enable a larger selection of reused elements at the sourcing stages. Further, it is argued that reuse requires a closer collaboration between the client, entrepreneurs, consultants, and architects (Johansson, 2018). Other factors that may help reuse become mainstream includes good case study projects, education across the construction sector, government incentive, a network of suppliers, a showcase of how reuse can become cost-efficient, on-site testing, government leadership, deconstruction plans, and clear overall guidance on how different sectors can work with reuse (Tingley et al., 2017).

3.3 Design for deconstruction

Design for future reuse and demountability have become more popular over the years. Johansson (2018) lists several strategies that designers can use to benefit future reuse in new projects. These points include:

- The building design should protect the materials from rot, destruction and excessive wear.
- Attachments should be based on mechanics and gravity rather than chemical substances (such as glue).
- Logbooks that describe the elements should be established early and be updated throughout the building service life.
- Make a demolition and reuse plan as soon as possible, preferably when the building is being built.
- Work with standard sizing and modules to make it easier to move and replace elements if needed.

- Pick materials that allow for maintenance and are easy to replace and recycle.

3.4 The workflow of reusing steel

Figure 3.1 illustrates an overview of the process of reusing steel as described by the Steel Construction Institute (SCI) in the UK (Brown et al., 2019).

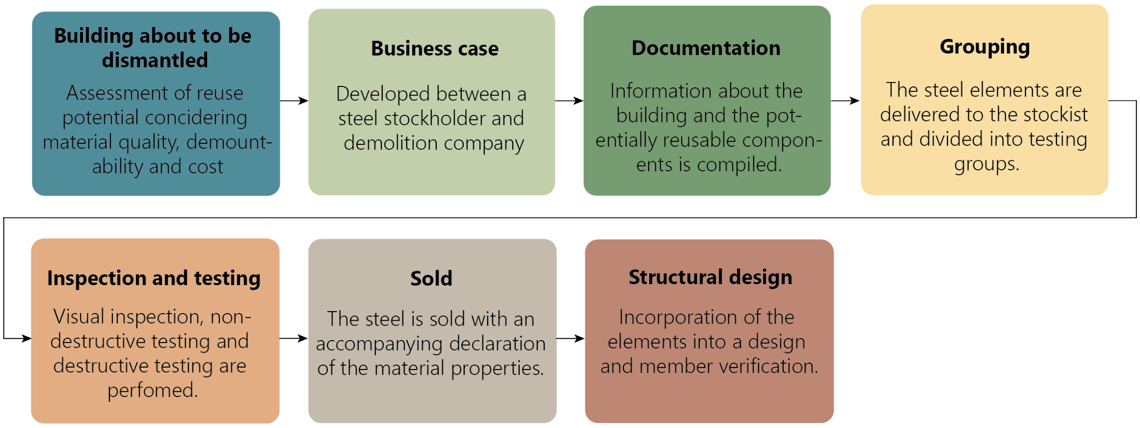

Figure 3.1: Process of reusing steel according to SCI.

The parts of the process which are most relevant for the testing is also described in the guide by MVR (Husson and Lagerqvist, 2021). This is shown in Figure 3.2 where the colours are consistent with the colouring in Figure 3.1.

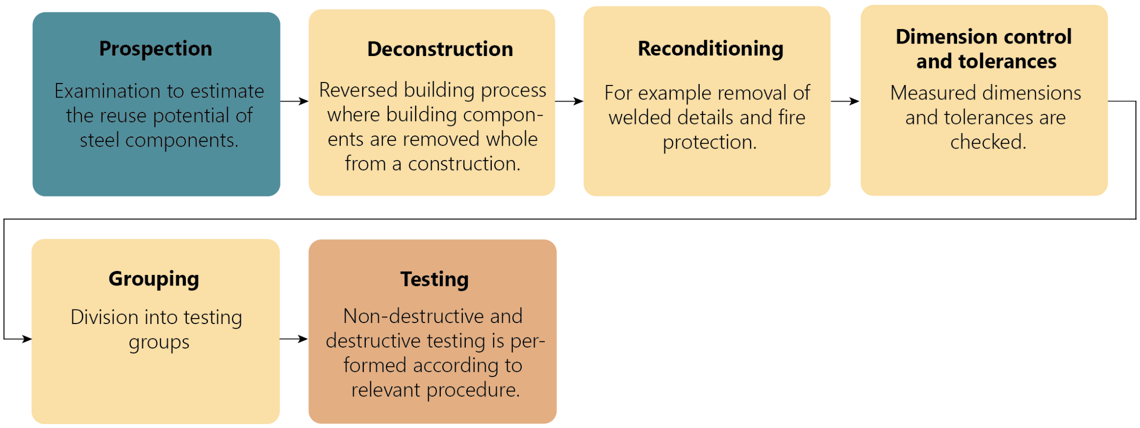

Figure 3.2: Process of reusing steel according to MVR.

3.5 Design methodology

Designing with reused components is often more challenging compared to using new ones. While new components can be designed to match the needs of a structural system exactly, reused components have predefined limitations concerning dimensions, steel grade, and quantity. Additionally, stocks of reused components are often irregular and change over time (Huang et al., 2021).

When working with reused steel, Varghese (2022) describes two alternative design approaches. The first one is referred to as *Form-Focused Design* and represents a more traditional way of working where a design is developed first and the material is identified and incorporated into the design later, see Figure 3.3. In this approach, the form of the structure is prioritised and will determine which material becomes appropriate to use. The second approach is referred to as *Material-Driven Design* and means that the material plays a more fundamental role from the beginning of the design process, see Figure 3.4. In this approach, the material of the structure is prioritised and will determine its shape (Varghese, 2022).

Figure 3.3: Form-Focused Design process.

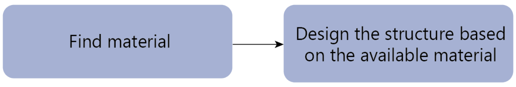

Figure 3.4: Material-Driven Design process.

According to Varghese, these alternative approaches present designers working on reuse projects with the dilemma of whether the best approach is to first identify available reclaimed materials and design around them or to design first and identify the materials later. With Form-Focused Design, there is a risk that the material which is available can't be efficiently incorporated into the design, and with Material-Driven Design, there is a risk that the freedom of the architect is limited and that it becomes difficult to meet functionality requirements from the client. This dilemma can cause tensions which is described by Varghese as the 'design-acquire paradox'.

To avoid this tension it is proposed to combine the two approaches into a workflow called an Ambidextrous Process Tool where respective approaches dominate the way of working during different stages of the design process. The process is initiated by the architects developing a preliminary design following a Form-Focused Design approach, and an estimation of the materials needed for the design is made. Then, available materials are identified by exploring donor buildings, demolition contractors, steel stockists, steel contractors and digital inventories. This is followed by a design phase where the Material-Driven Design approach dominates the way of working, and the preliminary design is developed and altered to enable a more efficient incorporation of the reused elements. In the final stages of the design process, the Form-Focused Design approach is dominating again and the currently available materials are incorporated in detail into the final design. This workflow is shown in Figure 3.5.

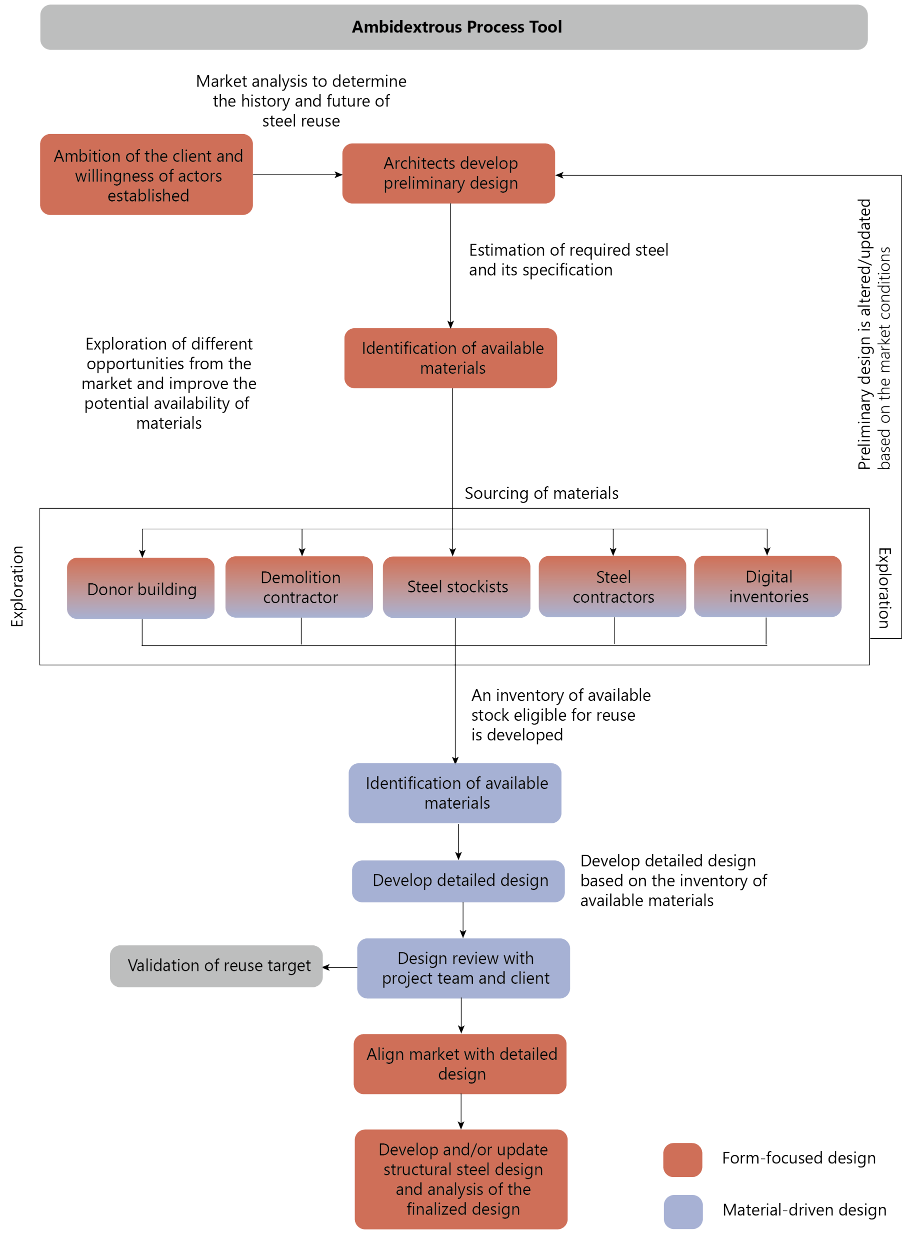

Figure 3.5: Diagram of the Ambidextrous Process Tool. The content of the diagram is developed by (Varghese, 2022) and layout is created specifically for this thesis.

3.6 Computational design tools

Incorporating reused elements into a design includes deciding which elements in the reuse stock to choose and where in the structure to place them. To manually assign reused elements of an available stock into a designed structure is time-consuming and costly, and if the stock changes, the assignment process might need to be done several times (Tomczak et al., 2023). The workflow of this process is shown in Figure 3.6 where the coloring is consistent with the overview diagram in Figure 3.1. As solutions to these challenges, there are several examples of digital design tools described in literature to be used in combination with digital databases of available elements.

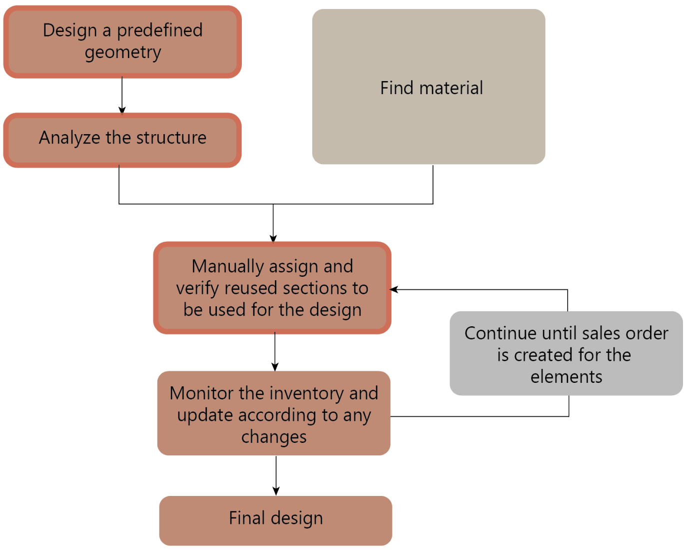

Figure 3.6: Example of a workflow where reused steel elements are manually incorporated into a structural design. Red frames represent a Form-Focused Design approach.

The type of digital design tool which is most appropriate to use and the way of using it might vary depending on the project stage, available time, the required level of accuracy and the amount of available information (Tomczak et al., 2023). Most available tools take a starting point in a predefined structural geometry and progressively replace the elements with available reused elements to find an optimal assignment based on set criteria, see e.g., (Brütting et al., 2019a; Huang et al., 2021; Bukauskas et al., 2017; Tomczak et al., 2023). There are also examples of tools that optimize the design to achieve an efficient matching (Brütting et al., 2019a; Huang et al., 2021). Less common, but mentioned, is the approach of using algorithms to collect available parts into architectural assemblies given certain boundaries (Rossi and Tessman, 2019). For example, by sequentially adding elements together in a process which is usually guided by geometry such as points and curves. Examples of such algorithms are growth and attraction algorithms (Bukauskas et al., 2017).

One of these matching tools has been created in Grasshopper by Yijang Huang using an open-source optimization algorithm by MIT (Vivet and Datsiuk, 2020). The matching process is, according to him, rooted in conventional parametric design optimization where the predefined structural system is described as a target design and elements from the reuse stock are selected and matched to the target elements in terms of geometrical fit and structural capacity. The matches are usually not exact and the elements in the inventory often need to be cut to be used for the target design (Huang et al., 2021). Other examples of matching tools are the Grasshopper plugin Phoenix3D by Jan Brütting (Warmuth et al., 2021) and the tool described in the article *Form-Fitting Strategies for Diversity-Tolerant Design* by Aurimas Bukauskas (Bukauskas et al., 2017). Computationally, the matching problem can, according to Bukauskas, be formulated as a bin-packing problem, and according to Huang as an unbalanced assignment problem. There are several solution approaches and alternative algorithms for solving these problems. The limitation of the matching method is that the solutions are restricted to those matching the predefined topology while more optimal designs are overlooked (Bukauskas et al., 2017). An example of a workflow based on a matching tool can be seen in Figure 3.7.

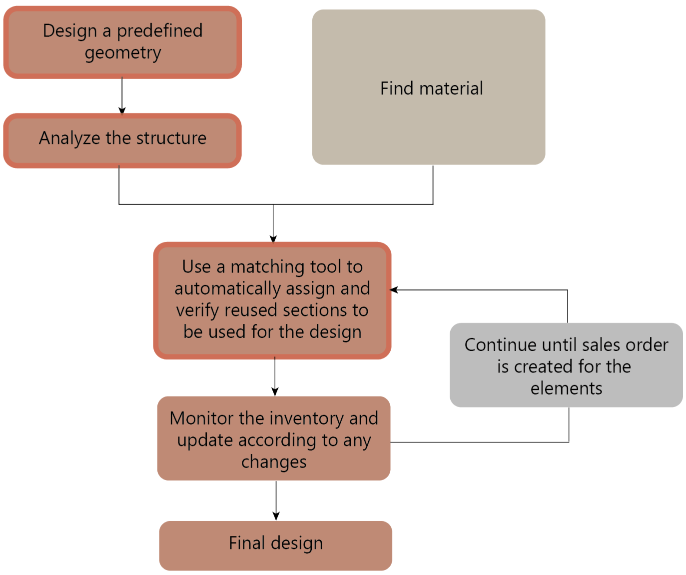

Figure 3.7: Example of a workflow where reused steel elements are automatically incorporated into a structural design using a matching tool. Red frames represent a form-focused design approach.

One way of achieving more efficient matching and getting closer to an optimal design in terms of reuse is to not only optimize the assignment of the inventory elements onto the target elements, but to also optimize the target design. An example of such a workflow is found in Figure 3.8. In a case study made by Huang, the target design is a geodesic dome which is parameterised and an inventory consisting of reused linear timber elements is matched to the target elements. The number of designed domes, their radius, and their subdivision are then optimized with the objectives of minimising scrap material, achieving a structural utilisation close to, but not above, 100% while maximising the floor area (Huang et al., 2021). A similar optimization process is described by Brütting where a matching tool is first used to optimize the assignment of reused elements onto a design and then the location of the nodes are modified to minimise the amount of scrap material. This approach is used for a theoretical case study where steel elements from power transmission line pylons are reused in the design of a train station roof. The steel elements have existing bolt holes, and after an optimal assignment is found, the location of the nodes is optimized in such a way that the bolt holes can be used in the new structural assembly (Brütting et al., 2019b).

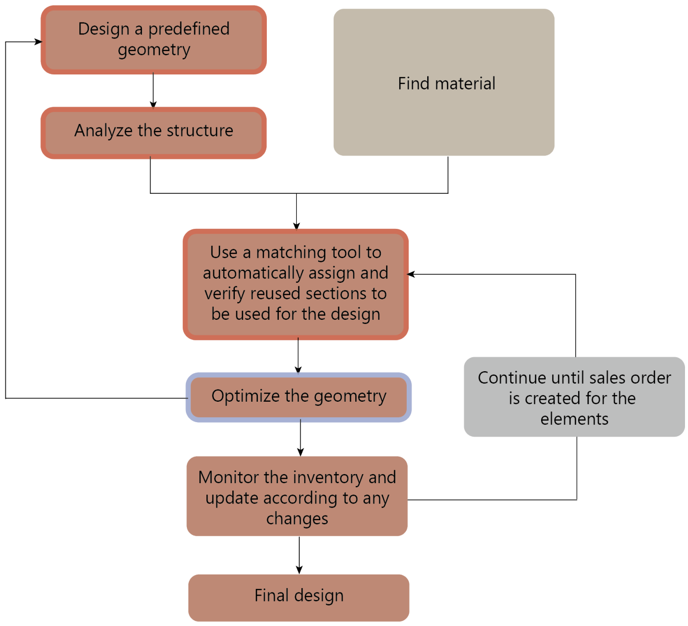

Figure 3.8: Example of a workflow where reused steel elements are automatically incorporated into a structural design using a matching tool and a geometry optimization. Red frames represent a form-focused design approach and blue frames a material-driven approach.

To guarantee a geometric fit of the reused element in the design, the third approach using algorithms to aggregate elements into assemblies without a target design, can be used. An examples of that workflow is seen in Figure 3.9. The disadvantage of this approach is, according to Huang, that it is difficult to control the final design and meet additional design requirements (Huang et al., 2021).

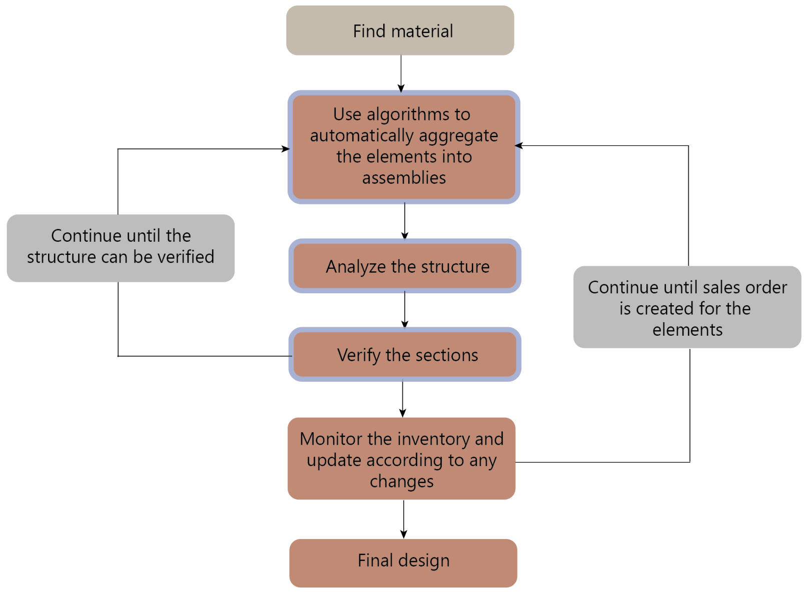

Figure 3.9: Example of a workflow where the structural geometry is generated from the available material using algorithms. Blue frames represent a material-driven approach.

4

Informal interviews

To get an understanding of how people have practically worked with reused steel, several informal interviews in a conversation format have been carried through. The interviewees have different expertise, and all have experience with steel reuse.

4.1 Frida Utterhall - Reuse expert at Stena Stål

Stena Stål is a steel supplier who has recently started to offer reused steel elements for sale, and Frida Utterhall is working as a development coordinator within reuse. The process of reusing steel, from the perspective of the steel supplier, can be divided into parts which are described by Utterhall according to the diagram in Figure 4.1. The colors of the diagram are consistent with the coloring of Figure 3.1.

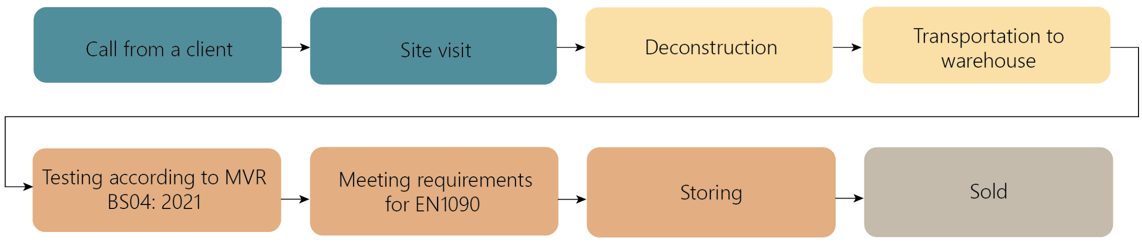

Figure 4.1: Process of reusing steel. The content of the diagram is created by Stena Stål and the layout was created specifically for this thesis.

Initial reuse potential assessment

The process starts when Stena gets a call from a client who owns steel elements they think might be appropriate for reuse. The client is asked about the age of the elements, how they have been loaded, in which building they have been used and for what purpose, if there are drawings documenting the elements and if the client has their material certificates. Then a site visit is made to visually inspect the elements. According to Utterhall, Stena only accepts elements which have been produced later than 1971, that have not carried exceptional loads, are in a visually good condition and that come from a known project for which there is enough documentation. Usually, they only accept members who are longer than six meters, but if there is a buyer in need of shorter elements they can make exceptions. They do accept elements with bolt holes, stiffeners and end plates since they can be cut off if requested by the buyer. So far, all of the elements they have been contacted about are produced less than twenty years ago and if they were not reused they would have gone to recycling. The price for Stena to buy a reused member is around 60% higher than for steel going to recycling under the condition that the client has the material certificates. If not, the price becomes around 30% higher compared to steel going to recycling.

Work done at the warehouse
If all the conditions for the elements are met, they are transported to Stena's warehouse after dismantlement. There, they are divided into testing groups, get unique identification codes to ensure traceability, and their dimensions are checked to be within the allowed tolerances. Stena is continuously in contact with buyers of reused elements and will send images and information about the new elements to clients who could be interested. The elements are then tested according to the guide from MVR described in Section 3.1.3. Right now, Stena is only using procedures A and B, meaning that elements not covered by these requirements will not be accepted. The time delay for performing the destructive test for procedure B is around two weeks and usually increases the cost per kg of material.

Selling reused elements
The elements that pass the testing are added to their stock lists and are stored until they are sold. There is no formal way to reserve an element during the planning stages of a project, but Stena is continuously in contact with potential buyers and a sales order can be created a long time before they ship the elements. If it is requested by the client, the elements can be sand-blasted and re-painted for a small fee and the testing documentation will accompany the element if purchased. The price per kg is approximately equal for a reused element as for a new one.

Response from the industry
Many different actors are interested in steel reuse and Stena has gotten a lot of questions, but, according to Utterhall, there are not many actors building with reused steel in practice so far. However, the reason for this might be that the planning stages for ongoing reuse projects take time, and as more and more projects are completed where reuse is successfully implemented, more actors will be motivated to work with it in practice as well. The interest has come from both entrepreneurs, building clients and consultants and it is usually individuals taking the initiative.

4.2 Linda Cusumano - Structural engineer and design manager at NCC

Onsala Rymdrum is a visitor centre in Sweden at Onsala Space Observatory and was completed in 2019. The project had the ambition to reuse 85% of the materials for the building, including not only the load-bearing structure of steel but the entire building. Linda Cusumano was the lead structural engineer of the project and for parts of the process also the design manager.

Having high reuse ambitions

According to Cusumano, the high reuse ambition was requested by the client of the project and was important since it made everyone on the team consider reuse in every part of the building. In the end, the team managed to reuse about 50% of the total project and 20% of the load-bearing structure, which Cusumano states was the hardest part to reuse. Other elements, like installations, were found to be surprisingly easy to find and incorporate into the design.

A challenging process

The project team took the approach of designing the structure first and then they tried to find suitable elements, although this proved to be a challenge. The architectural design required the structural engineers to work with special solutions, that cancelled out the initial idea of reusing timber for the load-bearing structure. When the team changed direction and researched steel reuse, it became more challenging since steel scrap has an economic value and it is usually a part of the entrepreneurs' budget to sell it for recycling. Also, demolition processes often damage the elements, and it was not easy to find companies willing to demount a building carefully due to time constraints. In 2019 there were no steel suppliers that offered reused elements, so the project team working with Onsala were themselves responsible for sourcing and testing the material which made the logistics of the project extensive. Cusomano sees that a problem was that a large responsibility fell on individuals, where few people became responsible for the entire reuse procedure of the structural elements. Additionally, the economy of the project was a big struggle since the budget had strict limitations and the cost of the project had to be close to equal to the cost of a project using newly produced elements. In general, the economic struggles proved to be more challenging than the testing and the structural verifications. Therefore, Cusumano sees that there is a need for demands on projects to map and present their emissions of CO_2e for reuse to be economically feasible.

Having to work with what is available

The steel elements offered for reuse that they did manage to find was often two –three times larger than the elements they would need, which primarily led to challenges when working together with the smiths. Welds on larger elements become longer than welds for smaller ones leading to unnecessary labour and costs. It was also challenging to find large quantities of members of the same sizes which made the logistics of transporting elements from several demolition sites and finding space to store them difficult. Due to the uncertainties of which elements would be available at what time, the team defined strategies that allowed for larger flexibility concerning member dimensions. One of these was to not build the columns into the walls, but rather offset them.

Different goals within the project team

Another challenge of the project was that there were differences in opinion between the engineers and the architects about how to work with reuse. While the goal of the architects was to make it visible that the elements were reused, the goal of the engineers and entrepreneurs was to make a project look and work the same way as any newly built project but using reused elements. Therefore, Cusomano highlights the importance of discussing the project goals and defining the meaning of reuse early during the process.

4.3 Practitioners at WSP in England, Canada and the Netherlands

Isis Bennet[1], Sally Walsh, David Leversha, and Thomas Musson are all practitioners who have experience working with the reuse of steel. Bennet is a structural engineer in Canada and Walsh is a structural engineer in England and both are working with reuse projects. Leversha is working as a director and NetZero Carbon Lead in England within the area of buildings and has contributed with the engineer's perspective on working with reuse in an article about circular economy by The Institution of Structural Engineers (Leversha et al., 2022). Musson is working with project management and has supervised a master thesis about the reuse of steel (Varghese, 2022).

Experiences from the Parliament Building in Canada
The preconditions and way of working with the reuse of steel have differed between different projects. In Ottawa, Canada, Bennet is working on a renovation of the Parliament building known as the Centre Block. This project includes a seismic upgrade, meaning that many steel members need to be removed from the building and new structural assemblies complementing the existing structure need to be constructed. So here, the source of the steel members and the project in which they will be reused is the same building (WSP, 2023).

The building was constructed in 1917 so the steel members are more than one hundred years old. This meant a significant amount of testing of the material composition and tensile strength of the members. However, due to the size of the project and that it concerns the life extension of an existing building where a significant amount of steel will remain, a large amount of testing would have been necessary anyhow. For a more typical project, it is likely that the time for removing the steel, testing it, and bring it back to the site would have made the building process longer. However for this project, a lot of construction work needs to be done for the basement anyhow, so the schedule allowed for this. In Canada, the codes state that if the steel grade of a member is unknown it can be assumed to have a yield strength of 210 MPa, so that is what they have done in the project. In Europe, there is no such lower bound of the steel grade which would make a similar process more difficult here. The material composition testing showed that the carbon content was too high for the members to be considered readily appropriate for welding, so only bolted connections can be used in the design (WSP, 2023).

[1] The only content of the conversation concerning the Centre Block project which is included in the thesis is also included in public sources.

Experiences from the Sloan Square House in the UK
Several projects across the UK are being designed with reused steel elements today. Here, it is more common for steel suppliers to have large inventories of reused members compared to Sweden, so these suppliers have been the source of the material for the projects. One of these projects is the Sloan Square House which is an office refurbishment where a two-story extension is added onto an existing building (The Alliance for Sustainable Building Building Products, 2023). In this project, it was proposed by the engineers to use reused steel members and both the architect and client were willing to do it.

Since the project is smaller it has been relatively easy to iterate the design until 100% reuse was achieved. There are still uncertainties concerning the exact inventory that will be available when the structure is built, but since the building is designed using sections that are common in the reuse inventories and they have a digital tool which can find replacements fast if a section goes missing they are confident that 100% reuse will be achieved. Instead of setting predefined building heights, the engineers and architect specified ranges of ceiling heights to account for a larger flexibility on which reused sections can be chosen for the project.

Using computational tools and automated workflows
Both in the Ottawa Parliament project and for the projects in the UK, automation and optimization algorithms have been important parts of the workflow. They start by designing the structural system and verifying it using new sections. A model is then created in Revit and a schedule of members is exported which, together with the reuse inventory, becomes the input for the optimization tools. The tools check that member capacities and properties like the beam depth, area, second moment of area etc. are not smaller for the reused members compared to the new ones, and reused members are matched to the members in the design in such a way that the amount reused steel is maximised. The updated schedule of members is exported to an Excel sheet and then loaded back into the Revit model and drawings, which are automatically updated to include the reused sections (WSP, 2023; The Alliance for Sustainable Building Building Products, nd).

The Ottawa Parliament project has been more constrained than the UK projects due to the nature of the task of renovating a structure of cultural historical value. Also, the introduction of modern mechanical systems into the existing spaces has put an increased pressure on reducing section depths, which has made steel reuse more challenging. Therefore, the main function of the optimization tool developed in Canada is to match reused members to the design in a more finalised stage. Since all reused members have a lower steel grade than the new members, accounting for differences in material grades is important for the tool to be useful. Some geometrical clashes between the matched sections and architectural or mechanical systems are anticipated, and to avoid this a maximum depth parameter is set for each floor plate (Gismondi, 2023).

In some of the UK projects, the preconditions have allowed for a bit more flexibility to iterate the designs based on the availability of sections (The Alliance for Sustainable Building Building Products, 2023). It is most common that they use their optimization tool after the conceptual design is completed when there is a Revit model and a cost consultant on board in the project. Then, the tool is used as support for making alterations on a detailed level, such as allowing for other material grades for certain members and making smaller geometric adjustments, to achieve a greater reuse percentage. For a few projects, the tool has also been used in more conceptual stages to estimate the reuse percentage for rough concept schemes based on the currently available inventory.

Existing rivet holes and accounting for section loss
For the Ottawa Parliament project, the reused members had previously been riveted together, which means that they have existing holes. It is decided in the project that they want to allow for these holes but not for larger openings from mechanical systems. A maximum percentage of section loss is therefore determined and considered in the resistance calculation for each unique member. The existing holes are not used for the new connections (WSP, 2023).

Coatings and fire protection
In the UK they have taken the approach of sand-blasting the sections, removing all current coatings and then painting them. Galvanized steel has proven more challenging to work with in this aspect since it changes the material composition. Therefore, in the designs, they are only using galvanized members in areas where no additional coatings or welding is needed.

Reflections on increases in section sizes due to reuse
Since the alternatives of section sizes are not infinite when working with reused elements it is common that larger sections need to be used compared to when producing new members. A rule of thumb that they use in the UK is to not use a reused section if it increases the weight by more than 30% compared to a new member, and they consider that if the utilisation of a reused member is less than 70% the carbon saving would be greater if the member was used in another project. There is no official paper stating these numbers, but it has been discussed at conferences that Walsh and Bennet have attended. Leversha also points out that since the cost of steel is set per kg it becomes more expensive to use heavier sections when using an inventory from a steel supplier.

Reflections concerning market forces and attitudes towards reuse
Today reuse is still new and non-standard and the sustainability aspect is more and more being used as a selling point for projects and a way for companies to increase their competitiveness in the market. When doing research for the master's thesis in the Netherlands, the student supervised by Musson found it difficult to find practitioners willing to talk about their reuse projects. This because they did not want to share trade secrets.

Additionally, the cost of reused steel has changed a lot in the UK over the last 18 months according to Leversha. Before, the steel suppliers could buy steel scrap for 30% of the price of a new member and after testing it and reconditioning it they could sell it for a price lower or comparable to the price of a new member. Now the market demand has increased and reused steel is becoming more expensive than new steel. So currently, the largest benefit of reusing steel is its large potential to save carbon. A way to make it economically feasible would be to introduce carbon taxes. In the future, we are hopefully past the stage of making pilot projects and reuse is a more standard and integrated part of construction. Then the reuse inventories are hopefully more extensive and Leversha raises the question of whether it will be necessary to divide the reused members that are being sold from the new members. Maybe, the structural engineers can specify their needs and it will be up to the steel supplier to find the most appropriate section among a mix of reused and new elements.

4.4 Tommy Nilsson - Reuse expert at Rival

Part of the inventory from Stena Stål comes from a preschool that was dismantled by the Stockholm-based demolition firm Rival. The idea to reuse the steel structure by doing a dismantlement rather than demolition came from Rival and not the client. ‘When I came to the site I saw that the structure was in excellent condition, it was only a few years old, had bolted connections and had been protected by fire insulation’, says Tommy Nilsson in a conversation with us. Nilsson works with reuse and sustainability at Rival and he was the one who contacted Stena Stål to buy the steel from the preschool. Although the steel did not have any good documentation, the shape and the look of the steel were as good as new, and thereby it underwent and passed the testing procedures. In total 144 m of HEA-beams were salvaged from the project. Rival has tried to initiate the reuse of load-bearing components in other projects that they have worked in, although, a lot of it is turned down due to age uncertainties and poor documentation.

Nilsson explains that bolted connections are preferable over welded connections. It takes a lot of time and money to cut down the elements, and it can also be more dangerous as a work environment. He further states that the interest in reuse and dismantlement over demolition has become larger and is talked about more broadly today than ever before. In a few years, Nilsson expects to see a large increase in demand regarding dismantlement, ‘the way we are demolishing today is not the future’. Still, most of the projects that have been done so far have been pilot projects, and the industry as a whole needs to become better at implementing reuse on a large scale.

Figure 4.2: Picture from the dismantlement of the preschool. Source: Rival.

Challenges of dismantlement and reuse

When being asked about what barriers exist to reuse Nilsson states that a lot of the construction today was not made with reuse taken into consideration, a lot of welded connections make the dismantlement harder. He also mentions that the property owners must realise the value of the material that they already have. Today dismantlement is more expensive than demolition as it takes a lot longer to do. However, the property owners already own the material, and if they can reuse it it may generate savings in costs and time in the long term, as one does not need to produce every element from scratch in later projects. He additionally sees a knowledge gap when it comes to dismantlement. In his experience, office buildings are often quite easy to work with when it comes to renovations and reuse, as there are a lot of set measurements and large quantities of similar elements.

Into the future

Going into the future Nilsson sees a value in establishing a dismantling plan for the building before it is even built. This could save a lot of hassle when reuse becomes the norm. Also, when a project is planned to be demolished or rebuilt, one should involve the demolition firms early on, to maximise the possibilities of reuse. Time to plan a dismantlement gives the demolition contractors time to make a proper inventory study of the elements suitable for reuse, and it also gives the actor time to find potential buyers for the material.

5

Study visit to a reuse project

During October 2023, a study visit was done to Oslo to visit Kristian Augusts gate 13 which is both a renovation of a building threatened to be torn down and an extension project. It is a pilot project within a program for circular buildings initiated by FutureBuilt, and it was the first building to successfully implement reuse on a large enough scale to fulfil the program's criteria for being classified as a circular building (Entra ASA, 2021).

The extension is nine floors high and about 70% of the steel structure is reused. Also, many of the hollow core floor slabs are reused. It was the responsibility of the entrepreneur to source the steel elements, which ended up coming from a large variety of buildings that were being demolished in the area of Oslo. About 57 tonnes of reused steel were bought before the construction was started and about 45 tonnes ended up being used. The project mostly used steel elements with I, H and HSQ-profiles. A main challenge with working with reuse that is brought up in the experience documentation report about the project is that the design process took longer time than expected (Entra ASA, 2021).

The architectural ambition of the project was to show that reuse is not only possible but that it can also be attractive and innovative. They aimed for a motley and colorful expression and allowed the available material to influence the look of the design (Entra ASA, 2021).

Figure 5.1: Pictures from Kristian August gate 13.

6

Contextualisation summary

Hereby follows some important points that is learned from the literature, the site visit and the interviews:

- Many professionals across several sectors are talking about reuse, and the interest increases for every year. Still, there is an unwillingness to change due to economic concerns, primarily since scrap steel has an economic value.
- Elements exposed to fatigue, seismic loading, or fire should not be reused. The easiest profiles to reuse are cold-formed and hot-rolled, as the testing procedure is clearly mapped out and there are no welds to check. All existing coatings should not be relied on.
- Reused elements have to undergo testing to verify their material properties and that they are appropriate to use again. The amount of testing necessary is determined based on the elements' age and how much documentation exist.
- Some of the most common barriers to reuse is economy, lack of supply chain coordination and limited traceability of elements.
- To work successfully with reuse, there is a need for coordination over multiple sectors, and the structural engineer should be involved in the preliminary design stages.
- There are two common design approaches, Form-Focused Design and Material-Driven Design. However, the most optimal way of designing with reuse may be to work with both.
- Several computational design tools to help implementing reuse in design are mentioned in literature.
- Companies in Sweden, such as Stena Stål, have started to offer inventories of reused elements to clients. Nevertheless, reused steel stocks are still very small compared to the UK, where the steel suppliers have much larger inventories.
- When working with reuse, one must consider that inventories may change as there is no possibility of reserving elements for several years. Designers can account for this by defining design strategies, implementing digital tools, and involve multiple disciplines in the early design stages.
- Inventories of reused elements are not infinite, therefore designers may have to turn down elements that have a very low utilisation in one project, as they have the possibility of being much more efficient and generate larger carbon savings in another project.
- To encourage companies and clients to consider reuse in a larger context, there may have to be government incentives that forces projects to be transparent about their environmental impact, or the establishment of a carbon tax.

- To encourage reuse, there has to be good example projects to show that it is possible.
- The initiative to use reused elements may come from different actors, such as the engineer or the demolition firm, and not just the client.
- It is not the verification calculations that are the most affected by reuse, it is the way of assembling the reused parts into a whole and match the reused inventory to a design.
- A barrier to reuse is often that the design process takes a long time, and becomes repetitive when the inventory changes.

6.1 Flow of reused steel

The process of working with steel reuse can be summarised in multiple workflows. The preparations of reused steel is summarised in Figure 6.1 while differences in the workflows depending on the steels origin are described in Figure 6.2–Figure 6.4.

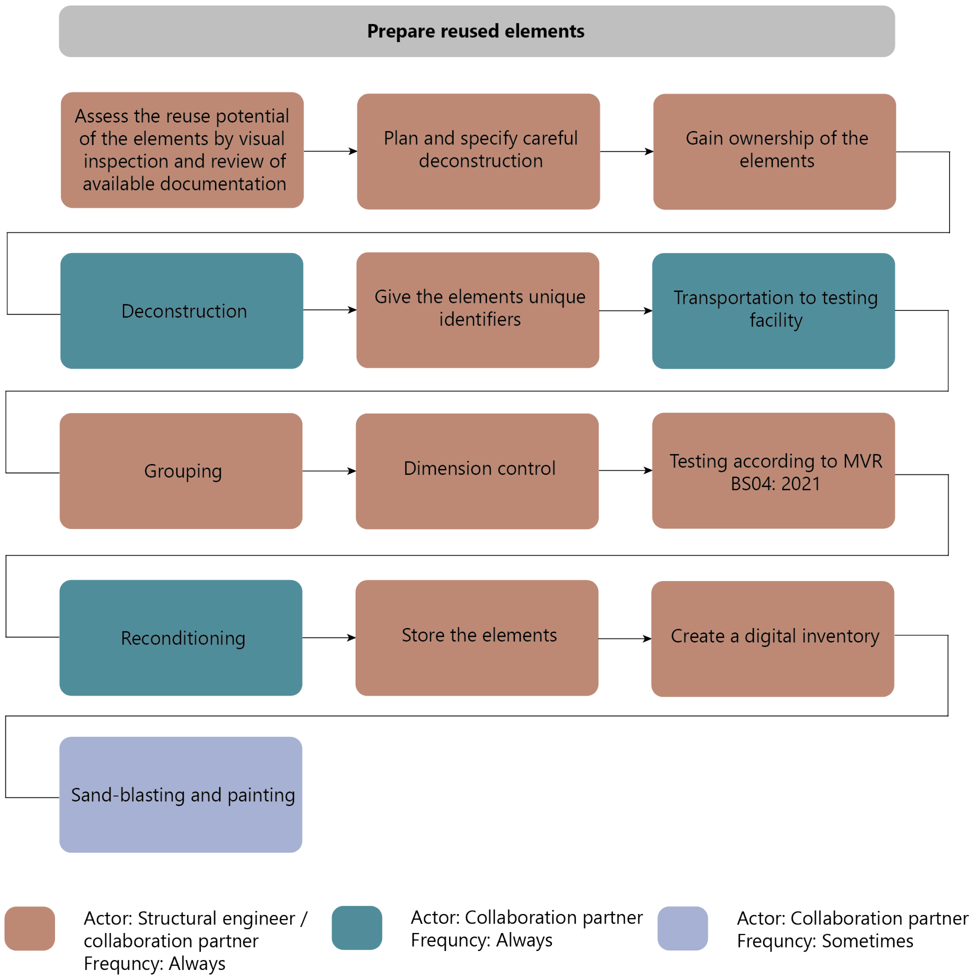

Figure 6.1: The workflow of preparing structural steel elements for reuse.

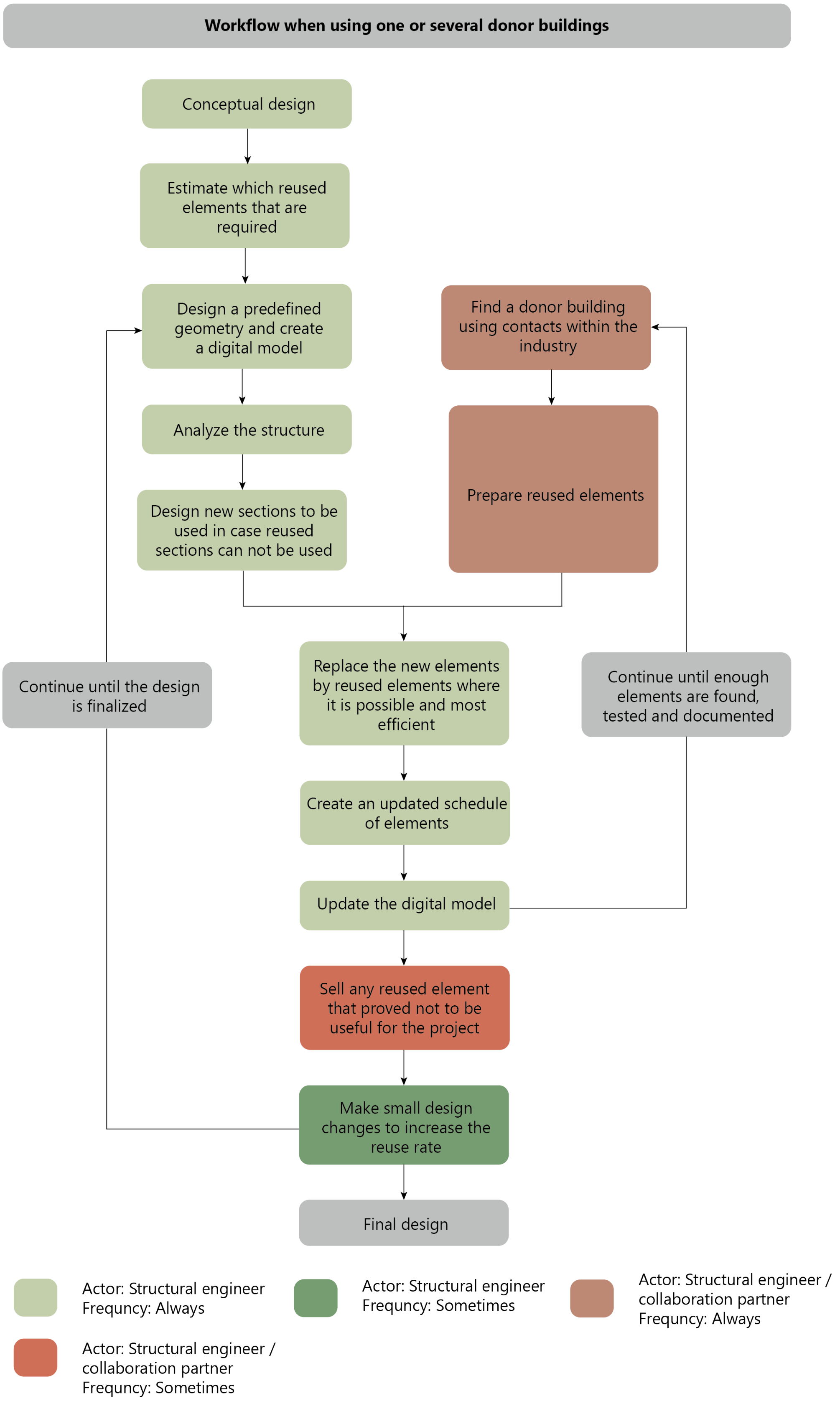

Figure 6.2: Possible workflow of designing a structural system using reused structural steel elements sourced from one or several donor buildings.

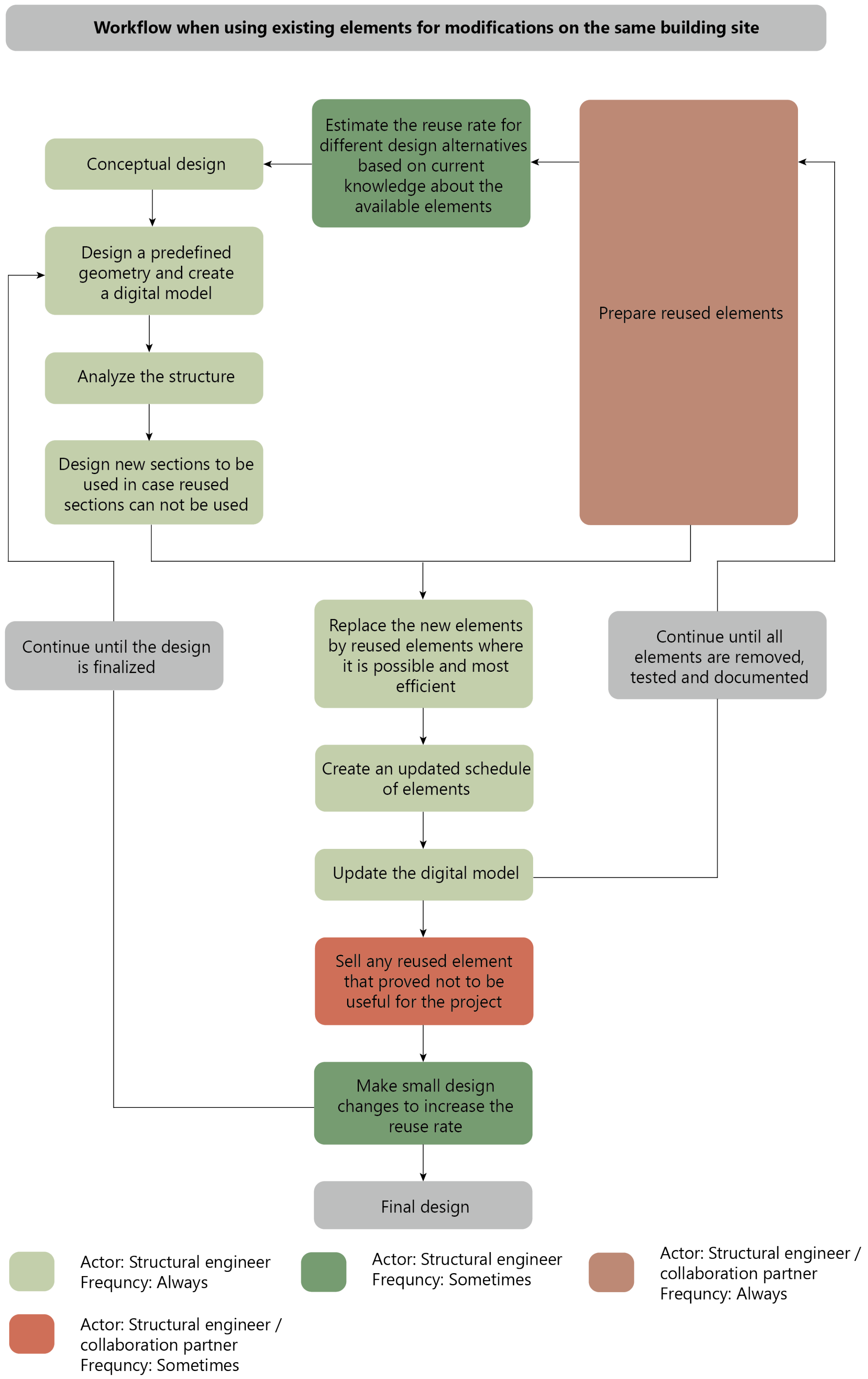

Figure 6.3: Possible workflow of designing a structural system using reused structural steel elements which are already at the building site in a part of the building which will be deconstructed.

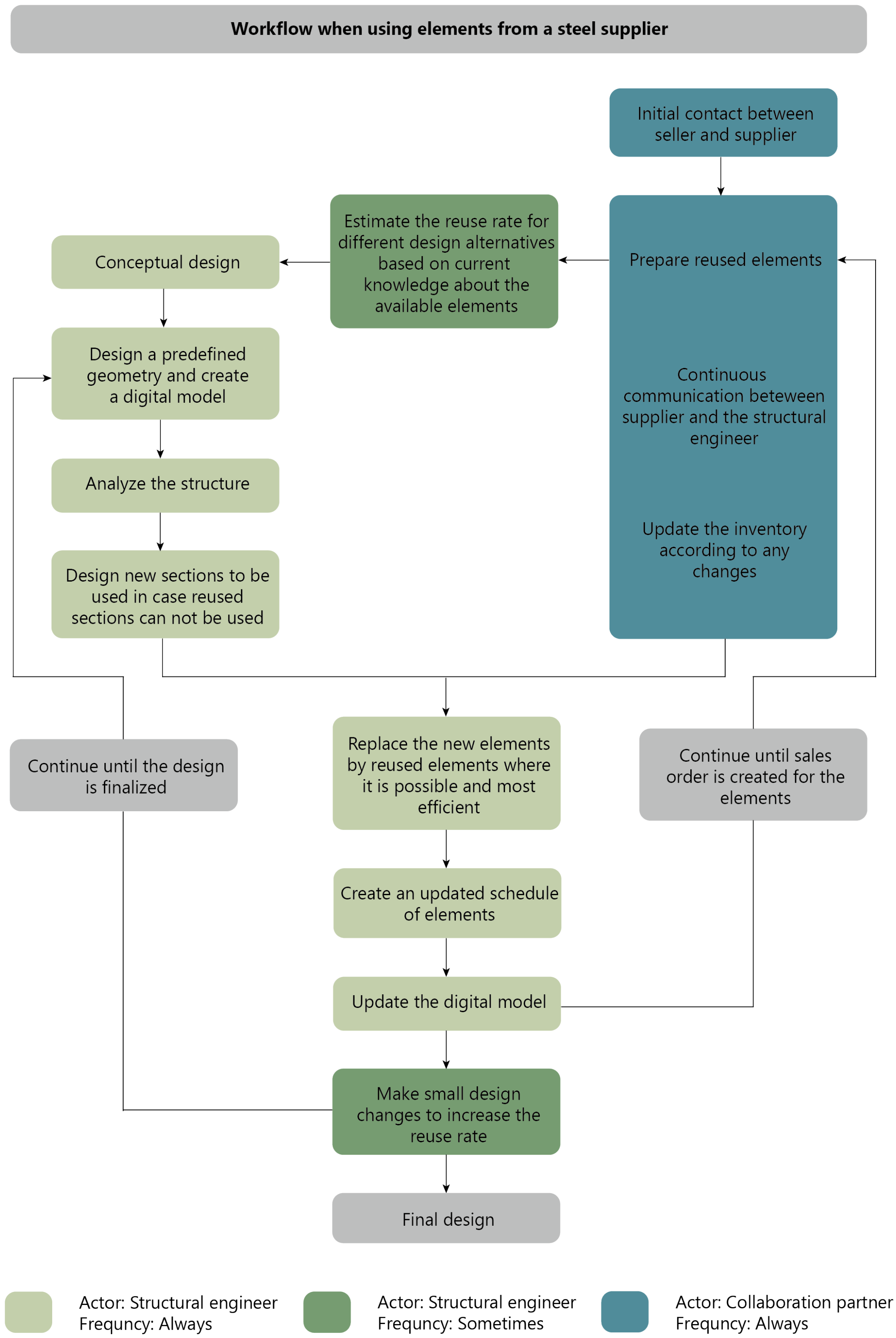

Figure 6.4: Possible workflow of designing a structural system using reused structural steel elements from a steel supplier.

Part II

The design workflow

7
Digital tools

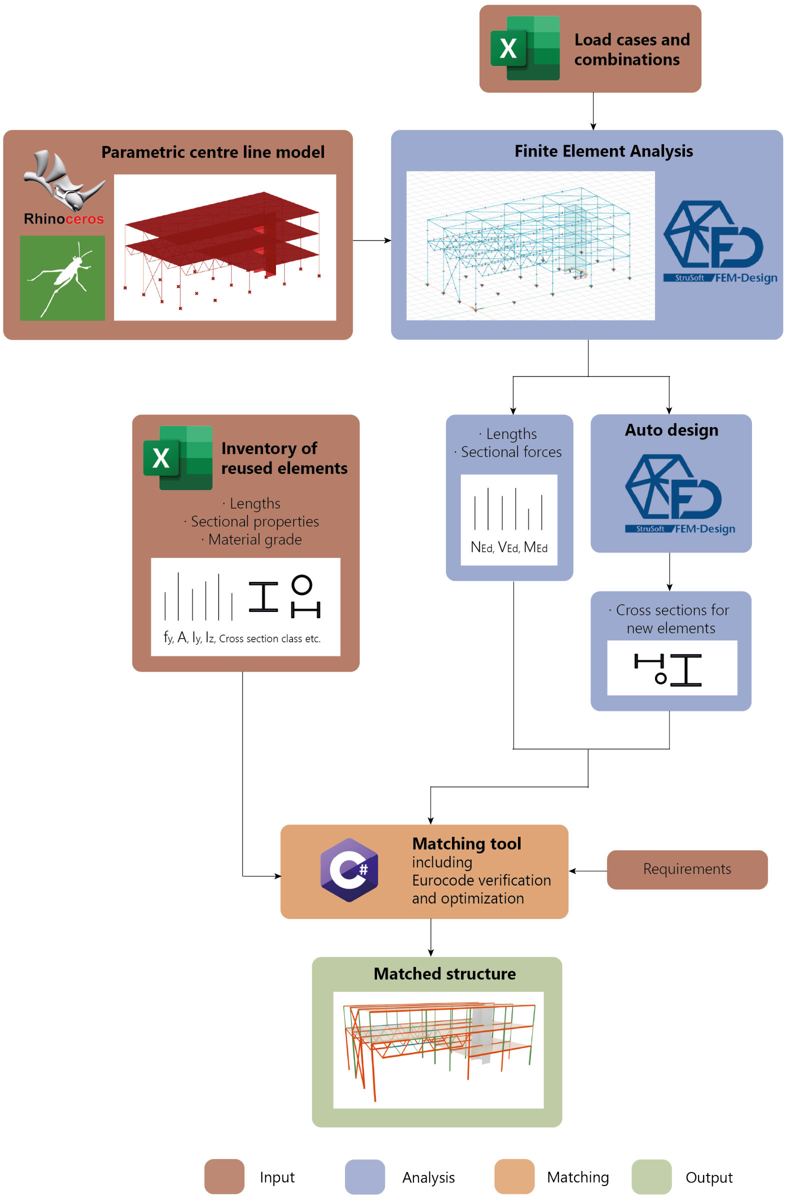

Figure 7.1: The workflow of digital tools aiding the design processes.

The workflow when designing using reused steel elements can be aided by several digital tools. The digital tools that are used for the thesis and an overview of how they are used are presented Figure 7.1. The workflow uses three main tools, Rhino, Grasshopper and FEM-Design. This workflow will be described in detail in the upcoming chapters.

7.1 Rhinoceros 3D

Rhinoceros (Rhino) is a 3D program used to create models using points, lines, surfaces, and solids (Rhinoceros3D, 2023). Rhino can be used to create models for building, analysis, renderings, or to simply showcase an object in 3D. This thesis uses Rhino to define geometry and as a visual tool to show all iterations and designs.

7.2 Grasshopper and parametric design

Grasshopper is a graphical algorithm editor that is connected to Rhino and allows one to parameterise 3D models (Grasshopper, nd). Grasshopper is a form of visual programming using components performing operations, where one gets a lot of freedom and flexibility when designing different structures. One can also implement and program components that can be integrated within a script using *C#* or Python.

Parametric design means that a model is built of parameters, relations, and constraints, rather than set values. It allows one to build, change, and iterate designs while maintaining control over set design elements and principles (Adobe, nd). A parametric model is thereby very easy to manipulate, for example, changing floor heights takes mere seconds as compared to readjusting an entire 3D model in Rhino.

7.3 FEM-Design

FEM-Design is a structural analysis software that allows one to perform a FEA (Finite Element Analysis) and verification on steel, concrete and timber in accordance with Eurocode (Strusoft, 2023). FEM-Design and Grasshopper can be linked using the FEM-Design Grasshopper plug-in. The plug-in allows one to take a parameterised centre line model, redefine the elements as bars, shells, supports and loads, and then open the model in FEM-Design. The model can then be both analysed and checked. FEM-Design has several additional features, such as auto design, to help designers design structural systems.

8
The inventories

In the design process, two different inventories of reused elements are used. One inventory is taken from Stena Stål's supply of reused elements (September 2023). The other inventory is based on a fictitious donor building, and inspired by the temporary mounting hall used in the construction of Skurubron.

8.1 Stock from a steel supplier

Today (September 2023) there are a limited amount of steel suppliers in Sweden that work with reuse. As mentioned in the interview with Frida Utterhall (Section 4.1), Stena Stål have started to offer an inventory of reused steel elements for sale. They aim to reuse well-documented steel and test them according to test procedures A and B. If the inventory changes during the design process and a reused element disappears, Stena offers to replace the element with a new one (Stena Stål, nd). In addition to Stena, Tibnor are also working with steel reuse and have participated in a pilot study by supplying reused steel elements that generated 97% in CO_2 savings (Tibnor, nd). The supplier's stocks vary widely between different countries. Cleveland Steel in the UK has 78,000 tonnes of reused steel, which makes reuse much more accessible there (Clevekand steel, nd).

The inventory from Stena Stål was received as lists in Excel with information concerning the cross section of the elements, their steel grade, their length, and the number of identical elements. The elements currently in the list come from a demounted industry building, a school, and various temporary structures used during construction work. Information about the elements are compiled in Table 8.1 and in Figures 8.2 and 8.3.

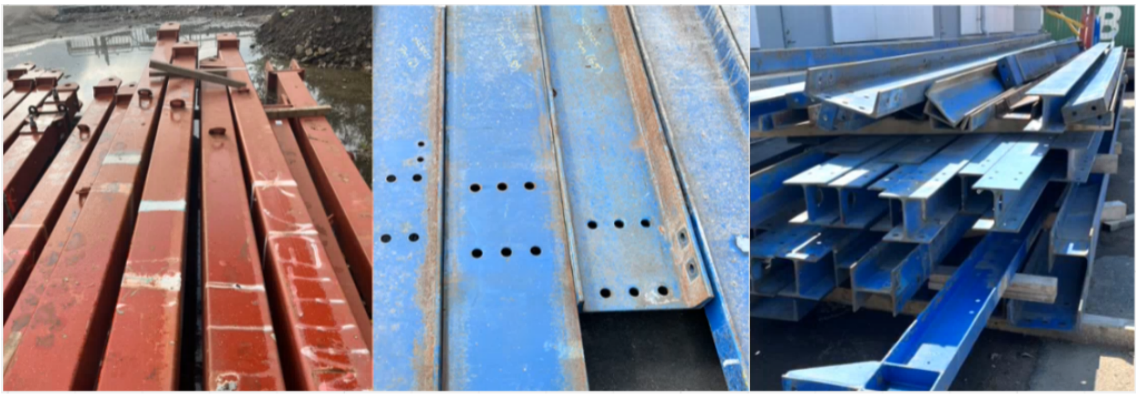

Figure 8.1: Photographs of some of the elements included in Stena's inventory (Source: Stena Stål)

Table 8.1: The inventory received by Stena Stål

Cross section	Steel grade	Number of elements	Origin
IPE160	S235J2	10	Volvo Cars Torslanda
IPE180	S235J2	99	Volvo Cars Torslanda
IPE180	S275J2	103	Volvo Cars Torslanda
HEA200	S275J2	5	Volvo Cars Torslanda
IPE220	S275J2	8	Volvo Cars Torslanda
IPE240	S235J2	15	Volvo Cars Torslanda
HEA300	S355J2	22	Ebba Brahe-Skolan and Scaffolding for the renovation of Lund's Domkyrka.
HEB300	S275J2	8	Support for a chimney in Linköping.
HEA400	S355J2	13	Scaffolding for the renovation of Lund's Domkyrka and a temporary building in Halmstad.
HEB400	S355J2	4	Scaffolding for the renovation of Lund's Domkyrka.
HEA360	S355J2	9	Temporary building in Halmstad.
HEB360	S355J2	2	Construction elevator in Stockholm.
HEB500	S355J2	2	Construction elevator in Stockholm.

Figure 8.2: Inventory from Stena Stål part 1. Green elements have passed the relevant tests for quality assurance, red elements have not yet been tested.

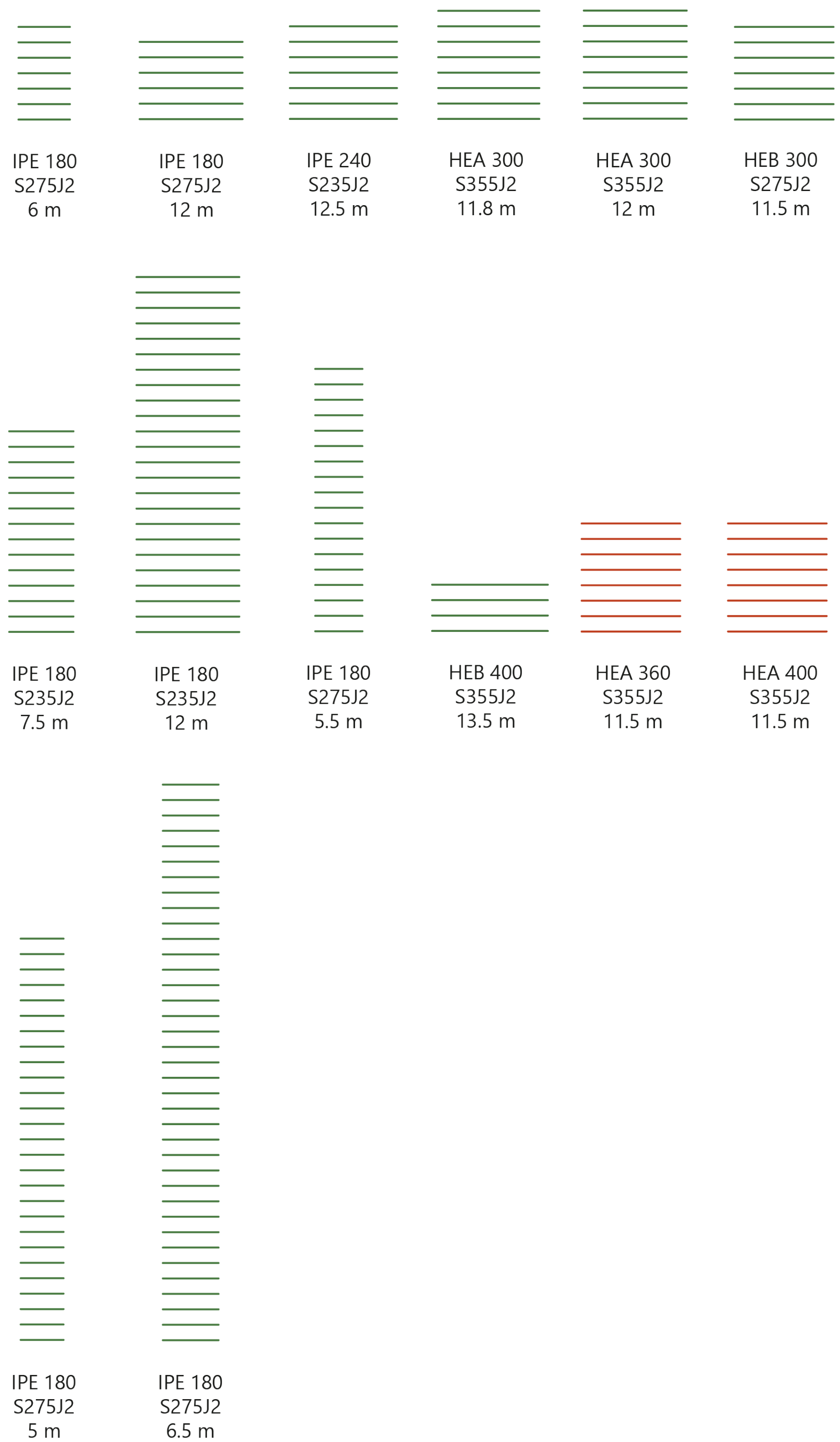

Figure 8.3: Inventory from Stena Stål part 2. Green elements have passed the relevant tests for quality assurance, red elements have not yet been tested.

8.2 Stock from a donor building

From 2019 to August 2023, the City of Gothenburg has approved 386 demolition permits[1]. Many of the buildings demolished or planned to be demolished are industrial buildings, office buildings, and storage buildings according to the city of Gothenburg. It is therefore not unreasonable to assume that there is a lot of elements that can be considered for reuse. Industrial and office buildings have the potential to be good donor buildings since they often have a large number of similar elements, and the structures in offices have generally not been subjected to cyclic loading.

Additionally, the Gothenburg Department of City Planning has recently handled a large number of temporary building permits[2]. Which includes everything from preschools and office buildings to construction sheds. Temporary buildings that are used in the construction process of new buildings are necessary but usually generate a lot of hidden waste. When construction sheds are stapled upon each other, there may be a need for supporting structures with large steel elements, and these can be seen throughout the city.

Waste generated from temporary structures being so common is one of the reasons that a temporary mounting hall is chosen as inspiration for a donor building for the second part of the inventory. The mounting hall was built for the construction of Skurubron, to shelter the materials and persons working on constructing the bridge. The hall sits on top of a temporary steel structure and is built with deconstruction in mind. The purpose is that the hall may be disassembled and used again elsewhere. The structure is made of L-beams and circular sections that are bolted together to form a robust truss (Darholm and Barraza Bergstrand, 2022).

As already mentioned, to make the testing of steel elements economic, the steel needs to be produced after 1971, there has to be good documentation and preferably material certificates. It is also beneficial if there are large quantities of identical elements that have been exposed to the same loads. The elements included in the mounting hall are likely to fulfil all of those criteria and therefore they are used as inspiration for creating a fictitious second inventory. Based on images of the mounting hall, the inventory consists of L-sections bolted together four by four and circular sections with plates welded in such a way that they can be bolted to other members, as seen in Figure 8.4. It is assumed that the elements have not been exposed to cyclic loading and that plates welded to the elements can be removed. Lengths presented for the circular tubes will not include the plate welded at the end. Information about the elements is compiled in an Excel list in a similar way

[1]This data was obtained by e-mailing kundservice@stadsbyggnad.goteborg.se and asking for lists of information about the demolition permits that have been approved between 2019 and 2023. It was received on September 13, 2023

[2]This data was obtained by e-mailing kundservice@stadsbyggnad.goteborg.se and asking for statistics concerning temporary building permits that have been approved or applied for between 2019 and 2023. It was received on September 13, 2023

as the inventory from Stena Stål.

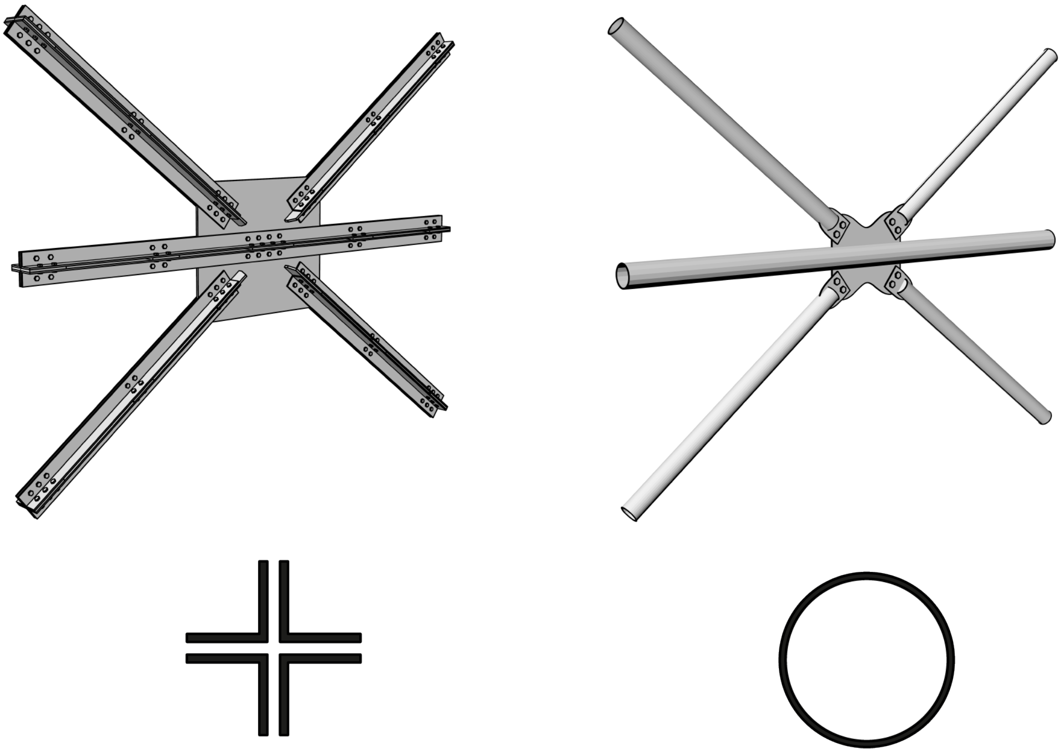

Figure 8.4: Principal sketches of the elements included in inventory two and their cross sections.

Table 8.2: The fictitious inventory inspired by the mounting hall.

Cross section	Steel grade	Number of elements	Bolt type
4 x L-40x40x4	S235JR	400	M8
4 x L-30x30x3	S235JR	188	M8
4 x L-80x80x10	S235JR	40	M16
4 x L-65x65x7	S235JR	8	M16
CHS-273x12.5	S335JR	10	M16
CHS-114.3x5	S335JR	10	M16
CHS-219.1x10	S355JR	20	M16

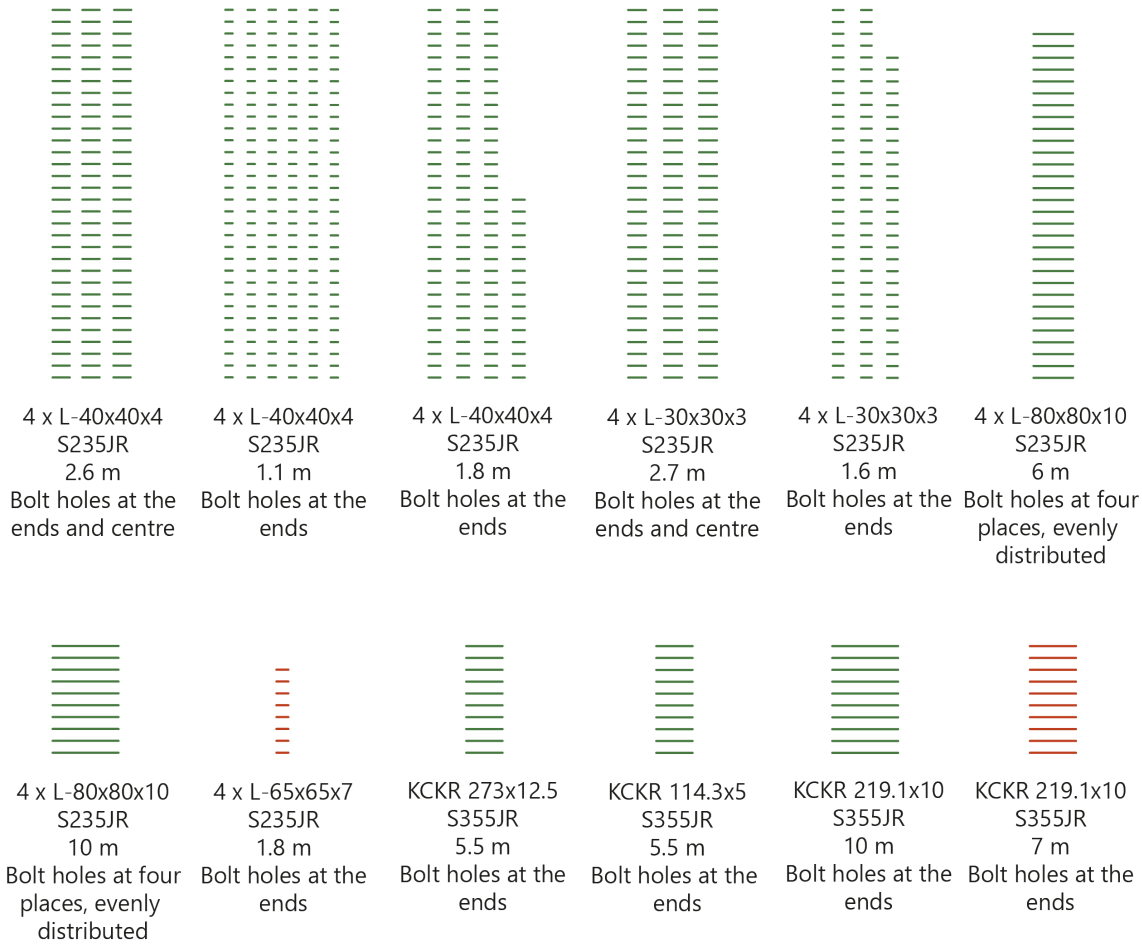

Figure 8.5: Inventory from the donor building. Green elements have passed the relevant tests for quality assurance, red elements have not yet been tested.

9
The Base Design

9.1 Design preconditions

The building typology chosen is an office building with a large public hall on the ground floor. The office typology was chosen since it is a common typology and has more tolerance for placing columns outside of the walls, compared to a residential building. The traditional office building usually follows a grid-like column-beam system, which makes the exploration of different designs easier. The idea of the office part is that it is an open landscape layout, however, no strict floor plan is established to allow for design freedom over the structural system.

The large hall on the ground floor serves two main purposes. Firstly, it gives one the possibility to explore how to work with reuse in a truss beam and forces one to consider large spans and lots of connections. Secondly, a project based on reuse could benefit from having part of the reused structure visible to the public to inspire other reuse projects. This aspect additionally gives flexibility concerning the geometry of the visible structural system.

A project centred around reuse is likely to have ambitious sustainability goals. So, the elements used in the design that are not reused are considered to be of better quality in terms of sustainability than their traditional form, for example, green concrete is used for the slabs, and the steel elements that are not reused are recycled. It is also assumed that all involved disciplines are aware that it is a project centred around reuse and that this might require new and innovative solutions. The project is designed with the current status of Swedish supplier stocks in mind, where successful reuse projects are of importance for increasing the interest in reuse in the industry and showing that it is feasible in practice.

9.2 Form-Focused vs Material-Driven Design

As the purpose of the thesis is to explore how one can design with reuse taken into consideration, the inventory of available elements will be allowed to have some influence over final the design. However, with the inventories that exist in Sweden today, to base the entire design concept on the available elements and aim for a reuse rate of 100 % would have a very large impact on the final outcome and would only be realistic for isolated pilot projects. The computational tools that aid strictly Material-Driven Design processes use mainly growth and attraction algorithms which are difficult to control and makes it difficult to meet additional requirements from the client (Huang et al., 2021). Also, there is no guarantee that a stable assembly will be found and no information on its structural behaviour can be provided until it is (Bukauskas et al., 2017).

Instead, as another aim of the thesis is to explore how reuse can become implemented on a larger scale, a starting point will be taken in a Form-Focused approach allowing for more architectural freedom and making it easier to fulfil functionality requirements. Computational tools that aid the more Form-Focused approach are matching algorithms that start with a predefined structure and progressively replace the new elements by reused elements. These algorithms gives the designer a better control of the outcome and provides a structure that can be analysed throughout the design process. Therefore, a base concept following an architectural vision and meeting the client demands is developed first, then a matching tool is used to replace as many new elements as possible by reused elements. Then, a more Material-Driven Design approach is used and smaller design changes are made to enable a higher reuse rate.

An overview of the workflow that is explored in the thesis is presented in Figure 9.1. The parts of the workflow which is the main focus are the matching process and how to make smaller design changes to enable a higher reuse rate. No changes to the inventory will be made along the design process, but strategies to make the design less vulnerable to inventory changes will be presented.

To further allow reuse to influence the design and to move towards a more Material-Driven approach, several versions of the base concept are created and used for the workflow presented above. The reuse rate and environmental impact will then be included among the factors deciding which versions of the base design that is chosen to be further developed.

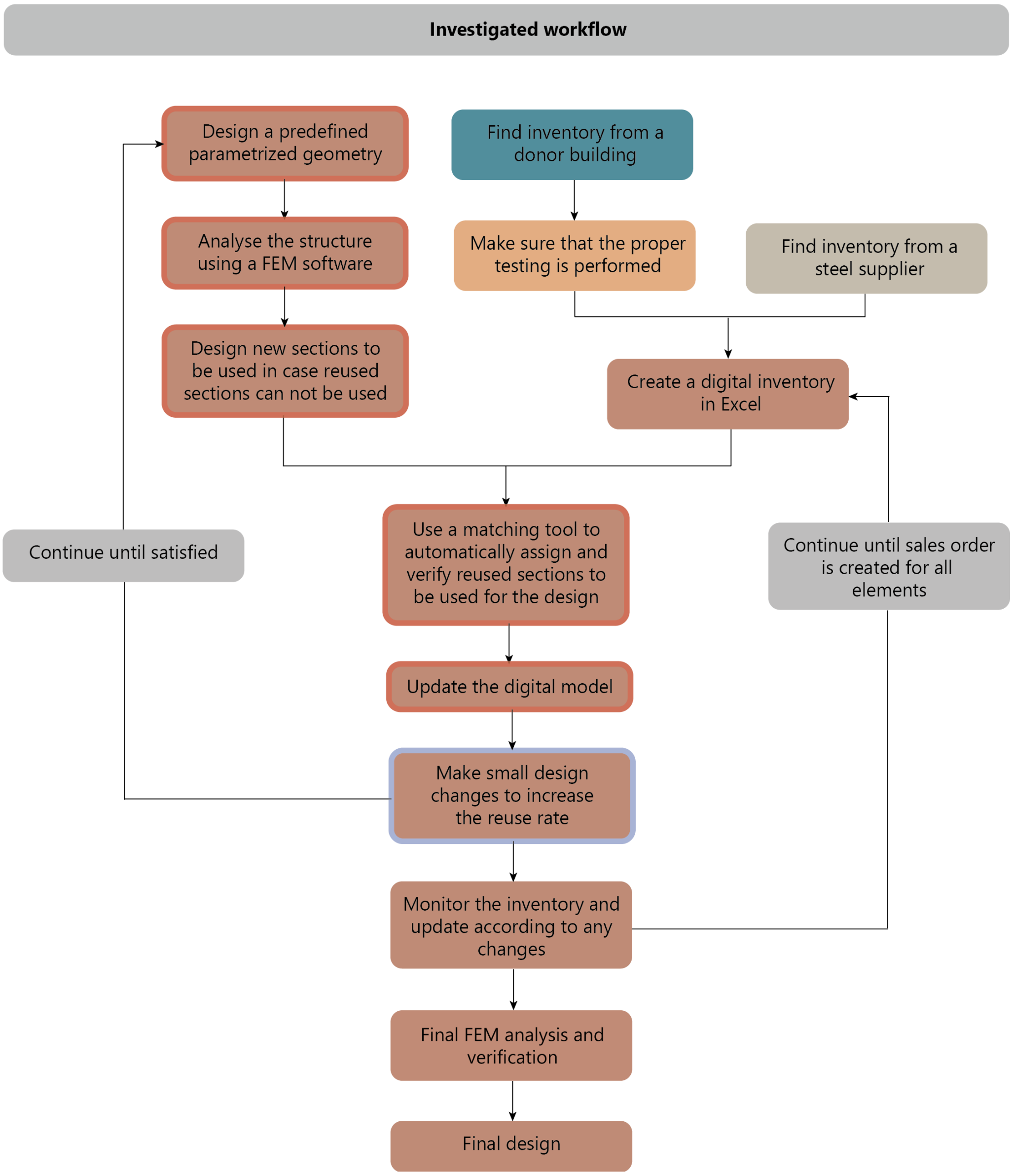

Figure 9.1: The investigated design workflow. Red frames represent a Form-Focused design approach and blue frames represent a Material-Driven design approach.

9.3 Centreline model

The centreline model and base design is a building with a length of 32m and a width of 16m. The load bearing steel structure is divided into two parts, one consisting of a beam-column system that is imagined to be the office part of the building. The second part is an open hall consisting of four large 2 dimensional trusses that span 16 m in the x-direction. In the x-direction the building is divided into 4 spans, and in y-direction there are 3 spans. The elevator shaft as well as the cross elements are the elements that will handle the horizontal loads.

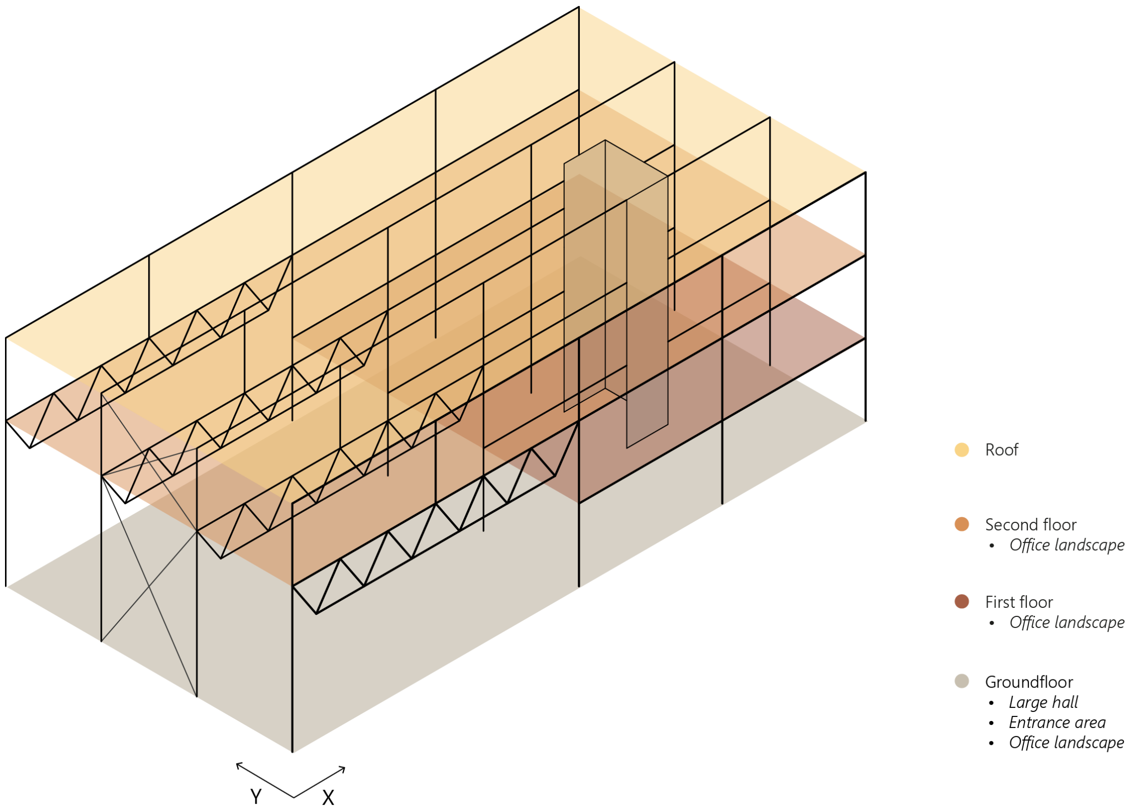

Figure 9.2: Centreline model - Base design

The centreline model is constructed with the help of Rhinoceros 7 and the Grasshopper plug-in. In the base design, the following factors have been parameterised:

- Building width (in x-diretion)
- Building length (in y-diretion)
- Width of floor 1 (in x-diretion)
- Number of spans in x-diretion
- Spacing in y-diretion
- Height of each floor (z-direction)
- Number of spans within the truss
- Truss height

The script is made in a way that makes it easy to do geometric adjustments, such as making the spans irregular, moving/adjusting specific elements, making elements continuous and so on.

9.4 Structural analysis

The purpose of the structural analysis is to get the cross sectional forces of the elements in the structure, so that they can be matched to reused elements having enough capacity. To do this, the structural analysis is divided into different parts: constructing a FEM-model in FEM-Design 3D structures, analysing and checking the results, and finally extracting the results to be used as input for the matching tool.

9.4.1 Loads

The building is assumed to be placed in Gothenburg, Sweden. It is assumed that the landscape around the building is designed in such a way that accidental loads from cars hitting the building can be avoided. Horizontal forces from unintended inclination are not included in the calculations for the intuitive phase since the wind load is assumed to be much larger and a separate calculation would need to be done for each sketch. Since the building is only three floors high and it is an early design stage the reduction factors for area and number of floors are ignored. This to have a larger safety margin for later stages in the design. In addition to the self-weight of the building, the structure is subjected to wind, snow and an imposed load. The wind loads are presented separately in Table 9.2 while the rest of the loads are presented below in Table 9.1.

Table 9.1: Summary of loads (excluding wind).

Load type	**Loads**	**Value** [kN/m^2]
Self-weights	$g_{\text{installations}}$	0.50
	$g_{\text{dividingwalls}}$	0.40
	$g_{\text{outerwalls}}$	0.40
	g_{HCF420}	5.56
	$g_{\text{CLTslab160}}$	1.10
	$g_{\text{CLTslab180}}$	1.24
	g_{roof}	5.56
Imposed load	$q_{\text{k.office}}$	2.5
Snow load	$g_{\text{snow.k}}$	1.2

9.4.1.1 Self-weights and imposed load

The self-weights of the slabs are taken and estimated based on values from Träguiden (Träguiden, 2023) and Strängbetong (Strängbetong, 2023). For the concrete slabs, hollow core floors with a depth of 420 mm are assumed, since they are able to span 14m. For the cross laminated timber slabs (CLT-slabs), a depth of 160 mm is used for the calculations in the intuitive phase, and refined to 180 mm in the intentional phase to handle a span of 5.33 m. The imposed load is taken from EKS 12, Table C-1.

9.4.1.2 Snow loads

Since the roof of the design is assumed to be flat, the snow loads can be assumed to be evenly spread and calculated according to SS-EN 1991-1-3 Equation 5.1. The snow zone is based on the Gothenburg context according to Figure C-2 in EKS 12. The value is reduced according to SS-EN 1991-1-3 Table 5.1, 5.2 and Section 5.2.

9.4.1.3 Wind loads

The wind conditions assumes a wind speed of 25 m/s according to EKS 12 Figure C-4 and a terrain class of IV according to SS-EN 1994-1-4 Table 4.1. The zone division of the walls and roof for which the external pressure coefficient differs is varying depending on whether the wind is acting on the long side of the building or the short one. The zone division of the walls follows the procedure of Figure 7.5 and Figure 7.6 in SS-EN 1991-1-4. They vary depending on the building dimensions, thereby the wind loads vary slightly between the different sketches in the intuitive phase. An example of how the wind zones can be divided is found in Figure 9.3.

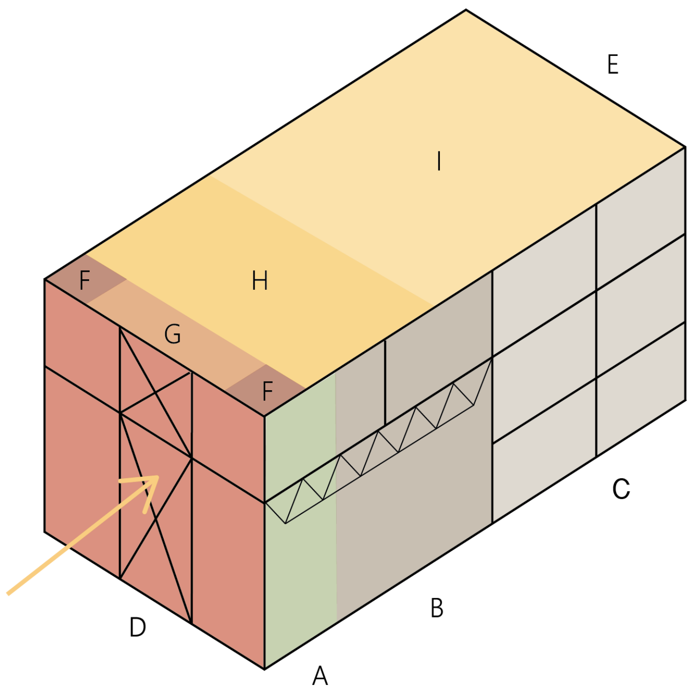

Figure 9.3: Example of wind zones when the wind is acting on the short side of the building

The vertical force from a positive internal pressure creates an uplift of the roof, which is favourable for the parts of the structure which are studied. Also, the horizontal force from a positive internal pressure has no effect on the stabilising elements since the resultant equals to zero. Therefore, only a negative internal pressure is considered in the calculations since it creates a downwards acting force on the roof, which is un-favourable for the parts of the structure which are studied. Since the sizes and placement of the doors and windows are unknown, an internal pressure coefficient of -0.3 is assumed according to Section 7.2.9 in SS-EN 1991-1-4.

The windloads acting on the base design (iteration 1) are summarised in Figure 9.2 below.

Table 9.2: Windloads in [kN/m^2] acting on zones A-I of the base design, when the wind is acting on respective sides.

Loads	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
Longside	0.522	0.290	-	0.621	0.083	0.290	0.522	0.232	0.058
Shortside	0.522	0.290	0.116	0.587	0.015	0.290	0.522	0.232	0.058

9.4.2 Load combinations

In total, 17 different load combinations are considered in the calculations. A comparison between the loads applied on the slabs and on the roof for combination 6.10a respective 6.10b according to EKS 12, is presented in Table 9.3. There it is seen that combination 6.10b is governing and therefore it is the only combination which is considered in ultimate limit state for the calculations, as shown in Equation 9.1. For the comparison, it is assumed that it is an hollow core concrete slab and that the self weight of the steel beams and columns are small compared to the applied loads. For serviceability limit state, equation 6.15 in SS-EN 1990 is used as shown in Equation 9.2, which is the frequent load combination.

Table 9.3: Comparison of applied surface load for load combination 6.10a and 6.10b.

Load combination	**Building part**	**Load** [kN/m^2]
6.10a	Roof	8.43
6.10b	Roof	9.30
6.10a	Slab	9.37
6.10b	Slab	12.1

$$q_{\mathrm{d,ULS}} = \sum_{j>0} \gamma_{\mathrm{d}} \cdot 1.35 \cdot 0.89 \cdot G_{\mathrm{k,j}} + \gamma_{\mathrm{d}} \cdot 1.5 \cdot Q_{\mathrm{k,1}} + \sum_{i>1} \gamma_{\mathrm{d}} \cdot 1.5 \cdot \psi_{0,\mathrm{i}} \cdot Q_{\mathrm{k,i}}. \tag{9.1}$$

Where:
γ_{d} = Safety coefficient depending on safety class (safety class 3 is assumed meaning that $\gamma_{\mathrm{d}} = 1.0$).
$G_{\mathrm{k,j}}$ = Characteristic permanent load.
$Q_{\mathrm{k,1}}$ = The main characteristic variable load.
$\psi_{0,\mathrm{i}}$ = Combination factor for respective accompanying variable load.
$Q_{\mathrm{k,i}}$ = Accompanying characteristic variable load.

$$q_{\mathrm{d,SLS}} = \sum_{j>0} \gamma_{\mathrm{d}} \cdot G_{\mathrm{k,j}} + \gamma_{\mathrm{d}} \cdot \psi_{1,1} \cdot Q_{\mathrm{k,1}} + \sum_{i>1} \gamma_{\mathrm{d}} \cdot \psi_{2,\mathrm{i}} \cdot Q_{\mathrm{k,i}}. \quad (9.2)$$

Where:
$\psi_{1,1}$ = Combination factor for the main variable load.
$\psi_{2,\mathrm{i}}$ = Combination factor for respective accompanying variable load.

The load combinations are generated by having the wind load acting on the short side of the building, on the long side, and not being present at all, by having different variable loads as the main load, and in both ultimate limit state and serviceability limit state. The product of the partial safety factors and combination factors for each load case in each load combination are shown in Table 9.4.

Table 9.4: Partial safety factors and combination factors for every load combination.

Loads (wind on longside)	LC1	LC2	LC3	LC4	LC5	LC6
	ULS			SLS		
Main variable load	Imposed	Snow	Wind	Imposed	Snow	Wind
Permanent load factor	1.20	1.20	1.20	1.00	1.00	1.00
Imposed load factor	1.50	1.05	1.05	0.50	0.30	0.30
Snow load factor	0.90	1.50	0.90	0.10	0.30	0.10
Wind load factor	0.45	0.45	1.5	0	0	0.2
Loads (wind on shortside)	LC7	LC8	LC9	LC10	LC11	LC12
	ULS			SLS		
Main variable load	Imposed	Snow	Wind	Imposed	Snow	Wind
Permanent load factor	1.20	1.20	1.20	1.00	1.00	1.00
Imposed load factor	1.50	1.05	1.05	0.50	0.30	0.30
Snow load factor	0.90	1.50	0.90	0.10	0.30	0.10
Wind load factor	0.45	0.45	1.5	0	0	0.2
Loads (no wind)	LC13	LC14	LC15	LC16	LC17	
	ULS		SLS			
Main variable load	Imposed	Snow	Imposed	Snow	-	
Permanent load factor	1.20	1.20	1.00	1.00	1.00	
Imposed load factor	1.50	1.05	0.50	0.30	0	
Snow load factor	0.90	1.50	0.10	0.30	0	

9.4.3 Finite Element Model

The finite element model was made using FEM-Design 3D Structure and Grasshopper. All columns, beams and stabilising elements are assigned assumed cross sections and material grades according to Table 9.5. The ends are assumed to be hinged in all directions.

Table 9.5: Assumed cross sections for the different element types

Element type	Material grade	Cross section
Columns	S275	HEA300
Beams	S275	HEA300
Stabilising cross	S275	HEA300
Truss	S275	CHS 193.7-20.0

Changes of the cross sections may lead to a redistribution of forces, which will be discussed in greater detail further down in the report. To get the FEM-model to behave as close to reality as possible, the slabs are defined as covers, which are surfaces distributing the loads to the load-carrying structure without being structural elements themselves. To ensure stability without the slabs, fictitious diagonal beams as well as fictitious bars in the y-direction are defined.

In addition to the elements, all of the support conditions on the ground floor must be defined. All the columns are defined as having point supports, while a line support is added by the elevator. Only translations are restricted and no rotations.

FEM-Design automatically calculates the self-weight of the beams and columns and the elevator. All other loads, such as the self-weight of the slabs, the snow loads and the wind loads must be defined in Grasshopper and plugged into the FEM-Design plug-in. The load combinations and load cases are imported to Grasshopper via an excel list, and then read by the FEM-Design plug-in, to ensure that all 17 load combinations are included.

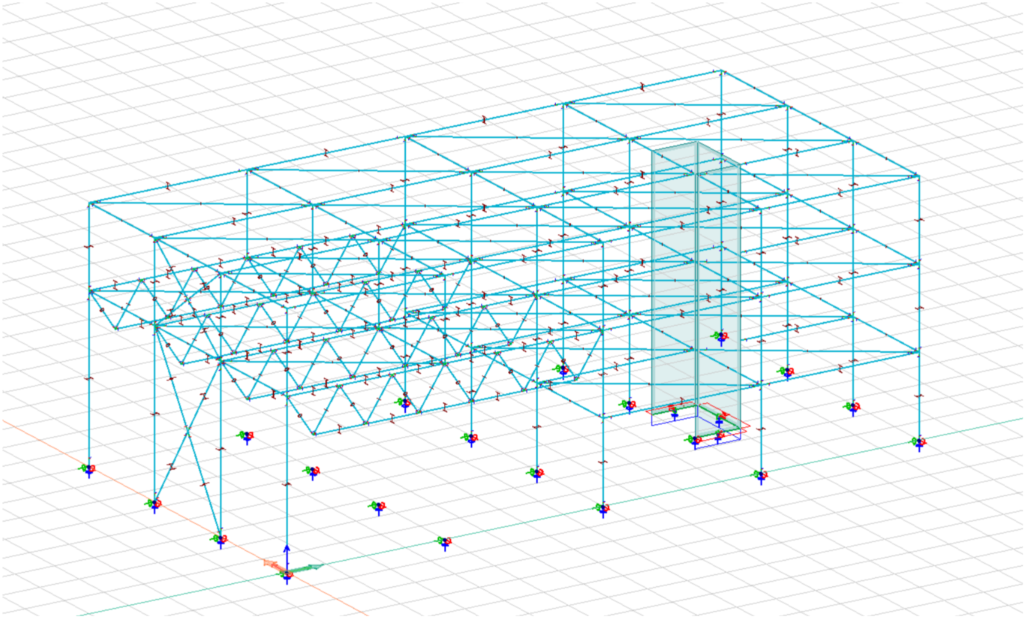

Figure 9.4: The Finite Element Model used for the structural analysis

9.4.3.1 FEM-analysis

When the FEM-model is constructed, the model is checked to make sure that the load distribution looked reasonable. For each model, a first order analysis is performed and the deflection of the truss is checked to confirm that it is lower than $L_{span}/300$. To check that all of the normal forces are within a reasonable domain they are checked and compared to hand calculations. It was also checked that the sum of the applied loads and the reaction forces were similar.

Table 9.6: Applied load handcalcualtion vs Reaction forces from FEM-Design

Calculation	**Value** [kN]
Applied load (Hand calculation)	8358
Reaction forces (FEM-Design)	8255

9.4.3.2 Auto design

Going back to Grasshopper, another FEM-Design plug-in script is created to auto design the structure and find out which cross sections that would be needed if the entire structure was built using new elements. The built in auto design function in FEM-Design uses the sectional forces obtained in the structural analysis and finds the most optimal cross section to carry the forces among some specified alternative sections. No consideration is taken to any redistribution of forces due to changes in stiffness. This is performed for all elements in the structure by the Grasshopper script after the model have been verified. The output from this is a list of elements that will be used where the matching tool is unable to find a match with a reused element, and to calculate the saving in CO_2e that is made by using reused elements.

To make this process quicker and run more smooth, parts of the building are divided into design groups for which the auto design plugin will assign the same sections. Since this project is focused on reuse, the elements that are not reused are likely to have high sustainability demands, and the new elements are thereby assumed to be recycled with a CO_2e/kg of 1.27. The main limitation of auto design is that the tool only optimises the elements of the same cross section type as the initially defined element. For an example, if one sets a beam to a IPE200, auto-design can optimise and replace the the cross section with another IPE beam, but it will not replace the section with a circular section or an HEA-beam. This means that the replacement elements will only be CHS for the truss elements and only HEA elements (see Table 9.5) for the columns and beams.

9.4.3.3 FEM-output

When working with the matching tool, there are two alternative approaches of ensuring that the matched elements have sufficient capacity to carry the applied loads. The first approach would be to input the sectional properties, such as area, second moment of area etc., of the auto designed sections into the tool. Then only allow matches with reused elements for which the sectional properties are equal to, or larger than those of the auto designed sections. The second approach would be to input the sectional forces from the FEM analysis into the tool and perform verification according to Eurocode within the algorithm.

The first approach is simpler and faster to implement in code, but the user has less control over the impact that the changes in cross sectional properties have on the verification checks. The fact that the reused elements might have a different material grade than the auto designed elements would need to be accounted for, or potential matches might be discarded unnecessarily. Additionally, updated utilisation rates will not be known until the structure is verified after the matching is already performed, and it is more difficult to discard matches leading to unnecessarily low utilisation rates.

For the second approach, more calculations are needed to be performed by the tool, but the structural verification can be more controlled and custom made for the specific project preconditions. It is easier to discard matched elements leading to unnecessarily low utilisation rates and changes in material grades are automatically taken care of. For the matching tool, it is chosen to work with the second approach, and the output from the FEM model that is plugged into the algorithm are the sectional forces.

The following outputs are extracted from the parameterised Grashopper script with the FEM-Design results to the matching tool:

- Element type (example: beam, column, truss...)
- Element Id (example: truss0, truss1, truss2...)
- $N_{Ed,Min}$
- $N_{Ed,Max}$

- $V_{Ed,Weak}$
- $V_{Ed,Strong}$
- $M_{y,Ed}$
- $M_{z,Ed}$
- $V_{Ed,Strong,SLS}$
- Element length
- CO_2e (of the auto designed elements)
- Cross section (of the auto designed elements)

10
The matching tool

10.1 Existing matching tools

Some tools that matches reused elements to a set design already exist and are free to use. Two examples of such tools are Stockmatcher and Phoenix 3D which were considered to be used in the workflow developed during the thesis.

Stockmatcher is a tool where one plugs in two Excel lists of elements, one with already designed elements which would have been used if the entire structure was new, and one with reused elements. The program then attempts to replace as many of the designed elements as possible with reused elements while minimising the weight added from cut-off parts and from reused cross sections having a larger area than the designed sections. To avoid generating matches with very low utilisation rates, the user can limit the allowed amount of extra weight to be added for each match. The user can also define the minimum length for a cut-off part of an element to be added back to the inventory, the maximum increase of section depth and which types of cross sections that can be considered for replacing the designed elements. However, the same definitions must be applied to all elements. So, for example, if there are different requirements on the cross section type for different elements in a structure, they have to be matched separately. The main limitations of the tool are that the structural check is limited to a verification of the second moment of area and differences in material grades between the elements are not considered (Stockmather, 2023).

Phoenix 3D is a Grasshopper plug-in that takes a centreline model, support conditions, loads, and two lists of structural elements as inputs. One of the lists is the inventory of reused elements and the other is a list of new elements that can be used if the reused elements are not appropriate for some elements in the structure. The tool does both a Finite Element Analysis and a matching of reused and new elements. The user can choose between having the total weight of the structure, the total amount of embedded CO_2e, or the amount of generated waste as the optimization objective. Some main limitations of the tool are that only truss elements and normal forces are considered in the structural analysis, and that the values for embedded CO_2e are hard-coded and differ from the values in the Climate Database compiled by Boverket (Boverket, 2023b). Also, no limits can be defined for section depths and the minimum allowed utilisation (Warmuth et al., 2021).

The limitations concerning structural checks performed by both tools make them difficult to apply in design processes of more complex structural systems with several different structural members. A lack of flexibility also makes it difficult to adjust the tools for project-specific considerations. In practice, many similar tools exist and are currently being developed, but they are developed internally by companies and are based on case-to-case situations. Therefore, the matching tool used in this thesis is a self-scripted tool made using Grasshopper and C# .

10.2 Choice of optimization algorithm

As mentioned in Section 3.6 there are several ways to computationally formulate the reuse assignment problem and several algorithms available to solve it. In the tool developed by Huang, an open-source Hungarian algorithm is used, which is developed specifically for finding globally optimal solutions to linear assignment problems (Huang et al., 2021; Vivet and Datsiuk, 2020). However, for the application of assigning reused elements onto a designed structure, the algorithm is limited since cut-off parts from the reused elements cannot be considered for reuse elsewhere in the structure. Also, certain modifications to the algorithm would be needed to account for the case when no matches at all are found for certain elements in the structure, which is likely to occur for the designs.

In Phoenix 3D, the user can choose between using a Mixed Integer Linear Programming (MILP) solver and a Heuristic 'Best Fit' algorithm. The tool can consider cut-off parts and, as mentioned, perform Finite Element Analysis within the algorithm, so no external Finite Element program is needed (Brütting et al., 2022). However, finding pedagogic material and easily understandable pseudocodes on the exact formulation of the MILP problem and implementation of a specific solver proved difficult.

Heuristic algorithms are the types of algorithms that are most likely to achieve a good trade-off between speed and quality of results (Bukauskas et al., 2017). Also, according to Huang, the so-called 'Best First' algorithms have proved to be effective when used practically for the reuse assignment problem Huang et al. (2021). However Heuristic and 'Best First' algorithms are generally not globally optimal. The A* search algorithm is an example of a 'Best First' algorithm which uses heuristic functions to solve the problem efficiently (V. Goldberg and Harrelson, 2004; Hart et al., 1968). It is developed to solve problems formulated as finding minimum cost paths by using weighted graphs which have applications in a large variety of fields, such as navigation systems, routing of telephone traffic, robotics, etc. It can be proved that the solution is globally optimal (Hart et al., 1968) and the algorithm is commonly used due to its flexibility (Xu et al., 2023).

Lack of flexibility and lack of possibility of adapting to project-specific requirements are the main limitations of the currently available matching tools. So, the A* algorithm is chosen for the matching tool as it is described as flexible with many possible applications in the literature. It also implements strategies for being efficient and there is easily accessible pedagogic material and pseudo codes describing it (Javatpoint.com, nd; Ravikiran, 2023).

10.3 A* search algorithm

As already mentioned, the A* algorithm solves problems formulated as finding the minimum cost path between a start node and an end node by using a weighted graph. Due to its visual quality, the problem of finding the shortest travel distance between two points using a predefined network of roads is often used to explain the basics of the algorithm, as illustrated in Figure 10.1 and Figure 10.2 (Codecademy, 2023). Relevant terms for understanding the algorithm are explained below:

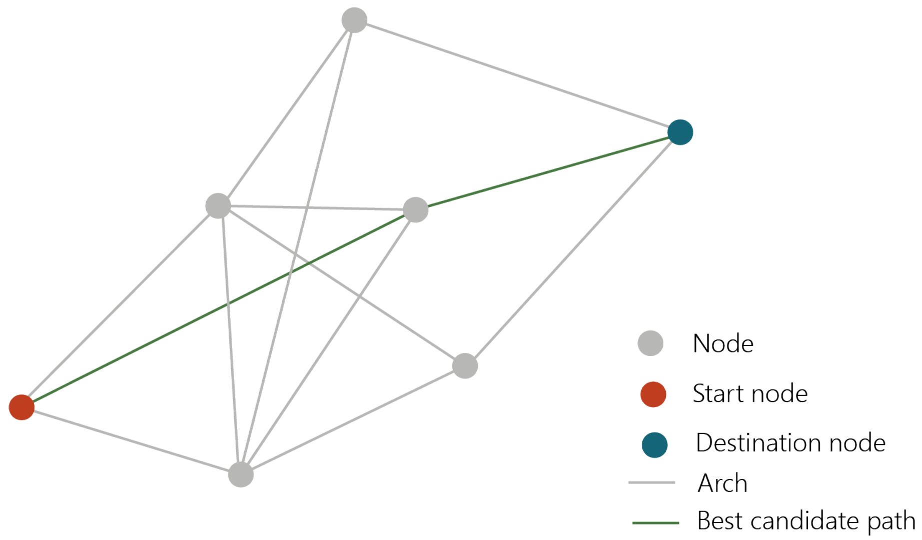

Figure 10.1: Example of a graph representing the problem of finding the shortest path between two points from a network of roads. The optimal solution is marked in green and has the lowest total cost which is equal to the length of the segments added together.

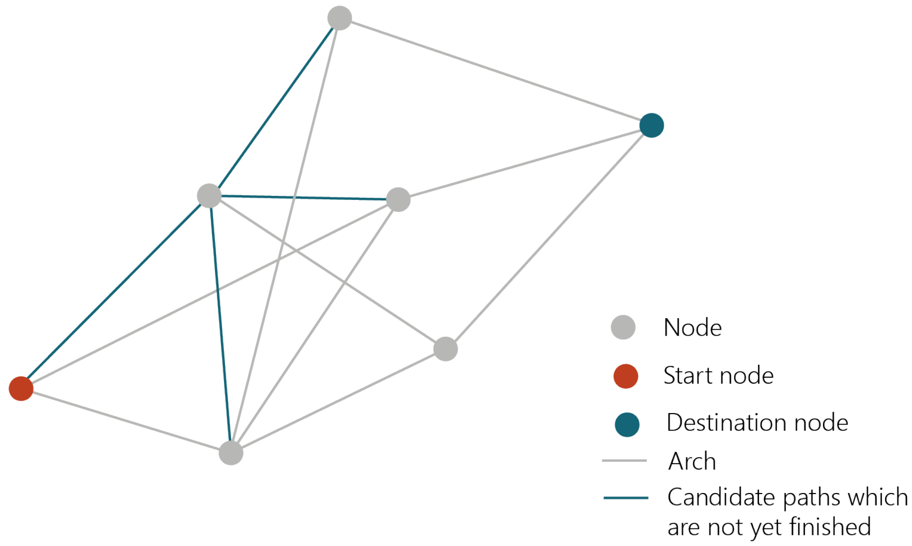

Figure 10.2: The blue line segments show a tree of cost paths which have not yet reached their destination. The weight of each of the three candidate paths is equal to the total length of the included line segments and an estimate of the remaining length needed to reach the destination. If the estimation is good enough the algorithm can quickly discard the paths as there is another more optimal path.

- **Node** - A sub-destination that might be necessary to pass to reach the end destination. For example, a crossing in a road network or a match between a reused element and an element in the designed structure.

- **Arch** - A segment connecting two nodes representing the action necessary to reach the second node while standing on the first one. For example, walking the road between two crossings or creating the next match by replacing a new element in the designed structure with a reused element.

- **Graph** - A set of nodes and arches. For example, a network of roads and crossings or all possible combinations of matches between reused elements and elements in the designed structure.

- **Path** - A set of nodes connecting the start node and end node. For example, the set of roads and crossings of one of the alternative driving paths connecting two points, or one specific combination of several matches between elements in the designed structure and reused elements.

- **Candidate Path** - A started path that might not yet have reached the end destination but might be the solution to the problem.

- **Best Candidate Path** - A finished path which is the optimal solution to the problem.

- **Cost** - The cost is how the optimization objective is introduced into the problem. Each arch is associated with a cost that the action necessary to reach the next node has. If, for example, the objective is to minimise the driving distance between two points, the cost of using a road is equal to the distance between the two connected crossings, and the cost of a finished path is the total length of all passed roads. If, instead, the objective is to minimise the travel time between the two points, the cost is instead formulated as time. The optimization objective used for the design tool is formulated in terms of the CO_2e embedded in the elements and is further explained in Section 10.4 and 10.6.1

- **Heuristic estimate** - Even though the accumulated cost of a non-finished candidate path is low, the future arches that must be passed to reach the destination might have costs that are very high. So, a candidate path that started out promising, might not at all be the optimal solution to the problem. To get an idea of this, heuristic estimates are made to asses the total cost that is likely to be associated with the remaining arches that need to be passed before reaching the destination. Each started candidate path will have one value that makes up the heuristic estimate which uses information about the specific problem to optimistically represent the sum of all future costs.

- **Weight** - All candidate paths have a weight which is used to evaluate their potential. The weight consists of two parts added together where the first is the sum of the known costs of all passed arches and the second part is the heuristic estimate. For a finished path, its weight is equal to its cost since no estimation is needed.

To find the path between the start node and destination node having the lowest cost, the algorithm builds a tree of cost paths, successively expanding the paths by adding nodes until the destination is reached. For the algorithm to be efficient, wasted effort should not be spent on expanding the path to nodes which cannot possibly be part of the optimal solution, and to avoid this informed decisions on which node to expand to next need to be made by evaluating the nodes. This is where the weight becomes important as it determines which paths that are expanded and to which nodes. For the algorithm to find a globally optimal solution the heuristic estimate included in the weight must be optimistic, meaning that it is lower than or equal to the actual cost of the remaining path to the destination (Xu et al., 2023).

Important distinctions of the reuse problem from the general minimum cost path problem are that the end node and destination node, in other words, the first match and last match, are not predefined and the order in which the matches are made does not influence the final solution.

10.4 A* search algorithm applied to the reuse optimization problem

For the reuse optimization problem, two different categories of steel elements are relevant. The first category consists of the elements in the designed structure, which are referred to as target elements. Target elements have a length which is input from the parametric centre line model, sectional forces which are input from the FEM model and embedded CO_2e. The CO_2e are calculated from the area of the auto-designed cross sections and values for recycled steel from the climate data base by Boverket. The second category consists of the reused elements, which are referred to as inventory elements. Inventory elements have a length, sectional properties and a material grade which are all defined in Excel files. They also have embedded CO_2e which are calculated from their volumes and values from the climate database by Boverket for reused steel (Boverket, 2023b). Definitions of both target elements and inventory elements are presented in Figure 10.3.

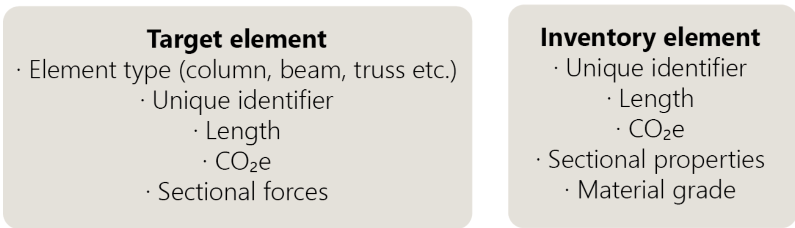

Figure 10.3: Definitions of target elements and inventory elements.

When matching target elements with inventory elements, two questions need to be answered. 1) Which inventory elements are allowed to replace which target elements and 2) how can this be done as efficiently as possible?

To answer the first question some requirements need to be formulated for each target element and checks performed to establish which of the inventory elements fulfill those requirements. This is the first part of the matching tool and the output from this is a compatibility matrix $\mathbf{C}$ of zeros and ones with one row for each target element t and one column for each inventory element i. If an inventory element fulfils the requirements formulated for target element, then $C_{t,i}$=1. If the inventory element does not fulfill the requirements, then $C_{t,i}$=0. The checks performed to determine the compatibility between the elements can, for example, be to ensure that the inventory element is long enough to replace the target element and that the inventory element passes the Eurocode verification for the sectional forces of the target element. These checks are described greater detail in Section 10.1 and 10.5.1 and an example that further explains the compatibility matrix is presented in Section 10.6.

The second question is answered by using the A* optimization algorithm which is the second part of the matching tool. The goal of replacing the target elements with inventory elements is to not use more material than necessary, in other words, to achieve as high utilisation rates as possible while generating as little waste as possible. One of the main reasons for reusing steel elements is to achieve a lower environmental impact, which can be measured in the amount of CO_2e embedded in the material. The amount of CO_2e embedded in a structural element is directly proportional to its weight. So, an element with a long scrap piece and large cross section leading to a low utilisation rate will have more embedded CO_2e than a structurally optimized element with a short scrap piece. Therefore, the total amount of CO_2e of the structure, including scrap pieces, is chosen as the single objective for the optimization.

Two other constructs important for understanding the algorithm are *assignments* and *candidates* which are defined in Figure 10.4. An assignment can not be made between a target element and inventory element which are not compatible with each other. So, all candidates are possible solutions and will never contain assignments that would not be allowed to make in reality. Since the optimization objective is formulated in terms of CO_2e, the cost of making an assignment is equal to the amount of embedded CO_2e in the replacing inventory element. The cost of not being able to make an assignment for a target element is equal to the amount of embedded CO_2e in a new recycled element having the auto-designed cross section. The weight of a candidate is the sum of the known embedded CO_2e of all performed assignments and an optimistic estimate of the sum of the embedded CO_2e of the assignments that have not been made yet. How this estimate is calculated will be further explained in Section 10.6. The best candidate is the finished candidate having the lowest total amount of embedded CO_2e, including scrap pieces.

Assignment
· Index of target element to be replaced
· Index of inventory element repalcing the target element
· Cost

Candidate
· List of assignments
· Weight
· List of indices of inventory elements available after the already performed assignments, including usable cut-off parts.
· List of scrap peices

Figure 10.4: Definitions of important constructs included in the algorithm.

An overview of how the algorithm has been adjusted for the reuse optimization problem is presented in Figure 10.5 and the algorithm is described in more detail using an example in Section 10.6.

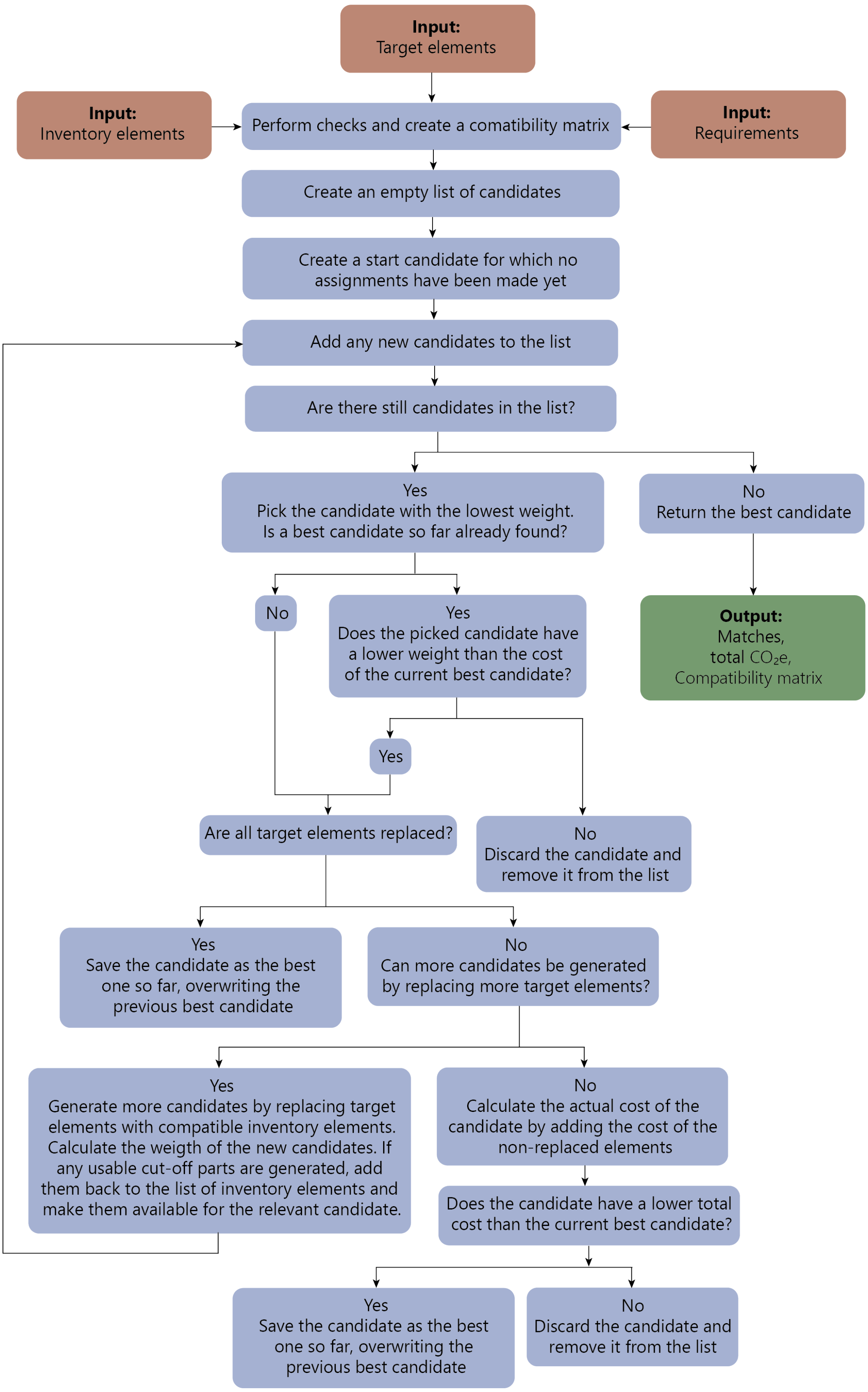

Figure 10.5: Overview of how the A* algorithm has been adjusted for the reuse optimization problem.

10.5 Compatibility checks

When evaluating whether an inventory element can be considered for replacing a target element or not several checks can be performed depending on the specific project. Also, the requirements on the inventory elements might need to be updated along the design process as more information is gained. The checks that are initially included in the tool and used for the intuitive phase are presented in Table 10.1. Additional checks added along the design process as more information about the project is gained is presented in Section 12 describing the intentional phase.

Table 10.1: Checks performed to determine compatibility between target elements and inventory elements

Type of requirement	Check
Practical	Is the type of cross section allowed?
Geometric	Is the inventory element long enough?
Structural verification in ULS according to SS-EN 1993-1-1	Is the utilisation below 1.0?
	Is the utilisation above a set minimum limit?
Structural verification in SLS	Is the deflection of beams within allowed limits?

The first check is to ensure that the inventory element has the right type of cross section, which can be specified by the user of the tool for each type of target element. When using the tool for the design sketches during the intuitive phase, the target elements are divided into Beam elements, Column elements and Truss elements. For Beam elements, only inventory elements having I-sections can be assigned, for Column elements inventory elements having either I-sections or CHS-sections can be assigned, and for Truss elements only inventory elements built up from L-sections can be assigned.

Secondly, a check is performed to ensure that the inventory element is long enough to replace the target element.

Thirdly, structural verification in the Ultimate Limit State is performed according to Section 10.5.1 to ensure that the resistance of the inventory element is adequate. The verification is only valid for elements of cross section classes one, two and three. So, if an inventory element is in cross section class four, it will be discarded by the tool. If the maximum utilisation in ULS is above 1.0, the inventory element is not compatible with the target element. In Section 3.1.5 some reflections from representatives of Stena Stål and MVR concerning reused elements having very low utilisation rates are presented. They are concluding that, depending on the utilisation rate, it can be more sustainable to not use reused elements but rather leave them for another project or for recycling (SBI Stålbyggnadsinstitutet, 2022). In Section 4.3, similar reflections are shared in the interview with the structural engineers involved in reuse projects in the UK, where they usually limit the minimum utilisation to 70%Ȧlso, the cost aspect of having low utilisation rates is brought up during the interview as the cost of reused steel is set per kilogram. Additionally, in the interview with Linda Cusumano in Section 4.2, it is discussed that using unnecessarily large elements can have consequences in the detailing, as welds of end plates will become unnecessarily long leading to additional costs and labour. Therefore, a check is also added to ensure that the utilisation rate in ULS of the inventory element is not too low. The minimum allowed utilisation rate is added as an adjustable input parameter to the tool.

The final check that is performed is to ensure that inventory elements replacing target Beam elements do not have a deflection that is too large. The deflection is calculated using elementary cases using a line load converted from the maximum shear force at the supports of the target element of the frequent load combinations.

10.5.1 Structural verification in Ultimate Limit State

For matching tools to be useful in general cases they, according to Bukauskas, need to perform structural verification such as normal force, bending, shear, buckling and connection checks. The effect that the reused sections have on global behaviour also needs to be accounted for. This is especially important for statically indeterminate structures subjected to load redistribution and for checks of global buckling, dynamics and serviceability limit state (Bukauskas et al., 2017).

The focus of the verifications is on making resistance checks of individual structural members according to SS-EN 1993-1-1. The reliability of the results will be discussed for the design sketches, taking load redistribution into account. There will be an ambition to limit the final design to a geometry not prone to extensive redistribution of forces. As changes in the stiffness of stabilising elements have a large impact on the global distribution of horizontal forces, these elements are excluded from reuse consideration during the intuitive phase. A separate manual matching procedure is developed in the intentional phase to account for redistribution of horizontal forces. Global stability checks, global buckling and dynamic checks are out of the scope of the thesis. Serviceability is considered by making hand calculations of the deflection of beam elements, as described in Section 10.1. An overview of the checks performed for each type of target element is presented in Table 10.2 and the assumptions made for the checks are then presented below.

For columns, it is checked that the design value of the flexural buckling resistance of the inventory element is greater than the compressive normal force of the target element. It is assumed that the elements have hinged connections at both ends and that no lateral restraints are present in any direction. So, the check is only performed for buckling around the weak axis. It is also checked that the bending and shear force resistance is greater than the second order moment and shear force from initial bow imperfections. For calculating the bending resistance a reduction is made to account for the simultaneous presence of normal force. It is assumed that the moment will be around the weak axis and no check of lateral torsional buckling is performed. It is assumed that the compressive force is much greater than the

Table 10.2: Structural checks performed depending on the type of target element

Type of target element	Structural checks	Section in SS-EN 1993-1-1
Column	Flexural buckling	6.3.1
	Second-order effects	5.3.2, 6.2.5, 6.2.6, 6.2.9
Beam	Shear force	6.2.6
	Bending	6.2.5, 6.2.9
	Flexural buckling	6.3.1
Truss	Tension	6.2.3
	Flexural buckling	6.3.1
	Second-order effects	5.3.2, 6.2.5, 6.2.6, 6.2.9

second-order bending moment. So, the cross section class is determined based on the assumption of uniform compression.

For the beams, it is checked that the shear force capacity of the inventory element is greater than the maximum shear force of the target element. It is also checked that the bending capacity is greater than the maximum moment. In a similar manner as for the columns, a reduction of the moment capacity is made to account for the simultaneous presence of any normal force transferring the wind load to the stabilising elements. The presence and location of such a normal force would in reality depend on the detailing of the slabs and connection to the rest of the system. But in this case, it is taken from the FEM-model where stability is created from having fictitious diagonals and beams in y-direction, and only the weight of the slabs is considered and an applied load. For compressive normal forces, a flexural buckling check is also made. The beams are assumed to be simply supported and continuously restrained by the floor slabs in the lateral direction, so lateral torsional buckling does not need to be checked and the flexural buckling check is performed for buckling around the strong axis.

To assess the need for performing an interaction check according to Section 6.3.3 in SS-EN 1993-1-1 taking instability into account, the beam having the maximum compressive normal force is studied in the FEM model created from the base centre line model. A verification using these sectional forces is then performed in FEM-Design for an inventory element with cross section HEB300, since it is the element with the largest utilisation rate which passes the checks. A comparison is made between the interaction check taking instability into account and the moment check with reduced capacity due to the simultaneous presence of normal force. As seen in Table 10.3 the difference in utilisation between the two checks is only two percentage points, which is reasonable since the compressive force is small compared to the bending moment and there is no risk of lateral torsional buckling. Therefore, the interaction check taking instability into account is not included for simply supported beams in the design tool.

Since the normal force is small compared to the bending moment, the cross sec-

Check	Section in SS-EN 1993-1-1	Utilisation [-]
Interaction	6.3.3	0.86
Moment with capacity reduction due to normal force	6.2.5, 6.2.9	0.84

Table 10.3: Comparison between the calculation which is included in the tool and an interaction check which is not included in the tool

tion class of beams is determined based on the assumption of pure bending, and torsional-flexural buckling is assumed not to be governing.

The only inventory elements which are allowed to replace the truss elements are the sections made from bolting four L-sections together from the inventory inspired by the mounting hall. If bolt holes reduce the cross sectional area by more than 15 % the net cross sectional properties should be used (Brown et al., 2019), which is the case for these elements. Therefore the net cross sectional properties, as shown in Figure 10.6, are used for the verification.

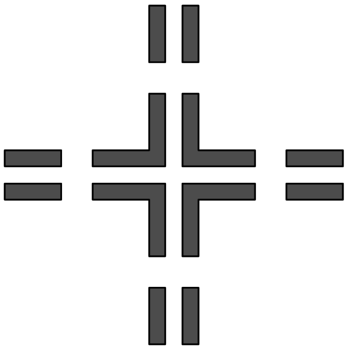

Figure 10.6: Net cross section used for the verification.

According to Section 6.4.4 in SS-EN 1993-1-1, there is a minimum allowed distance between the bolts for full interaction between the L sections to be assumed. It is here assumed that, if this minimum distance is not already fulfilled by the existing bolt holes, more bolts can be added before mounting the elements in the new structure, which in reality would need to be verified. This meaning that full interaction between the sections is assumed for the calculations.

For truss elements in compression, the same checks and assumptions as for columns are used and the cross section class is determined based on the assumption of pure compression. The buckling length of the elements is assumed to be equal to their own lengths, so no global analysis of buckling modes for the truss is performed. For truss elements in tension, it is checked that the normal force resistance of the inventory element is greater than the normal force of the target element. Global truss calculations according to Section 6.4 in SS-EN 1993-1-1 are not considered by the tool.

10.6 An example describing the application of the A* algorithm

To further explain how the A* algorithm is applied to the reuse optimization problem a basic example of three target elements and three inventory elements is presented below. For the sake of simplicity, the fact that cut-off parts can be used to replace more target elements is not taken into consideration here, but its implementation will be described in Section 10.6.1.

The target and inventory elements are visually represented by lines in Figure 10.7. Indices representing target elements are referred to as t and indices representing inventory elements as i. Descriptions of which properties each element contains are presented in Figure 10.3, but since the cost representing the amount of embedded CO_2e is of great importance for explaining the algorithm it is the only property that is written explicitly in the following images with fictitious numbers used for this specific example.

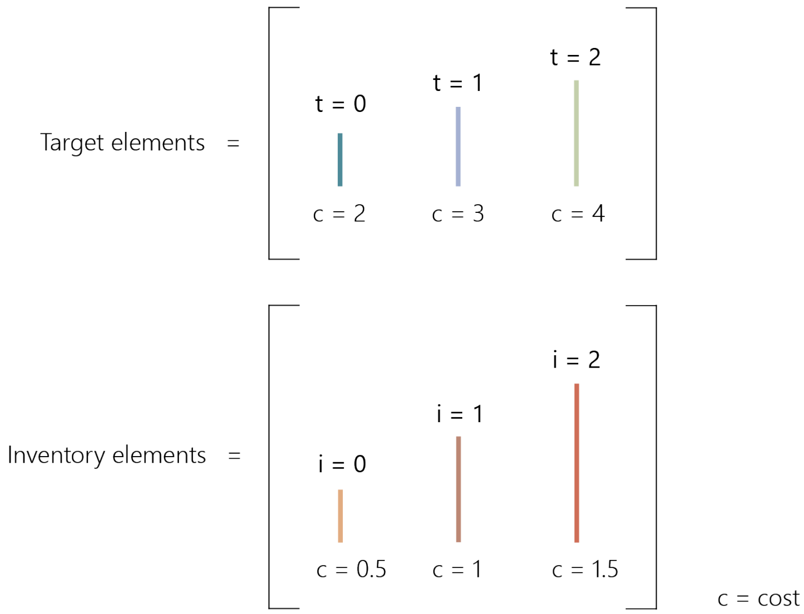

Figure 10.7: Target and inventory elements.

The first part of the algorithm is to investigate which of the inventory elements are compatible with which of the target elements, using the checks described in Section 10.1. The result is compiled in a compatibility matrix **C** where the rows represent target elements and columns represent inventory elements. If inventory element i passes the checks for target element t, then $C_{t,i}$=1. If it does not pass the checks than $C_{t,i}$=0. For this example, the compatibility matrix is presented in equation 10.1 and contains fictitious results from the checks.

$$\mathbf{C} = \begin{bmatrix} 1 & 0 & 1 \\ 0 & 1 & 0 \\ 0 & 1 & 1 \end{bmatrix} \tag{10.1}$$

The algorithm will then perform several steps s where assignments creating matches between target elements and inventory elements are made and combined into several candidates. Definitions of assignments and candidates are presented in Figure 10.4. In step s=0 an empty start candidate is created for which no matches have been created yet. In step s=1 the candidates will contain one match, in step s=2 the candidates will be combinations of two matches and in step s=3 the candidates will be combinations of three matches. Since there are three target elements, the maximum amount of steps to be performed by the algorithm is four.

Steps s=0 and s=1 for the example is shown in Figure 10.8 where it is seen that each candidate has a weight w which is the sum of the known cost c of the already created match and an optimistic estimate of the cost of creating the two remaining matches using a heuristic function h. This estimate is made by, for each target element which has not yet been replaced, adding the lowest cost of the remaining inventory elements with compatibility. If there is a target element with no compatible inventory element, the cost of the target element is added instead.

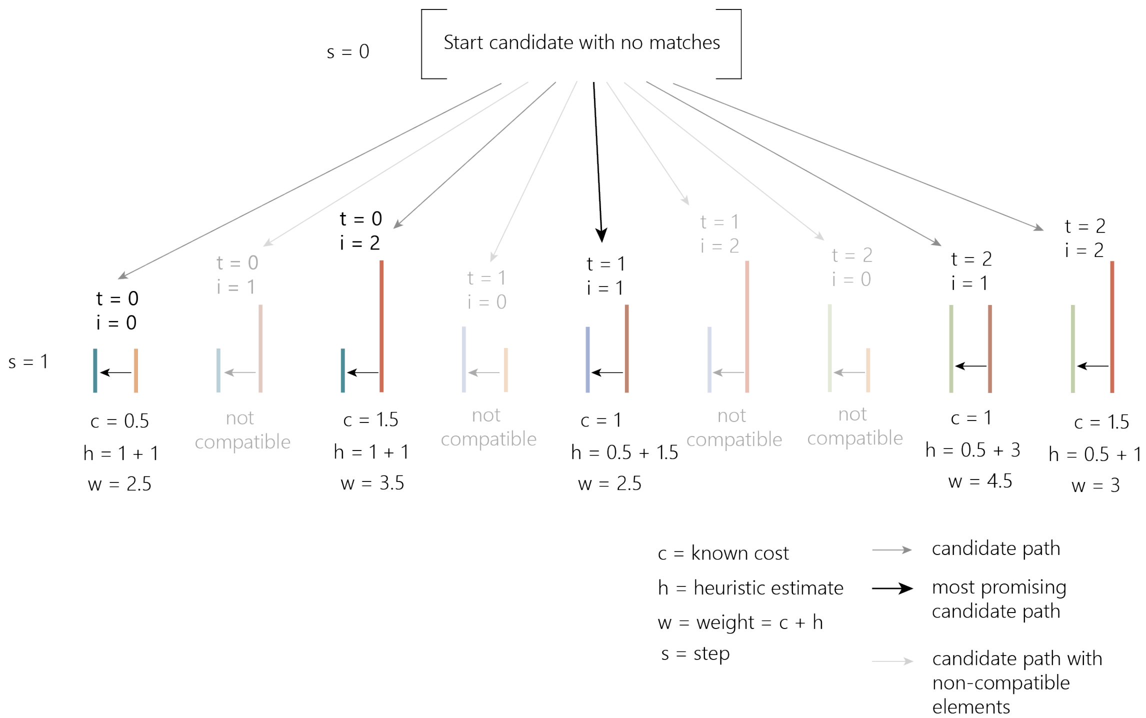

Figure 10.8: Candidates after making step zero and step one. Gray candidates contain matches where the inventory element has not passed the relevant checks formulated for the target element.

The first matches are generated by creating every possible combination between the target elements and inventory elements. However, some of these matches will be between elements which are not compatible. For example, it can be seen that the match between target element $t = 1$ and inventory element $i = 0$ will not be possible since the inventory element is too short. Also, the match between target element $t = 0$ and inventory element $i = 1$ will not be possible since the inventory element either has the wrong type of cross section, has a utilisation above 1.0, has a utilisation below the set minimum value or has a deflection that is too large. To create an efficient algorithm, candidates containing non-compatible matches will never be generated and will not be included in the images following Figure 10.8.

In summary, the compatibility matrix is used both for determining which candidates can be generated and for creating the estimates determining which candidates are most likely to be worth continuing to expand. The number of candidates that are created in step one is equal to the number of ones in the compatibility matrix. So, for this example, five alternative candidates are generated.

In step two, the candidate having the lowest weight is chosen to be expanded further as it is most likely at this stage that it will provide the optimal solution. Since, in this example, several candidates have the same weight, the one furthest to the right is chosen which has to do with computational efficiency and how the candidates are arranged in the code, but is not relevant to the conceptual understanding of the algorithm. The chosen candidate is then expanded by creating all compatible matches between the target elements which has not yet been replaced and inventory elements which have not already used. In other words, the compatibility matrix will change for every match that has already been made since the rows representing replaced target elements and columns representing used inventory elements are removed. The most promising candidate after performing step one in the example is the one starting by replacing target element $t = 1$ by inventory element $i = 1$ and its compatibility matrix $\mathbf{C}^{\mathrm{s,t,i}}$ is presented below. It is seen that three ones remain, meaning that for the next expansion, three new candidates are generated as shown in Figure 10.9.

$$\mathbf{C}^0 + t_{replaced} = 1, i_{replacing} = 1 \rightarrow \begin{bmatrix} 1 & 0 & 1 \\ 0 & 1 & 0 \\ 0 & 1 & 1 \end{bmatrix} \rightarrow \tag{10.2}$$

$$\mathbf{C}^{1,1,1} = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix} \tag{10.3}$$

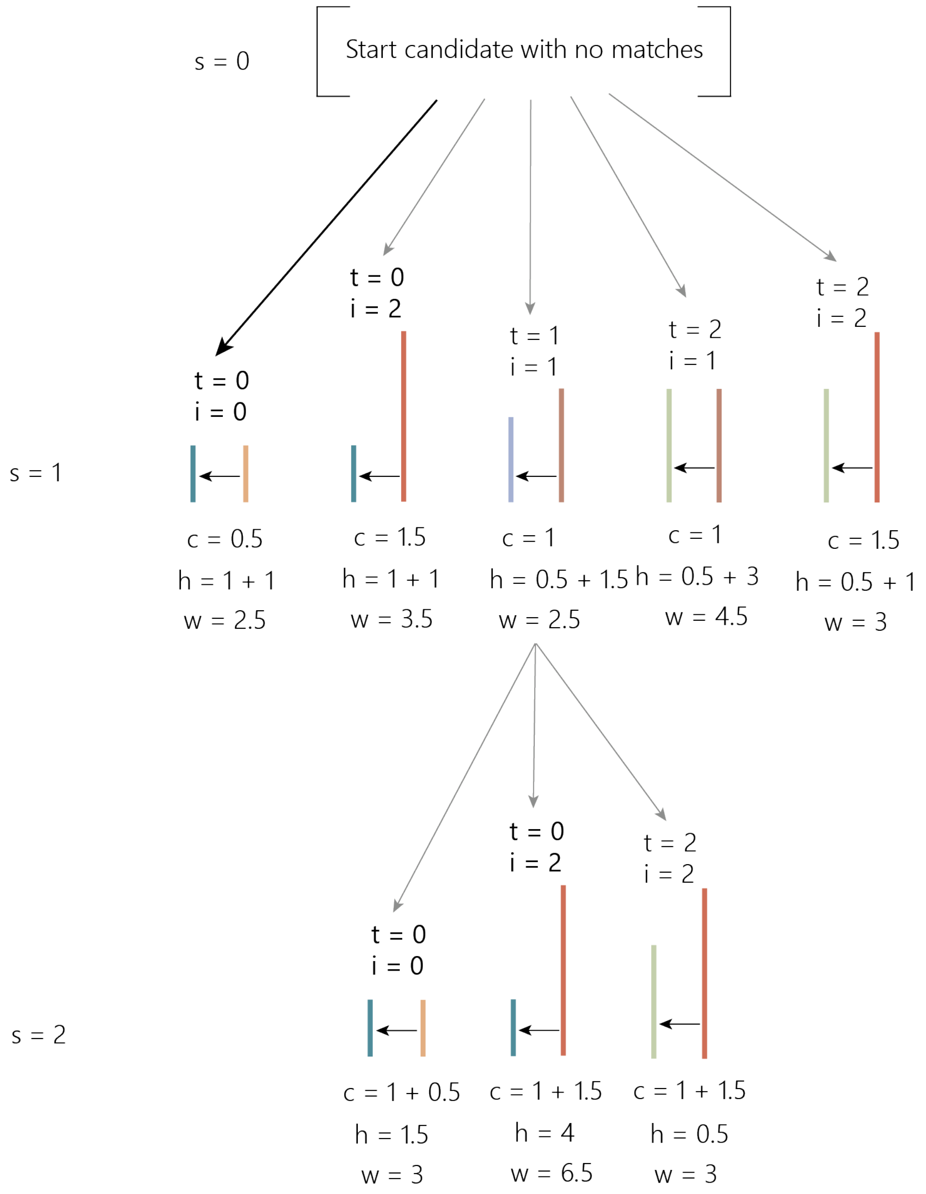

Figure 10.9: Candidate paths after making steps 0,1 and 2.

After the most promising candidate from step one is expanded, it is seen that the candidate having the lowest weight is still one where only one match has been made, replacing target element $t = 0$ by inventory element $i = 0$. Therefore, this candidate is expanded using its resulting compatibility matrix generating three new candidates as shown in Figure 10.10.

$$\mathbf{C}^0 + t_{replaced} = 0, i_{replacing} = 0 \rightarrow \begin{bmatrix} \cancel{1} & \cancel{0} & \cancel{1} \\ \cancel{0} & 1 & 0 \\ \cancel{0} & 1 & 1 \end{bmatrix} \rightarrow \tag{10.4}$$

$$\mathbf{C}^{1,0,0} = \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix} \tag{10.5}$$

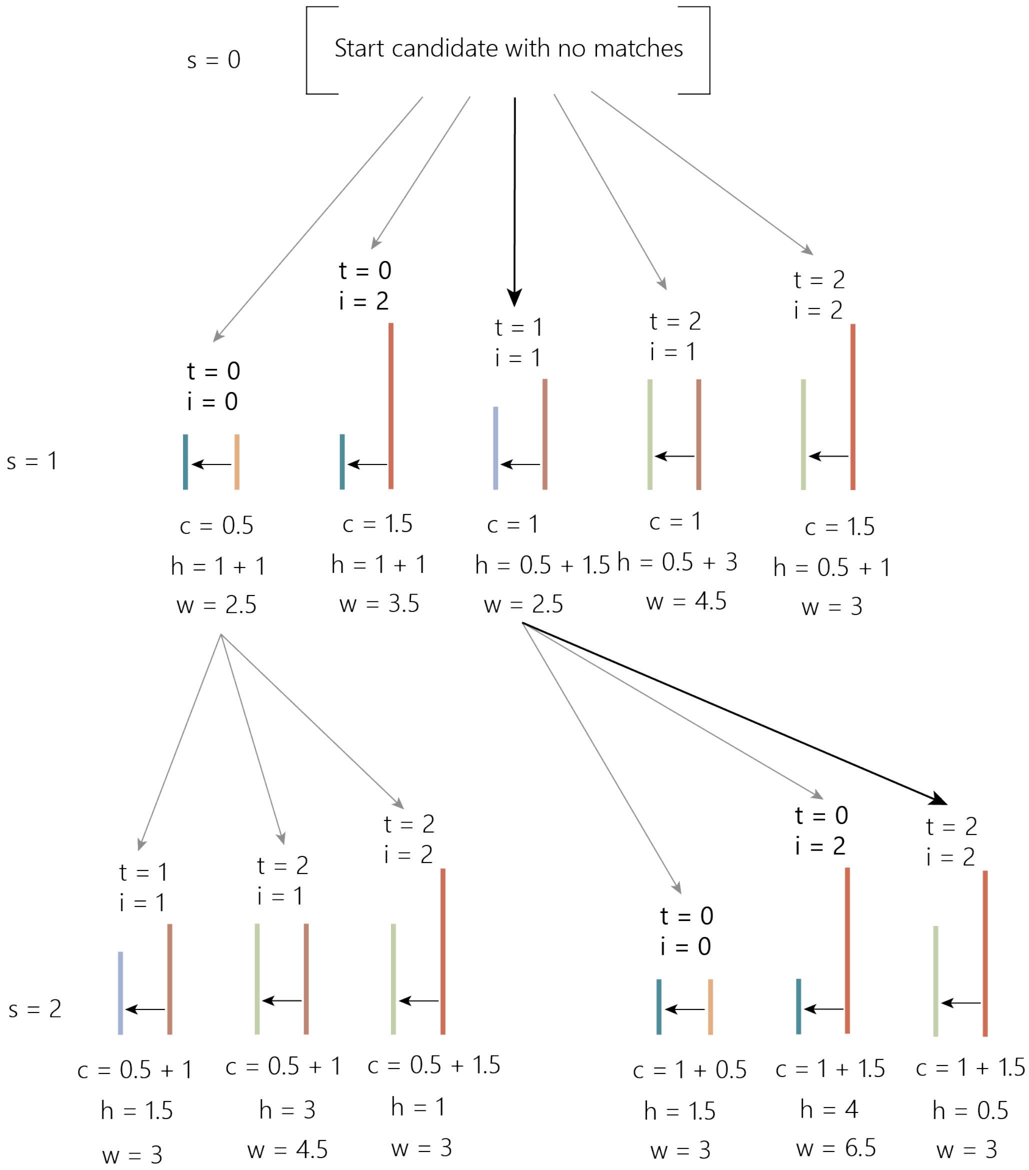

Figure 10.10: Candidate paths after making step zero, one and the second expansion of step two

Again, the candidate having the lowest weight is chosen and expanded one more time. Now the most promising candidate contains two matches, so the next expansion will be in the third and last step.

$$\mathbf{C}^{1,1,1} + t_{replaced} = 2, i_{replacing} = 2 \rightarrow \begin{bmatrix} 1 & \cancel{1} \\ \cancel{0} & \cancel{1} \end{bmatrix} \rightarrow \tag{10.6}$$

$$\mathbf{C}^{2,1+2,1+2} = \begin{bmatrix}1\end{bmatrix} \tag{10.7}$$

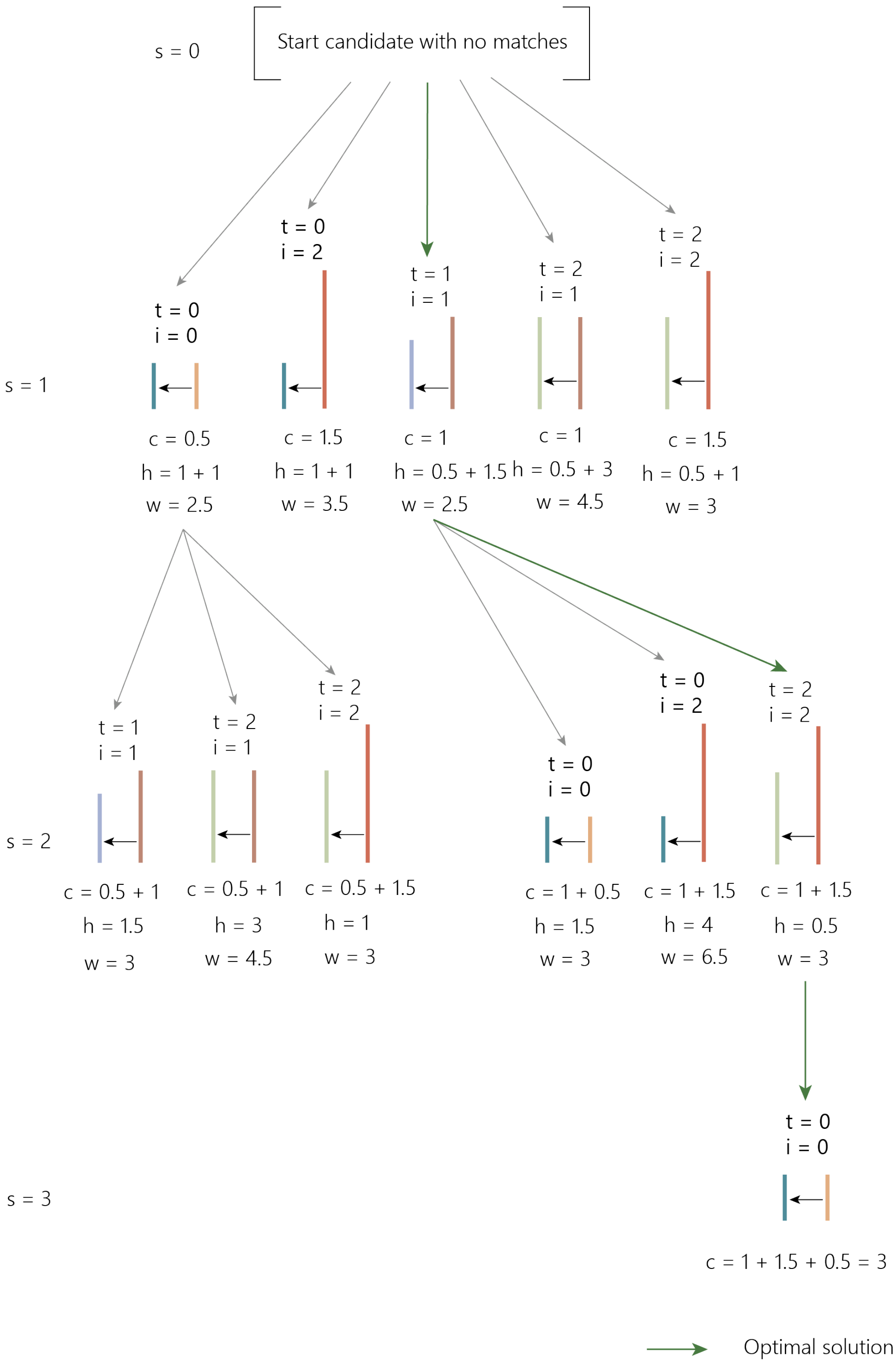

Figure 10.11: Candidate paths after making step zero, one, two and three.

It is now seen that the total cost c of the finished candidate is not larger than the weight w of any of the other candidates. Therefore, the other candidates are discarded as they can not improve the already found solution. If several solutions exist with the same total final cost, the first one that is found is chosen for the sake of efficiency.

It can be argued that the second expansion made after step one was not necessary since it would have resulted in the same matches as the chosen solution, but in a different order. Code improvements to deal with these types of problems aiming to improve the computational efficiency of the algorithm will be presented in Section 10.7.

10.6.1 Reusable cut-off parts

One way of further improving the solution is to also consider the parts of the inventory elements which has been cut off for replacing other target elements. To account for this the algorithm is modified in such a way that cut-off parts which are considered long enough to have potential for further reuse are added back to the set of inventory elements and made available for their respective candidate. The minimum length is taken as an adjustable input parameter to the tool.

To illustrate this, the candidate starting by a match between target element $t = 0$ and inventory element $i = 2$ from the example presented in Section 10.6 is studied. It is seen that only one-third of the length of the inventory element is needed for the match and the cut-off part can be re-inserted into the list of inventory elements as shown in Figure 10.13.

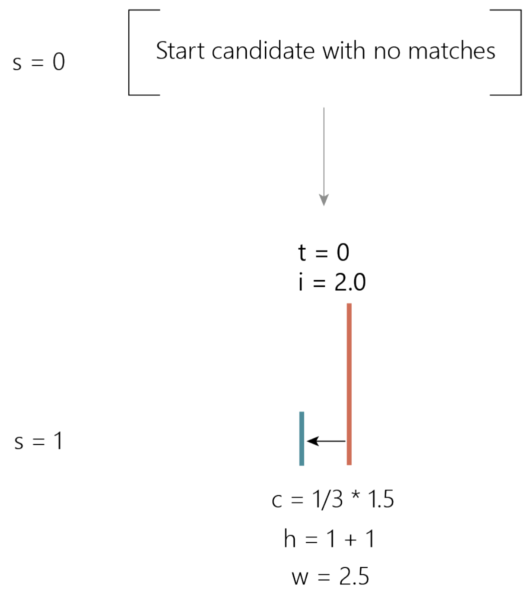

Figure 10.12: The candidate starting by replacing target element $t = 0$ by inventory element $i = 2$

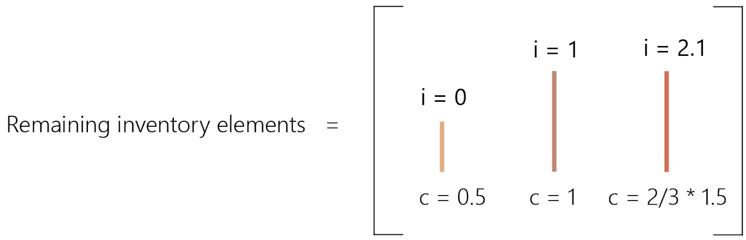

Figure 10.13: The inventory elements after re-inserting the cut-off part.

As before, the row representing the replaced target element is removed from the compatibility matrix along with the column representing the used inventory element.

$$\mathbf{C}^0 + t_{replaced} = 2, i_{replacing} = 2 \rightarrow \begin{bmatrix} \cancel{1} & \cancel{0} & \cancel{1} \\ 0 & 1 & \cancel{0} \\ 0 & 1 & \cancel{1} \end{bmatrix} \rightarrow \tag{10.8}$$

$$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{10.9}$$

To account for the cut-off part, a new column is then created to be added to the matrix. Since the cross section type, cross sectional properties and material grade will be the same for the cut-off part as for the original element, the only additional check to be performed when creating the new column is to ensure that the new element is long enough to replace each target element.

$$\mathbf{c}_{\text{t,cutoffindex}} = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \tag{10.10}$$

The new compatibility matrix is then created by adding the new column to the matrix after the relevant rows and columns have been removed. The matrix in Equation (10.9) combined with (10.10) thus yield:

$$\mathbf{C}^{1,0,2} = \left[\begin{array}{cc:c} 1 & 0 & 0 \\ 0 & 1 & 1 \end{array} \right] \tag{10.11}$$

After creating the remaining two matches it can be seen that a solution with a smaller total amount of embedded CO_2e is found.

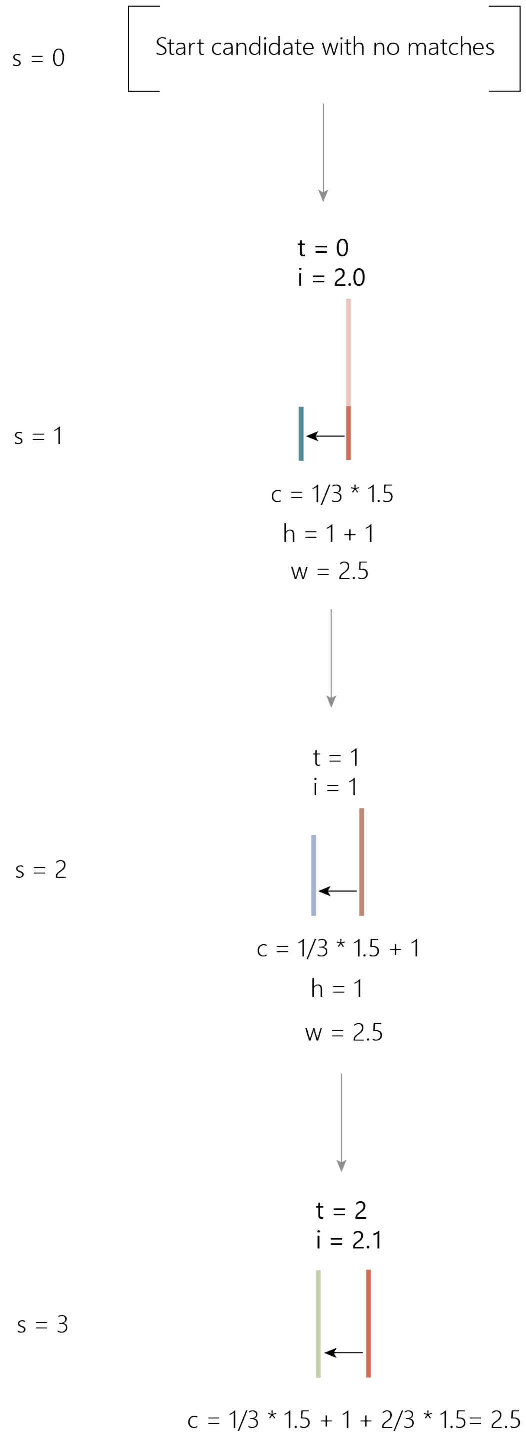

Figure 10.14: The best finished candidate starting by replacing target element $t = 0$ by inventory element $i = 2$.

Initially, when implementing the possibility of re-inserting cut-off parts into the the inventory, the cost of creating a match was decided depending on whether the cut-off part was long enough to have the potential of being reused elsewhere or not. If it was long enough, only the CO_2e embedded in the part of the element which was used were included in the matching cost. If it was not long enough the CO_2e embedded in the entire inventory element, including the scrap part, were included.

However, it was observed that the algorithm rather often assigned very long inventory elements to rather short target elements, with no guarantee that the cut-off part would be chosen to be used elsewhere in the same project. This could be an issue if another project needs very long elements, since they might not exist anymore because they have been cut into parts. So, even though the initial way of defining the matching cost might be beneficial for the environmental impact of the specific project, there is a great risk that it will be unfavourable for the environmental impact seen as a whole. Therefore, the definition of the matching cost of the tool was updated to include the CO_2e embedded in the entire inventory element regardless of the length of the cut-off part. This to avoid cutting long inventory elements if there are shorter compatible elements available.

10.7 Computational efficiently

For the tool to be practically applicable in a design process it has to both be able to provide reliable results and have a short run time. For larger amounts of target elements, the run time of the algorithm proved to be a problem, leading to some adjustments and compromises with the ambition of maximising the trade-off between speed and results accuracy.

Algorithmic complexity is a measure of the run time of an algorithm in relation to the size of the problem that is solved. Big-O notation, commonly referred to as *order of growth*, is a common way to asses the complexity of an algorithm and signifies its worst-case performance (Nasar, 2016). For the case of the search being uninformed, in other words that every possible combination of matches is examined, the time complexity of the A* search algorithm is $O(b^d)$, meaning that it is performed in exponential time. d signifies the depth of the solution, which for the reuse optimisation problem means number of matches. b is a branching factor and signifies the number of branches generated for each node expansion. However, the search is not uninformed as the heuristic estimates enable the algorithm to discard node expansions. So, the complexity of the algorithm depends on the quality of the heuristics and, if the error of the estimate is small enough, the search is performed in polynomial time which is faster than exponential time (Javatpoint.com, nd). This means that a precise and realistic heuristic estimate will shorten the run-time, as the number of candidates that are investigated unnecessarily is reduced.

How to compute the estimate h has been iterated several times during the development of the tool. Initially, it was created by taking the lowest cost of the remaining inventory elements and applying it to all non-replaced target elements.

$$h_0 = c_{\text{min}} \cdot n_{\text{nonReplaced}} \tag{10.12}$$

Where:

h_0 = First iteration of the heuristic estimate.
c_{min} = The lowest cost of the remaining inventory elements.
$n_{\text{nonReplaced}}$ = Number of non-replaced target elements.

In the next iteration, a list of costs is created and sorted in such a way that the lowest cost is put first in the list and the highest last. Then, as many of the lowest costs as there are non-replaced target elements are added together. So, for example, if there are three non-replaced target elements, the three lowest costs in the list are chosen and added together.

$$h_1 = \sum_{i=0}^{n_{\text{nonReplaced}-1}} c_i \tag{10.13}$$

Where:
h_1 = Second iteration of the heuristic estimate.
c_i = The cost with index i in the list $\mathbf{c_{min}}$, which contains the costs of all remaining inventory elements in increasing order.
$\mathbf{c_{min}} = \begin{bmatrix} c_0 & c_1 & \dots & c_{\text{nRemaining}-1} \end{bmatrix}$, $c_i < c_{i+1}$.
$n_{\text{Remaining}}$ = Number of remaining inventory element.
$n_{\text{nonReplaced}}$ = Number of non-replaced target elements.

For the chosen iteration of the estimate h, consideration is also taken to the compatibility between the elements. The estimate is then created by, for each target element which has not yet been replaced, adding the lowest cost of the remaining inventory elements with compatibility.

$$h_2 = \sum_{i=0}^{n_{\text{nonReplaced}-1}} c_{\text{minCompatible},i} \tag{10.14}$$

Where:
h_2 = Third and chosen iteration of the heuristic estimate.
$c_{\text{minCompatible},i}$ = The lowest cost of the remaining inventory elements for which there is a one on the row corresponding to the investigated target element in the compatibility matrix **C**.
$n_{\text{nonReplaced}}$ = Number of non-replaced target elements.

This estimate proved efficient for improving the run time and will ensure that a globally optimal solution is found for the original inventory elements. However, there is a risk that candidates finding better ways to use the cut-off parts are discarded. This problem and other future improvements of the algorithm are discussed further in Section 15.3.

An observation from the example presented in Section 10.6 is that some of the candidates contain identical matches but in different orders, which makes the branching factor b of the problem unnecessarily large. Examples of these candidates are highlighted in red in Figure 10.15.

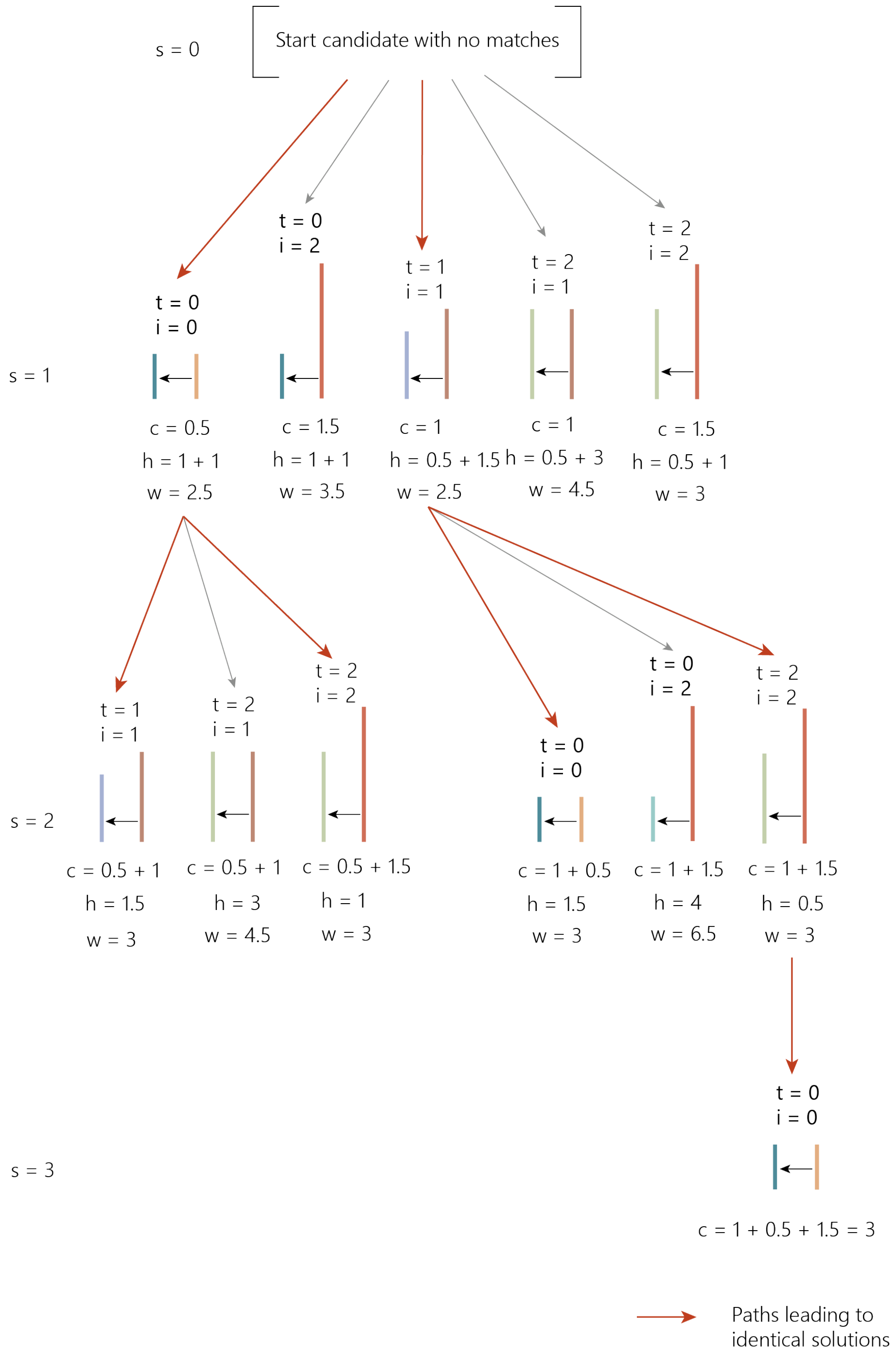

Figure 10.15: Candidates with identical matches in different orders.

This problem is avoided by restricting the matches depending on the index of the target element considered for creating the next match compared to the index of the target element of the last performed match of the candidate. If the index of the target element considered for creating the next match is smaller than the index of the target element of the last performed match, then only matches with cut-off parts are allowed. If, instead it is larger, matches with both original inventory elements and cut-off parts are allowed.

$$t^{s+1} < t^s \rightarrow \text{only cut-offs considered}$$
$$t^{s+1} > t^s \rightarrow \text{all inventory elements considered}$$

Following these rules, it is seen that the last match of the found solution of the example would not have been possible as the last target element has index $t^3 = 0$ but the index of the previously matched target element is $t^2 = 2$ which is larger (see Figure 10.15). Since this match is not allowed, the candidate starting by replacing target element $t = 0$ by inventory element $i = 0$ is more promising and the algorithm would have expanded that candidate instead. In step s=2, it is now seen the only match that makes a third match possible is to replace target element $t = 1$ by inventory element $t = 1$. In other words, these rules are a way to apply logic to force the algorithm to make the matches in the same order as the target elements are sorted, leading to no duplicate candidates.

In Figure 10.16, the run time is plotted as a function of the amount of found matches for the basic design. It is observed that the run time is rather short for fewer matches than ten, but fast becomes unreasonably long for a larger number of matches than eleven.

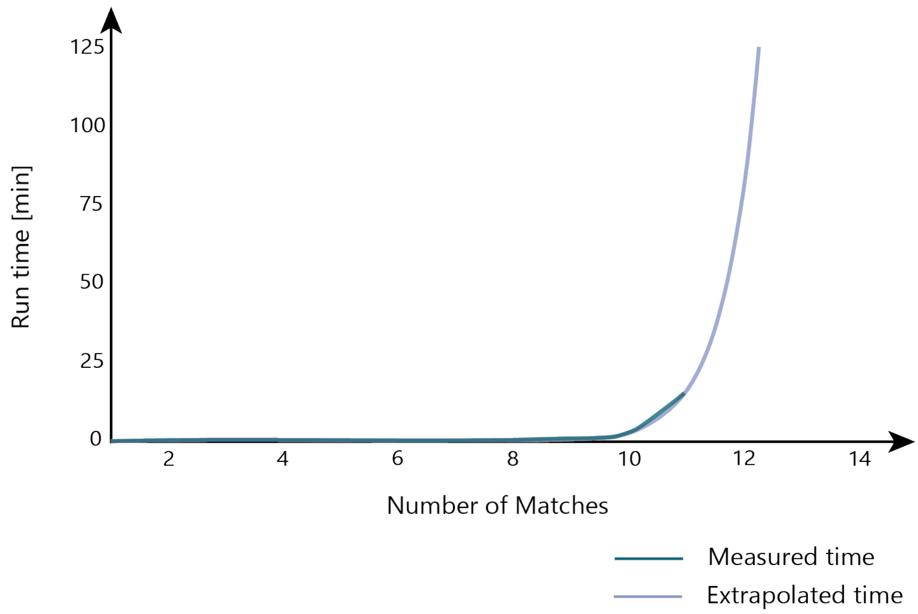

Figure 10.16: Run time as a function of the number of found matches. A maximum number of 57 target elements were used as input for the algorithm leading to eleven matches.

This problem can be solved by first sorting the target elements in such a way that the elements with the largest environmental impact are put first in the list and the elements with the smallest environmental impact last. Then the target elements are divided into sub-groups for which the optimization is run separately. An investigation of how this affects the accuracy of the result is presented in Table 10.4, where

57 target elements are used as a reference and three different group sizes are tested for comparison. 57 is used as a reference number since it is the largest amount of target elements for which the algorithm takes less than one hour to run. There, it is seen that one match is lost when using a group size smaller than 15, leading to a slightly higher value for the total amount of CO_2e embedded in the structure. However, the difference in the embedded amount of CO_2e is less than 1% of the total number.

Table 10.4: Investigation of how the accuracy of the result is affected by performing the optimization for separate groups of target elements.

Group size	**Number of matches**	**Total** CO_2e [kg]	**Increase** CO_2e [%]	**Run time**
57	11	22033	-	15.3 min
15	11	22033	0	2.5 min
10	10	22212	0.8	< 1 s
5	10	22212	0.8	< 1 s

Also, an investigation of how the amount of matches affects the run time for different sizes of the optimization groups is presented in Figure 10.17 - 10.18. It can be seen that for a group size of five, the run time is very short and its relation to the number of matches is almost linear. For a group size of ten, the run time is longer and a large jump can be observed in the graph. This is because the run time of each optimization group will depend both on the depth d representing the number of found matches and the branching factor b representing how easy it is for the algorithm to find which inventory element to use for each match. For the group representing the jump in the graph, a match was found for all ten target elements, meaning that d is maximised, and most of the target elements were compatible with the same inventory elements. So, many expansions leading to new candidates to evaluate had to be done by the algorithm before a solution could be found, meaning a large b. For the other groups, only a few matches were found and the target elements were usually not compatible with the same inventory elements.

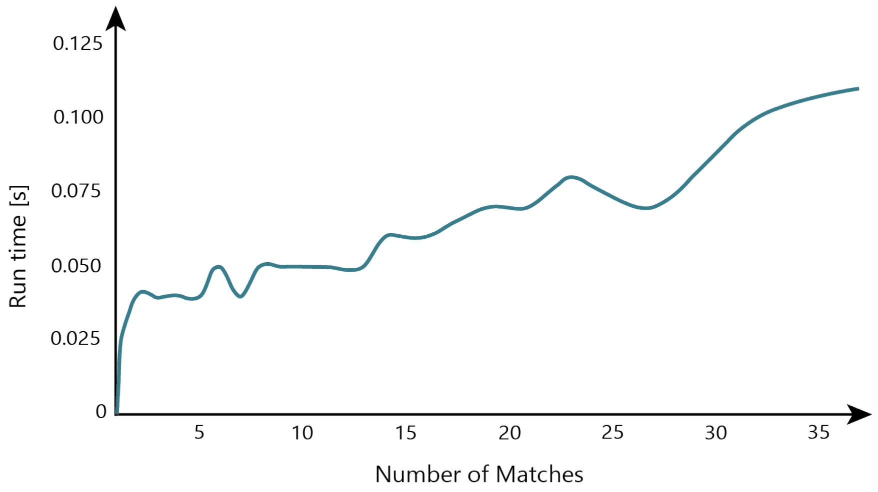

Figure 10.17: Run time as a function of the number of found matches for a group size of five. A maximum number of 110 target elements (all elements included in the design) were used as input for the algorithm leading to 37 matches.

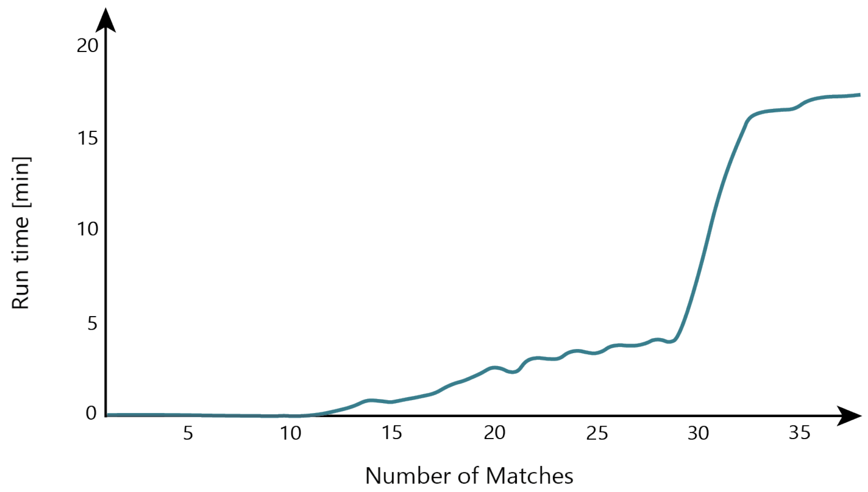

Figure 10.18: Run time as a function of the number of found matches for a group size of ten. A maximum number of 110 target elements (all elements included in the design) were used as input for the algorithm leading to 38 matches.

It is decided that the benefit of the improved run-time is larger than the loss of result accuracy and the optimization groups are applied when using the tool during the design process.

10.8 Tool summary

To summarise, the reason that the available open-source tools for matching reused elements are difficult to practically apply in design processes is due to a lack of flexibility and the possibility of adjusting the tool for project-specific requirements. A user of the matching tool in this thesis can control the following aspects:

Table 10.5: Project-specific adjustments of the tool that can be made by the user.

Aspect to be controlled by the user	**Implementation**
CO_2e/kg for reused elements	Parametric value
Minimum length for cut-offs to be re-inserted	Parametric value
Project-specific structural verification	Added as functions
Minimum allowed utilisation rate	Parametric value
Allowed types of cross sections for each element type	Inserted as lists of strings

The tool outputs information about the found matches, the environmental impact of the structural system and, for elements where no match was found, it outputs statistics about which of the checks that the inventory elements failed.

Table 10.6: Tool output

Type of output	**Information**
Matches	Unique identifier of target element Target element type Unique identifier of inventory element If it is a cut-off part, source inventory element Cross section of inventory element Cut-off length of inventory element The maximum utilisation rate Eigenfrequency of beams
CO_2e	Total for reused and new elements Saving by using reused elements
Reuse statistics	Number of reused elements Number of new elements
Updated inventory	Which inventory elements that have been used.
Check statistics	For unmatched elements, which of the checks that the inventory elements fail.

Part III

The design process

11
Intuitive phase

The purpose of the intuitive phase is to generate several design sketches and apply the workflow developed in Part II to match the inventory to the steel elements of the sketches. In total, six different sketches are created and compared to each other by studying the amount of reused elements and new elements used in the design, the reuse rate as well as the embedded CO_2e. The inventory elements used throughout the process are described in Section 9 and comes from two different sources, one from the inventory of Stena Stål, and one is a fictitious inventory based on a donor building, the mounting hall.

11.1 Design sketches

All of the design sketches are based on the initial centerline model (sketch one). Several parameters have been changed between the iterations such as the building width, span lengths, beam spacing, horizontal stabilisation, column heights and geometry of the truss. The sketches use two different types of slabs, sketch one and five have a cross laminated timber slab (CLT) with a a depth of 160 mm, while the rest of the sketches use a concrete hollow core slab (HCF) with a depth of 420 mm as these span up to 14 m. A summary of parameters that differ between the design sketches is presented in Table 11.1.

The use of cut-off parts has been included since the inventories consist of many large elements. If an inventory beam that is 14m long is used to replace a six meter beam, the rest of the eight meters goes back into the inventory. The minimum length that the cut-off needs to have to go back to the inventory is 3m. If the cut-off part is longer than three meters, then only the CO_2e of the part of the element that is used are included when calculating the total environmental impact of the proposal. If the cut-off is smaller than three metres, the environmental impact of the entire element is considered. The CO_2e of the different materials are taken according to the Climate Database by Boverket (Boverket, 2023b) and presented in Table 11.2. Since it is assumed that it is a project with ambitious sustainability goals, it is assumed that new steel elements are made of 100% recycled material and that the concrete is climate improved.

Table 11.1: Summary of the sketches and their geometric differences.

Geometry	**Sketch**					
	1	2	3	4	5	6
Building length [m]	32	32	32	32	32	32
Building width [m]	16	14	14	16	16	14
Building height [m]	12	11.1	12	10.5	12	12
Span x-dir [m]	8	6.4	4	4	8	6.4
Span y-dir [m]	5.33	14	14	8	5.33	14
Slab type	CLT	HCF	HCF	HCF	CLT	HCF
Truss span [m]	16	12.8	16	16	16	19.2
Truss height [m]	2	2	4	2	1.7	2.5
BTA [m^2]	1255.85	1140.65	1095.85	1255.85	1255.85	1051.05

Table 11.2: Summary of the CO_2e used in the calculations.

Material	**CO_2e/kg**
New steel (100% recycled)	1.2697
Reused steel	0.0045
Concrete (climate improved)	0.1604
CLT u 12% barrträ	0.16223

As already mentioned, if a reused element have a very low utilisation it might be more sustainable to use a new element instead, and leave the reused element for another project. However, there are not many actors buying reused elements in Sweden today and for reuse to be implemented on a larger scale there needs to be successful example projects showing that it is possible. Therefore, the the minimum allowed utilisation is taken as 50% when performing the matching. The result of the matching is shown in Table 11.3.

Table 11.3: Summary of the matching results.

Parameter	Sketch					
	1	2	3	4	5	6
Reused elements	71	60	33	87	62	46
New elements	106	46	80	95	119	71
Reuse rate [% n]	40	57	29	48	34	39
Reuse rate [% kg]	20	47	17	29	20	33
CO_2e savings [kg]	8628	22868	10135	15053	10351	20578
CO_2e total [kg]*	60573	128137	132954	147409	67883	141714
CO_2e [kg/m^2]*	48.2	112	121	117	54.1	135
CO_2e [kg/m^2]**	23.6	14.0	22.2	20.0	32.4	35.3
CO_2e [kg/m^2] new**	27.6	26.9	22.65	28.6	37.7	45.8
Steel weight [kg/m^2]**	27.7	37.0	35.3	27.9	36.1	54.7

* *Including the CLT or HCF slabs and elevator shaft*
** *Not including the CLT or HCF slabs and elevator shaft*

11.1.1 Design sketch 1

Sketch one is the base design with no applied changes. It has a reuse percentage which is quite low compared to the rest of the sketches and no match is found for any of the beams. Although, the CO_2/m^2 value is the lowest out of all the sketches due to having the slabs in CLT instead of concrete.

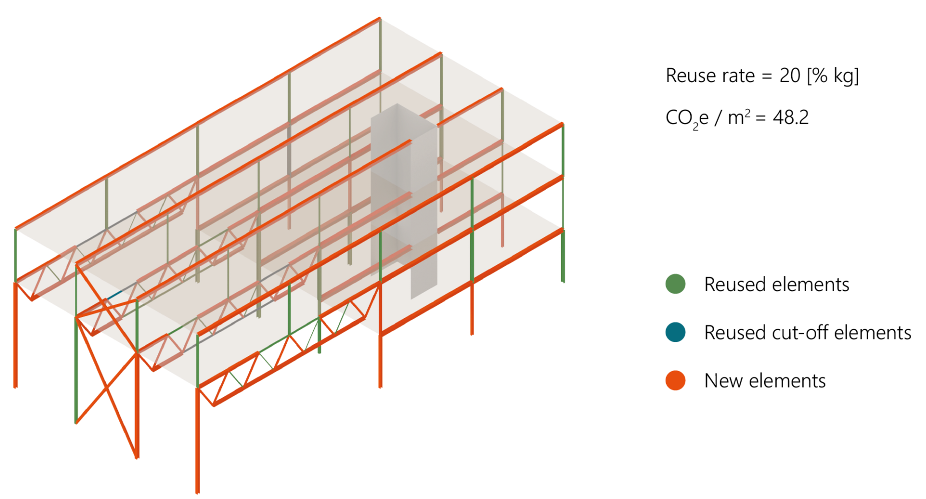

Figure 11.1: Illustration of Sketch one.

11.1.2 Design sketch 2

For Sketch two, HCF slabs are spanning all the way between the facades, the span lengths are slightly reduced compared to the base design. It has the highest reuse rate out of all the sketches and matches are found for all types of elements.

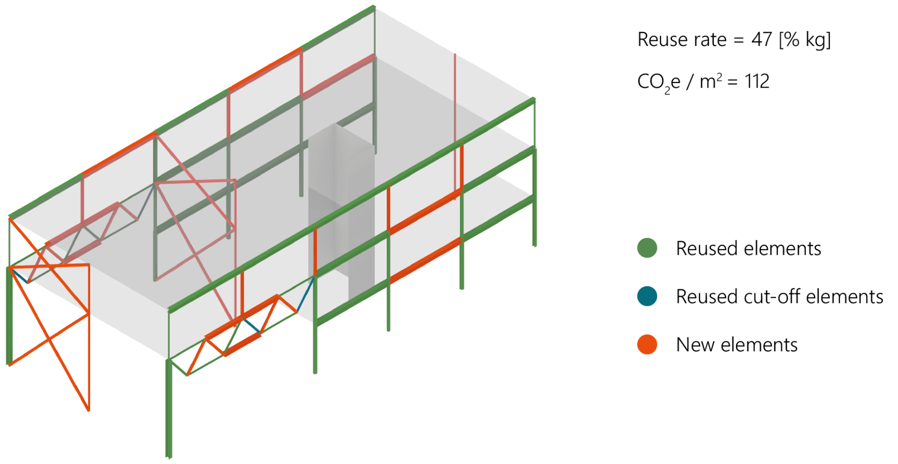

Figure 11.2: Illustration of Sketch two.

11.1.3 Design sketch 3

For Sketch three, the span lengths in the x-direction are much reduced compared to the base design and the truss takes up an entire floor height. It has the lowest reuse rate of all sketches with no found matches for the beam elements.

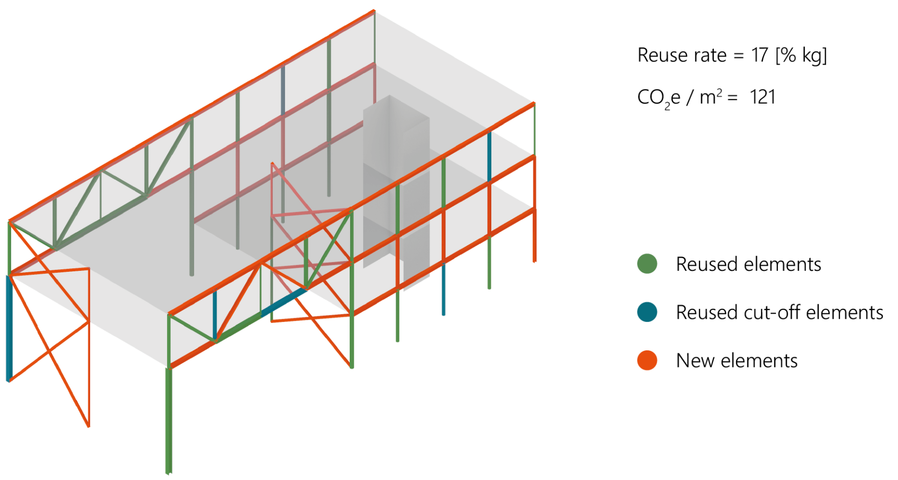

Figure 11.3: Illustration of Sketch three.

11.1.4 Design sketch 4

For Sketch four, the span lengths are reduced compared to the base design and there is one row of columns in addition to those along the facades. Matches are found for some of the beams and every column on the top floor. Although, quite large amounts of steel is used, as can be seen in the CO_2e/m^2 value.

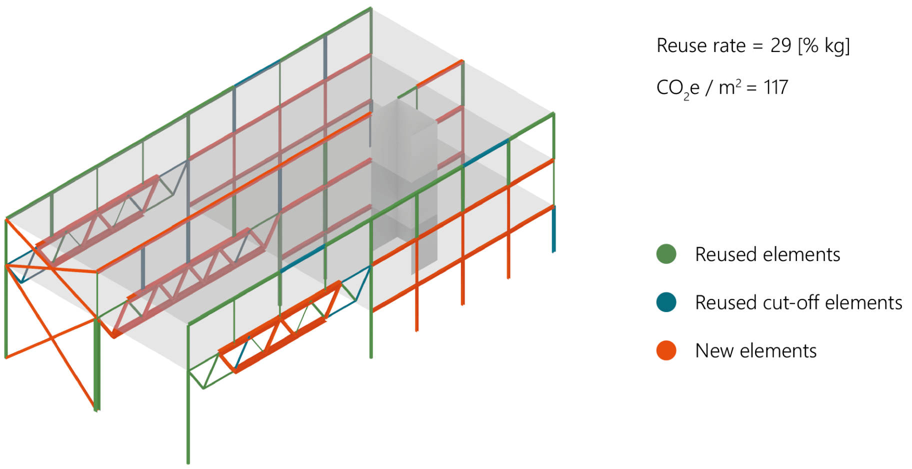

Figure 11.4: Illustration of Sketch four.

11.1.5 Design sketch 5

For sketch five, a three dimensional truss is used and there are two rows of columns in addition to those along the facades. The reuse rate is quite low and no matches are found for the beam elements.

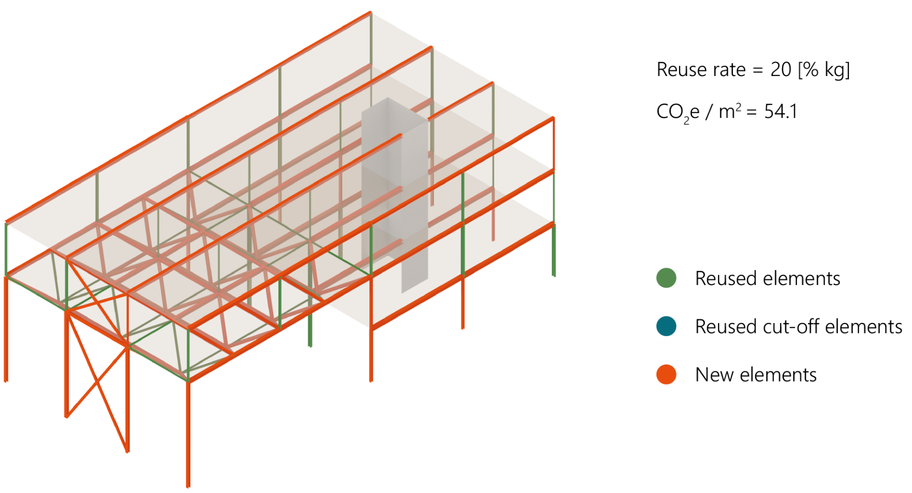

Figure 11.5: Illustration of Sketch five.

11.1.6 Design sketch 6

For sketch six, a more sparse three dimensional truss is used and there is one row of columns in addition to those along the facades. Some matches are found for all element types, however the CO_2e/m^2 value is the highest of all sketches.

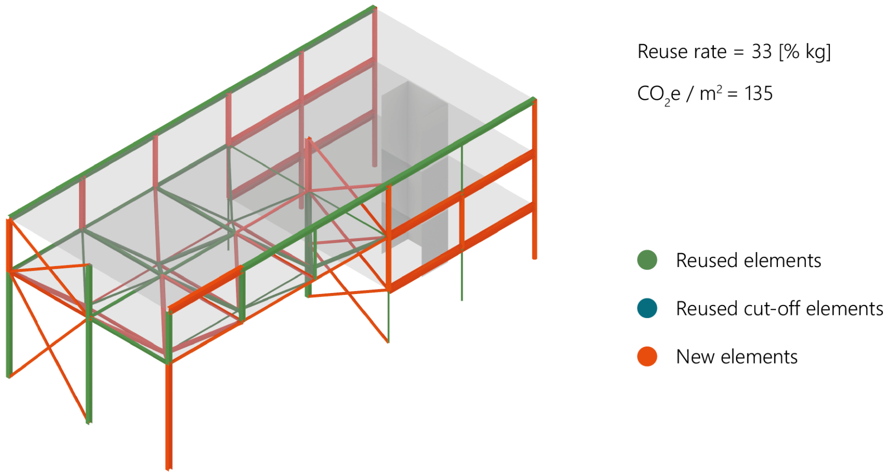

Figure 11.6: Illustration of Sketch six.

11.1.7 Matching trends

Many of the sections of the inventory are either quite small, such as IPE160 and IPE180, or quite large, such as HEA300 and HEB300. The sketches having CLT floors require smaller spacing of the beams and have lower self wights, which has resulted in very few matches since the inventory elements either have a utilisation above 1.0 or below 0.5. The same phenomenon can be observed for sketch three where HCF slabs are used, the span lengths are short, and the spacing is large.

The two sketches achieving the highest reuse rates are sketch two and six where HCF slabs are used and for which both the span lengths and spacing are large. Here, many of the larger inventory elements have a utilisation between 0.5 and 1.0 which lead to a large number of matches. Also, for sketch four, a larger number of matches were found since both short span lengths and a smaller spacing lead to many of the smaller inventory elements having a utilisation between 0.5 and 1.0. However, it is observed that the systems in sketch four and six consist of a large total amount of steel which gives them a higher value of CO_2e/m^2 than sketch two.

11.2 Design principles

Structural engineers working with reuse need to design structural systems with reuse in mind. This is especially important when the inventory of reused elements is unknown or has uncertainties. Even if one has an inventory at the start of the design process, it is not uncommon for elements in the inventory to be sold to another project in the period between the preliminary design and the time of constructing the building. If the design process is initiated before all of the elements of the inventory are tested, there may also be changes in material grades or elements disappearing from the inventory due to failed testing. Figure 11.7 lists some design principles that can be applied to prevent future inventory changes from having large consequences for the environmental impact of the project.

Design principle	Process stage	Implementation	Consequence
Define intervals	All	Intervals are defined rather than set values for, for example floor heights, slab depths, span lengths etc.	An increased flexibility increases the chances of finding a new reused element.
Use digital matching tools	Early	The tool automatically re-distributes the matches taking the updated stock into account.	The probablity of finding a design where a large number of elements can be reused is increased.
	Late	The tool finds the best match for the specific missing element in the updated stock.	The missing element can quickly be replaced by another reused element.
Don't use reused elements where changes in stiffness means large redistribution of forces.	All	Reused elements are avoided, for example, for stabilising elements or other statically indeter-minate structures. Or, if they are used and the element is no longer available, it needs to be replaced by an identical element, making the possibility of finding another reused element small.	Changing the stiffness of one element will not redistribute the forces within the structure.
Offset structural elements from walls and floors.	All	This is specified early in the project and agreed upon by all affected actors. Maximum dimensions, including fire protection, of each element is spec-ified, ensuring a reasonable effect on function and aesthetics.	If the missing component is replaced by a component of other dimensions, it will not affect important wall details meaning less coordination between different actors due to inventory changes.
Design using sections which are commonly available in reuse inventories.	All	Current and historic inventories are analyzed and elements which are common are favoured in the design.	The probability of finding an identical reused element increases.

Figure 11.7: Design principles.

If a reused element meant to be used for a design disappears from the inventory and a replacement element can not be found despite the preventive design principles, the time plan of the project should not be impacted. To prevent this, an additional design principle is to design new elements even though matches with reused elements are found and to have their specifications ready in case of any changes. In this case, there is a backup in the form of the auto designed new elements, where a re-run of the FEM analysis and verification of the new sections using FEM-Design would be necessary, see Figure 11.8.

Design principle	Process stage	Implementation	Consequence
Design new elements as a back-up.	All	New elements are designed and specified everywhere in the structure, regardless of whether a match is found or not.	The probability of performing the change of section without affecting the time plan is increased.

Figure 11.8: Design principle preventing an extended time plan.

The design principles are preventive actions that should be implemented before any changes to the inventory become a reality. However, if an element disappears there are actions that can be performed to adapt to the new reality, which are made easier thanks to the design principles. The actions which are possible and successful to perform may vary depending on the preconditions of the project and a guide for choosing the most appropriate action is presented in Figure 11.8. In this case, it is assumed that an inventory element is lost late in the project, where a re-run of the matching tool on the entire structure is not preferable since it could change many elements.

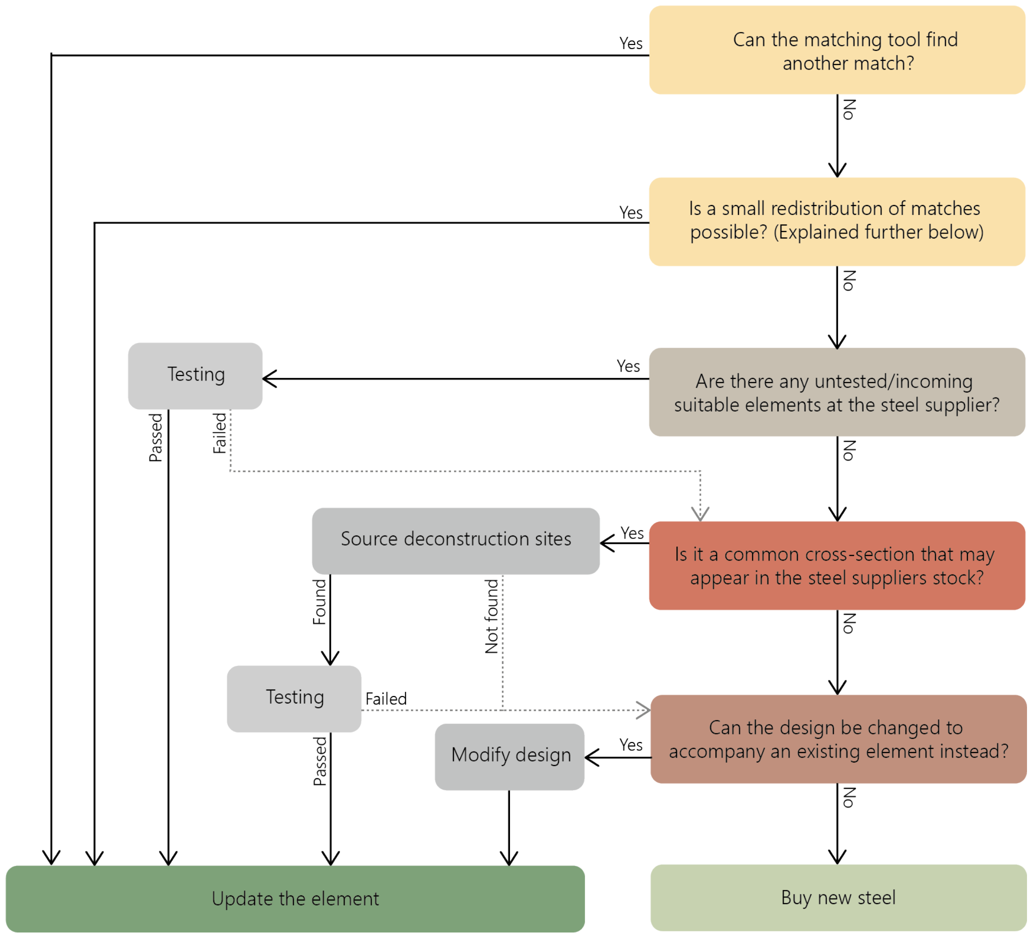

Figure 11.9: Flowchart of actions to be applied when an element from the inventory disappears. The colouring is consistent with the design principle that made the action easier.

To further explain the second action (from above) in Figure 11.9, the example from Section 10.6 is used again. Here, there are three target elements and three inventory elements, as shown in Figure 11.10, and the compatibility matrix **C** is shown in Equation 11.1.

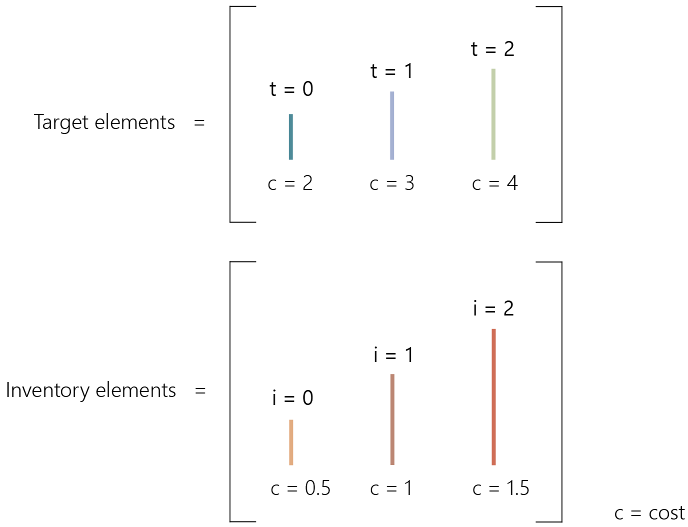

Figure 11.10: Target and inventory elements.

$$\mathbf{C} = \begin{bmatrix} 1 & 0 & 1 \\ 0 & 1 & 0 \\ 0 & 1 & 1 \end{bmatrix} \tag{11.1}$$

In section Section 10.6 it was shown that the most optimal matching, while ignoring the cut-off parts, is to match target element $t = 0$ with inventory element $i = 0$, target element $t = 1$ with inventory element $i = 1$, and target element $t = 2$ with inventory element $i = 2$. Let's now assume that the inventory element with index $i = 2$ disappears from the inventory. This means that the third column of the compatibility matrix will be removed, as shown in Equation 11.3, and there is no longer a match for target element $t = 2$.

$$\begin{bmatrix} 1 & 0 & \not{1} \\ 0 & 1 & \not{0} \\ 0 & 1 & \not{1} \end{bmatrix} \rightarrow \tag{11.2}$$

$$\mathbf{C}_{\text{updated}} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 1 \end{bmatrix} \tag{11.3}$$

Looking at the updated compatibility matrix, it is seen that target element $t = 2$ is also compatible with inventory element $i = 1$. As the new steel element needed for target element $t = 2$ have a larger environmental impact than the new element needed for target element $t = 1$, it is of higher priority to replace. Therefore, inventory element $i = 1$ is now more efficiently used when matched with target element $t = 2$.

In a more general case, there might also be elements left in the inventory which are not matched to any target element. In case there was an unmatched inventory element that was compatible with target element $t = 1$ but not with $t = 2$, the redistribution of matches could even lead to that all target elements are still replaced by a reused element.

12

Intentional phase

The purpose of the intentional phase is to refine the design which was started in the intuitive phase. It starts by evaluating the sketches and choosing the two best ones. Then, the design principles defined in Figure 11.7 are implemented to make the structures less vulnerable to changes of the inventory. The sketches are also revised to achieve a higher reuse rate. To do this, geometric changes are allowed to a certain degree, as the project is still imagined to be in the preliminary design phase. This is done to exemplify how small changes and modifications in the geometry can increase the reuse rate. As the FEM models used for the structural analysis are made more detailed, the matching tool is expanded to include more calculations and verifications.

12.1 Evaluation and selection

The evaluation of the sketches is made by using a matrix where seven criteria belonging to four categories are formulated. The criteria are ranked based on their importance and, for this fictitious project, the criteria within the sustainability category are ranked the highest. This since it is imagined that a project focused on reuse is likely to have high demands on sustainability. Since the weight of the elements can vary depending on the element type, the reuse rate most accurately measured as a weight percentage. All six iterations are compared based on points that they are awarded for each category. The scoring system goes from one to five, with five being the best score. Every score is multiplied by the importance percentage of the criteria, and each value is added together into a final score. The two alternatives with the highest scores are the ones chosen for further iterations. The full evaluation matrix and point distribution can be seen in Table 12.1.

Some of the criteria are based on values that can be quantified, such as 'reuse rate', kg/m^2 and CO_2e/m^2. Note that the value for CO_2e/m^2 in this phase also includes the CO_2e embedded in the slabs, and therefore vary widely depending on the their material. Sketches one and five that use CLT-slabs instead of HCF-slabs naturally have a lower carbon footprint.

Other criteria such as 'aesthetics', 'floor plan flexibility', and 'risk of extensive coordination' are assessed in a more qualitative manner. By 'risk of extensive coordination', it is meant that there may be clashes between the structure and, for example, mechanical systems. As welded box (HSQ) beams are not included in the reuse inventory, since the testing of the welds make them less economically feasible to reuse, the slabs must either be put on top of the I beams or special detailing must be made to ensure that the slabs can be placed on the lower flange. In the case of placing the slabs on top of the I beams, the beams are in the same space as the mechanical systems need to be, leading to an increased risk of clashes. Therefore, the sketches with additional rows of columns than the ones along the facade are given a lower score for this criterion. The sketches having many rows of columns in addition to those along the facades are also given a lower score for floor plan flexibility, as the columns may interrupt the floorplan.

Table 12.1: Evaluation matrix - Intentional phase.

Category	Criteria	Importance		Sketch					
		Points	[%]	1	2	3	4	5	6
Sustainability	Reuse rate	5	17.2	1	5	1	2	1	3
	CO_2e/m^2	5	17.2	5	2	1	2	5	1
Management	Risk of extensive coordination	2	6.90	2	3	3	3	2	3
	Design principle compatibility	4	13.8	5	3	3	2	2	1
Structure & economy	kg/m^2	3	10.3	5	4	4	5	4	1
Architecture	Aesthetics	3	10.3	4	3	5	2	5	1
	Floorplan flexibility	4	13.8	2	5	4	3	2	5
Score				**307**	**324**	245	231	266	193

Some of the design principles defined in Figure 11.2 can be used to evaluate which of the sketches that are the most sensitive to changes of the reuse inventory. The sketches that match a high degree of common cross sections get higher points, in this case the most common cross section in the reuse inventory is IPE180 which are a common match for sketch one. For the three dimensional trusses, there are multiple paths for the loads to be transferred to the foundation, and the load distribution is dependant on the stiffness of the included elements. So, changing the cross section of, for example, one column supporting the three dimensional truss might mean that the forces redistribute in the entire truss, and all of its members must be re-designed. Therefore, a lower score is given to sketch five and six. When off-setting the columns from the walls, it is reasonable to assume that some maximum dimensions are established to ease the coordination between the disciplines. For this case it assumed that a maximum width of a column along the facade, including fire protection, is 300 mm, and 250 mm for a column in the centre of a room. For sketch four and six, these maximum dimensions are exceeded for a number of columns and they are therefore given a lower score.

One potential aesthetic quality that could be observed for the sketches is that the large variety of cross section sizes can make the load paths part of the visual expression of the structures, as it can be seen clearly which elements that are the most loaded. The scoring for the aesthetics criteria evaluates both the geometry of the sketches and whether the reused sections disturb the look of the structure, gives a comparable appearance to new elements, or if the variety of the sections have the potential of creating a playful and motley expression making reuse attractive. The highest scores are given to sketch three and five which were both assessed to have pleasing proportions. For sketch three, the variation of the elements is clearly visible and leaves the architect with a possibility of creating a fun and playful facade and interior of the office space. For sketch five, the three dimensional truss creates an effectful public space for the hall, and the reused sections gives an appearance comparable to that from new sections. The lowest score was given to sketch six where the proportions were assessed as unbalanced and the many large sections gives a clumsy appearance. Overall, the sections look rather coherent than varied, except for some places where the sections look misplaced.

The results show that Sketch 1 and Sketch 2 get the highest scores and will be further developed in the following sections.

12.2 Application of design principles in the matching tool

Since compatibility with the design principles is one of the evaluation criteria, they are already considered in the design. In addition to this, the matching tool is in this phase updated to include some new aspects, which includes setting maximum dimensions for columns and beams. As previously mentioned, maximum dimensions are set to ease the coordination between different disciplines while allowing for a flexibility concerning cross sections. For columns, the maximum width is set to 250mm for columns in the centre of the room and 300 mm for columns along the facade, including fire protection which is assumed to take up 30 mm. The maximum depth for beams is set to 400 mm. In other words, this is an additional compatibility check and any inventory element exceeding these dimensions will have a 0 in the compatibility matrix for any corresponding target element which is of the relevant element type.

As there is a greater chance of being able to replace a reused element by an identical one if the section is commonly available in the reuse inventory, a favouring of common sections is also added to the tool. This is done by multiplying the cost of each match with a factor depending on how common the replacing inventory element is. For this case, the most common section is IPE180 and all other sections are relatively uncommon. Therefore the cost of matches where the replacing inventory element is an IPE180 is multiplied by 1.0, and all other matching costs are multiplied by a factor $k_{\text{uncommonSection}} > 1.0$. Since the amount of embedded CO_2e is still the most important part of the optimization objective, $k_{uncommonSection}$ can not be so large that it dominates. To determine this factor, each target element t is studied and the size of the range of CO_2e of all compatible inventory elements is determined. For example, if a target element is compatible with three different inventory elements, the size of the range is the maximum value of CO_2e of all the three elements minus the minimum value. The factor $k_{CO_2e,t}$, representing the impact that the CO_2e has on which match the algorithm chooses to perform for a specific target element, is then represented by the ratio between the range size and the maximum value.

$$k_{CO_2e,t} = \frac{CO_2e_{\max} - CO_2e_{\min}}{CO_2e_{\max}}, \tag{12.1}$$

The factor $k_{\text{CO}_2\text{e,average}}$, representing the impact that the CO_2e has on all the matches that are chosen to be performed by the algorithm, is then calculated by taking the average value of the impacts from all individual target elements. As the value for CO_2e/m^2 is given an importance point of five in the evaluation matrix and 'design principle compatibility' is given an importance point of three, the factor $k_{\text{uncommonSection}}$ is calculated as:

$$k_{\text{uncommonSection}} = 1 + \frac{3}{5} \cdot k_{\text{CO}_2\text{e,average}}, \tag{12.2}$$

Table 12.2: The factor $k_{\text{uncommonSection}}$ calculated for both chosen design sketches.

Sketch	$k_{\text{uncommonSection}}$ [-]
1	1.21
2	1.27

12.3 Statistics for unmatched elements

For each target element where no match was found, the matching tool outputs statistics showing which of the compatibility checks presented in Section 10.1 that the remaining inventory elements fail. This is complied into separate diagrams for each type of target element and is meant to function as a guide for making smaller design changes to increase the reuse rate. Reasons that the inventory elements could fail the checks are, for example, that they are too short, have a utilisation that is too high, or a deflection that is too large. Additionally, the diagrams indicate whether the inventory elements are close to passing the checks or not. If the utilisation rate is within ten percentage points from the allowed range, the probability that small design changes can solve the problem is higher than if the utilisation rate is many times larger or smaller. The design specific adjustments that were made based on these statistics are described in further detail in Section 12.6.

12.4 Design modifications

For the intentional phase, several modifications to the designs are made. It is assumed that the design process is still in an early stage, where there is a possibility of changing parameters such as span lengths. The following design modifications have been allowed:

- Changes in the heights of the floors (but not changing the total height of the building).
- Variations in the span lengths by adjusting the placement of columns.
- Geometric changes of the truss.
- Geometric changes and adjustments of the stabilising systems.
- Removal of columns having unreasonably low utilisation rates.
- Allowing for a larger variety of cross sections for new elements included in the truss, leading to a better optimised structure.
- Updated and refined wind loads, taking unintended inclination into consideration.
- Updated thickness of the CLT-slab.

Some design changes made during this phase are based on statistics from the matching tool, as explained in Section 12.3. Other changes are made to make the proposal more realistic. To exemplify, the ceiling heights are adjusted by increasing the ceiling height of the ground floor and slightly lowering the height for the remaining office floors. However, the total height of the building is constant.

The trusses are modified by making the top and bottom chord continuous, instead of being constructed of several smaller parts as before. This means that the element types ‘Top chord’ and ‘Bottom chord’ are added to the tool together with some relevant verification according to SS-EN 1993-1-1. Since there is now a moment causing compression of the bottom flange, which is not laterally supported by the slabs, a check of lateral torsional buckling is now performed. Also, the maximum bending moment now coincides with the maximum shear force, so a reduction of the moment capacity is made to account for this. As the magnitude of the compressive normal force of the top chord is now comparable to that of the bending moment, and there is risk of several instability phenomenons, an interaction check is also added to the tool. The cross section class for top chord is conservatively taken based on the assumption of pure compression. And the cross section class for bottom chord is conservatively taken based on the assumption of pure bending. The structural checks that are added to the tool are shown in Table 12.3.

Table 12.3: Structural checks performed depending on the type of target element.

Type of target element	Structural checks	Section in SS-EN 1993-1-1
Top chord	Shear force	6.2.6
	Flexural buckling	6.3.1
	Bending	6.2.5, 6.2.8, 6.2.9
	Second-order effects	5.3.2, 6.2.5, 6.2.6, 6.2.9
	Lateral torsional buckling	6.3.2
	Interaction	6.3.3
Bottom chord	Shear force	6.2.6
	Tension	6.2.3
	Bending	6.2.5, 6.2.8, 6.2.9
	Lateral torsional buckling	6.3.2
	Interaction	6.3.3

To get a better estimate of the loads acting on the structure, initial sway imperfections are taken into consideration by introducing equivalent horizontal point loads acting at the top of the columns (in accordance with SS-EN 1992-1-1 Section 5.2). The magnitude of the point loads are calculated by multiplying the normal force of the columns by a sway imperfection factor. The point loads act in different directions depending on whether the wind is acting on the short or long side of the building.

Also, the horizontal stabilisation are made more material efficient in the intentional phase. This will impact the total weight of the building, which is important to note when comparing the values in Table 11.3 and Table 12.5. In the intuitive phase, the possibility of using reused elements for the stabilising systems were not considered, due to the likeliness of force redistribution when changing the stiffness of the included elements. The stabilising systems are more sensitive to changes than the rest of the elements, as a change of one element can affect every element in the system. In the intuitive phase however, a separate routine for matching reused elements to the stabilising crosses are developed.

In this routine, the stabilising crosses are matched to reused elements manually before the matching tool is used. Here, sections from the inventory are manually applied to the cross elements before the the FEM analysis is run, and the sections are verified using FEM-Design. The used sections are then removed from the excel lists containing the inventory before the matching of the rest of the elements is performed. Applying the reused sections before running the FEM analysis will ensure that significant load redistribution will not take place, as the stiffness of the stabilising elements does not change after the analysis is run. If a reused element used for the stabilising crosses would disappear from the inventory at a later design stage, it would need to be replaced by either an identical reused element or by a new element. This unless another manual verification is made and all elements are re-matched. Figure 12.1 shows the new routine added to the workflow presented in Figure 9.1.

In addition to deflections, another serviceability requirement, that is especially important when having floor slabs of timber, is vibrations. For the matching process, no limit of the first natural frequency of the beams are used, but calculations to establish it are added and the first natural frequency is now output by the tool.

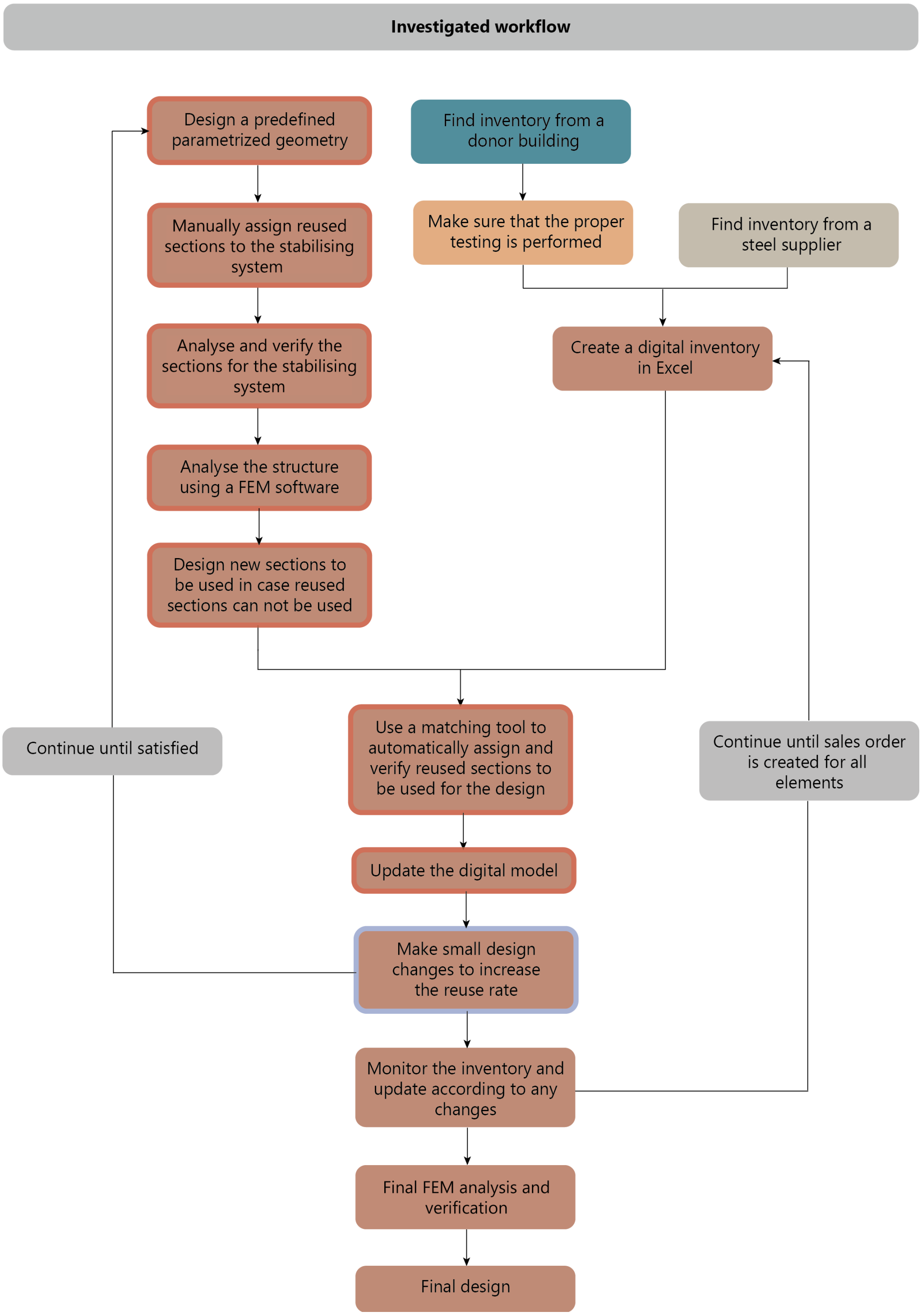

Figure 12.1: Updated workflow.

12.5 Summary of tool updates

Hereby follows a summary of the updates of the matching tool which has been made during the intentional design phase:

- Maximum dimensions for the columns and beams (relating to the design principles).
- Favoring of common sections (in this case IPE180, in accordance with the design principles).
- Support for continuous beams for the top and bottom of the truss.
- Revised allowed cross sections for certain element types.
- Output of eigenfrequency for beams.

12.6 Possible design concepts

The geometric changes that are made to the two designs during the intentional phase are presented in Table 12.4 and visualised in Figure 12.5 and 12.9.

Table 12.4: Summary of the geometric changes.

Geometry	**Design 1**	**Design 2**
Building length [m]	32	32
Building width [m]	16	14
Building height [m]	12	11
Floor 0	5	4
Floor 1	3.5	3.5
Floor 2	3.5	3.5
Truss height [m]	2	3.5
Truss span [m]	16	12.8
Spans floor 2 [m]:		
Span X1	8	12.8
Span X2	8	6.8
Span X3	6	5.6
Span X4	10	6.8
Slab type	CLT	HCF

The results from the matching of the modified structures using the updated matching tool are presented in Table 12.5.

Table 12.5: Summary of the matching results in the intentional phase.

Results	**Design 1**	**Design 2**
Reused elements	75	49
New elements	69	11
Reuse rate [% n]	52	82
Reuse rate [% kg]	55	93
CO_2e savings [kg]	18458	28550
CO_2e total [kg]**	18738	2304
CO_2e [kg/m^2]*	41.7	99.4
CO_2e [kg/m^2]**	14.9	2.02
Steel weight [kg/m^2]	26	23
Utilised mass [kg]	20843	24797
Total mass [kg]	32737	26061
BTA [m^2]	1255.85	1140.65

* *Including the CLT or HCF slabs and elevator shaft*
** *Not including the CLT or HCF slabs and elevator shaft*

12.6.1 Design 1

The modifications made for design one increase the reuse rate from 20% to 55%, and reduce the CO_2e/m^2 value from 23.6 to 14.9, only considering the steel. To achieve this, the statistics for failed checks output by the matching tool during the intuitive phase is used. This is compiled in the diagrams presented in Figure 12.2 – 12.4. When looking at the utilisation rates, only those within ten percentage points from the allowed range were considered to be guiding the design changes, as only smaller changes can be made.

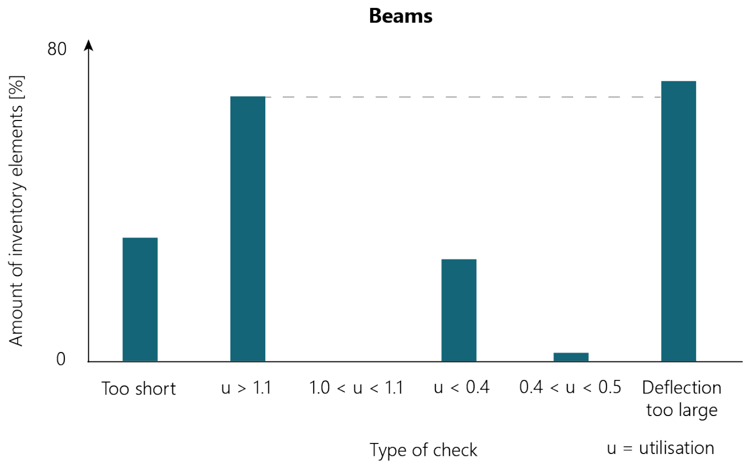

Figure 12.2: Statistics for failed checks of beams.

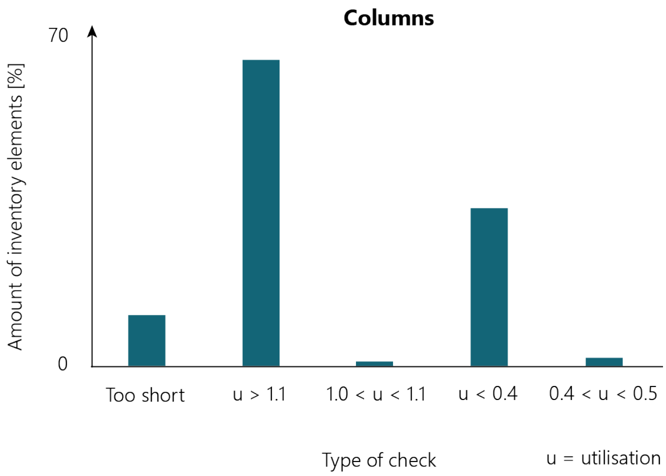

Figure 12.3: Statistics for failed checks of columns.

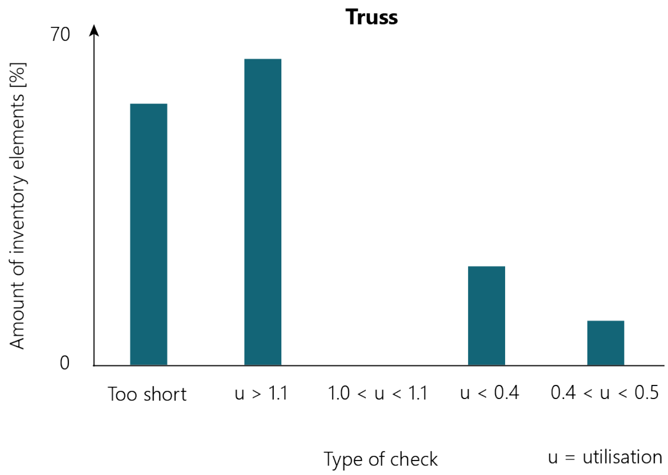

Figure 12.4: Statistics for failed checks of truss elements.

It is observed in the diagram for beams that there are some target elements for which there are inventory elements with a utilisation that is slightly too low. It is also observed that there are more inventory elements failing the deflection check than there are inventory elements having a utilisation above 1.1. This means that it is likely that there are some inventory elements that pass the utilisation check and only fails due to the deflections. So, some beams could benefit from a longer span length to increase the utilisation, and some beams could benefit from a shorter span length to reduce the deflection. It is also observed that there are some columns for which the utilisation of the inventory elements is slightly too high, and some columns for which it is slightly too low. So, the columns would also benefit from making some span lengths longer and some shorter. This is achieved by moving one row of columns by two metres.

For the truss elements, it is observed in the diagram that there are some target elements for which the utilisation rate is slightly too low. It was tested to reduce the height of the truss to hopefully increase the loading of each elements while reducing their lengths. However, this lead to fewer matches as inventory elements which had previously been matched now got a utilisation that is too high. So, the height of the truss is kept the same as it was during the intuitive phase.

Another change that is made for the truss is to only allow for matches with I sections for the top chord, instead of the built up L profiles as before. This since the top of the truss need to be flat for mounting the slabs. Since the span of the truss is quite long, one splice was added for the top chord and one for the bottom chord. These changes lead to more matches for the bottom chord, but fewer matches for the top chord.

By removing two elements from the stabilising cross, less material is needed for carrying the horizontal loads. Despite adding the routine for also matching these elements, no matches were found there.

When comparing the updated design with the sketch from the intuitive phase, it is noted that it is especially the number of matched beams that has increased. Generally, the beams are larger than the columns, so the carbon saving of matching one beam are often much larger than matching one column. Therefore, these changes has been efficient in reducing the environmental impact of the design.

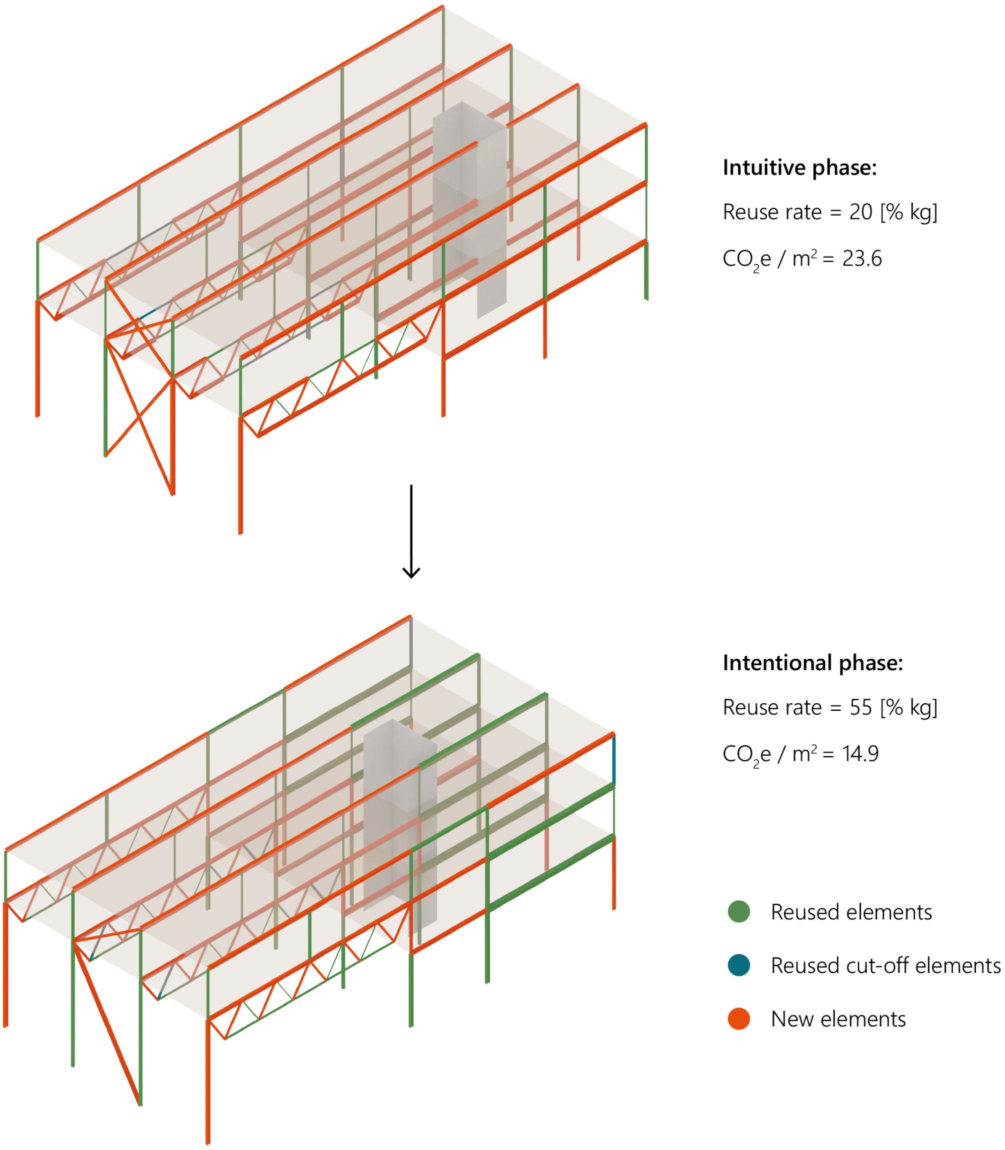

Figure 12.5: Illustration of design sketch 1.

12.6.2 Design 2

The modifications made for design two increase the reuse rate from 47% to 93%, and reduce the CO_2e/m^2 value from 14.0 to 2.02, only considering the steel. As for Design 1, this was achieved by using the statistics for failed checks output by the matching tool during the intuitive phase. This is compiled in diagrams presented in Figure 12.6 – 12.8.

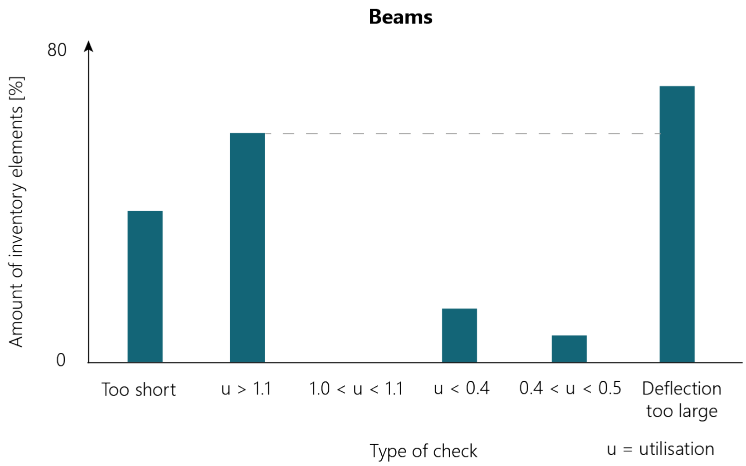

Figure 12.6: Statistics for failed checks of beams.

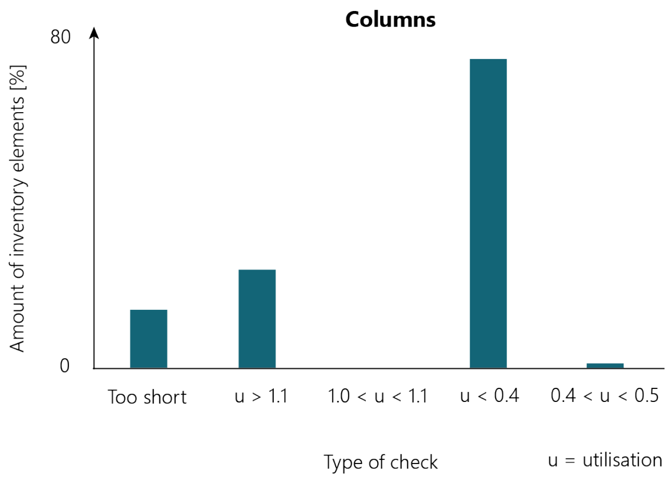

Figure 12.7: Statistics for failed checks of columns.

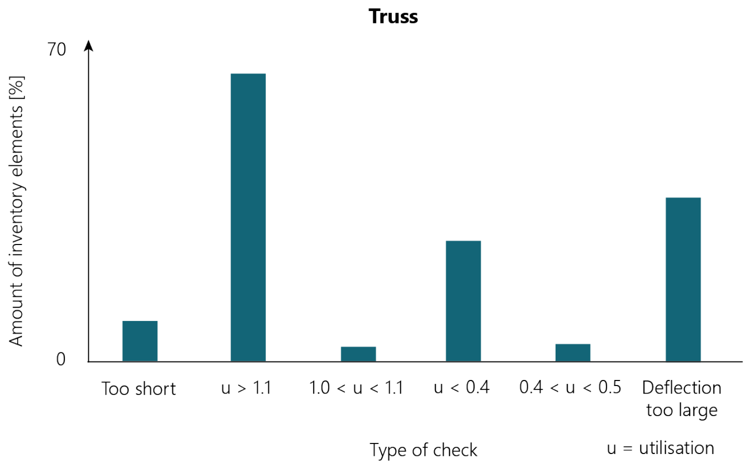

Figure 12.8: Statistics for failed checks of truss elements.

In a similar manner as for design one, it can be observed in the diagram for beams that there are some target elements for which the inventory elements have a utilisation that is slightly too low, and some target elements for which the the inventory elements have a deflection that is too large. Also, for the columns there are some target elements for which the utilisation is slightly too low, but no target elements for which the utilisation is slightly too high. As the beams are generally larger and has a higher environmental impact than the columns, the same strategy of shifting rows of columns as for design one is applied. Two rows are shifted by 0.4 metres. The result from this is a larger number of matches for the beams, while the matches for the columns are not significantly affected.

One part of the structure in the sketch from the intuitive phase where there are not as many matches is the truss. The sketch was also given a lower score for the aesthetics evaluation criteria due to the truss looking a bit misplaced. Sketch three got the highest score for aesthetics due to the varied and playful look that the truss has potential of giving the facade. Therefore, the truss from sketch three is used instead of the truss from the intuitive phase, the diagram in Figure 12.8 show the statistics from that truss.

The statistics for the truss from sketch three show that there are both target elements for which the inventory elements have a utilisation rate that is slightly too high, and slightly too low. When looking at the calculation results in more detail it is seen that it is the top and bottom chord for which it is most common that the inventory elements have a utilisation that is too high. For the vertical and diagonal elements, it is instead most common that the utilisation of the inventory elements is too low. The span length of design two is shorter than for sketch three, which enables matches for both the top and bottom chords. Removing the vertical truss elements while keeping only diagonal ones, enables a high enough utilisation to find matches for most of these elements as well.

The stabilising cross in the sketch from the intuitive phase that is the closest to the centre of gravity is not very efficient in handling torsion of the building. Therefore, it is removed as the other cross and the elevator shaft are enough to stabilise the building. The column added in the centre of the short facade is not carrying much vertical load, creating the risk of having to anchor a force in tension to the foundation generated by the wind load. Therefore, this column is removed and a cross is created over the entire shorter facade. By adding the routine for matching the stabilising cross elements, two additional matches are found.

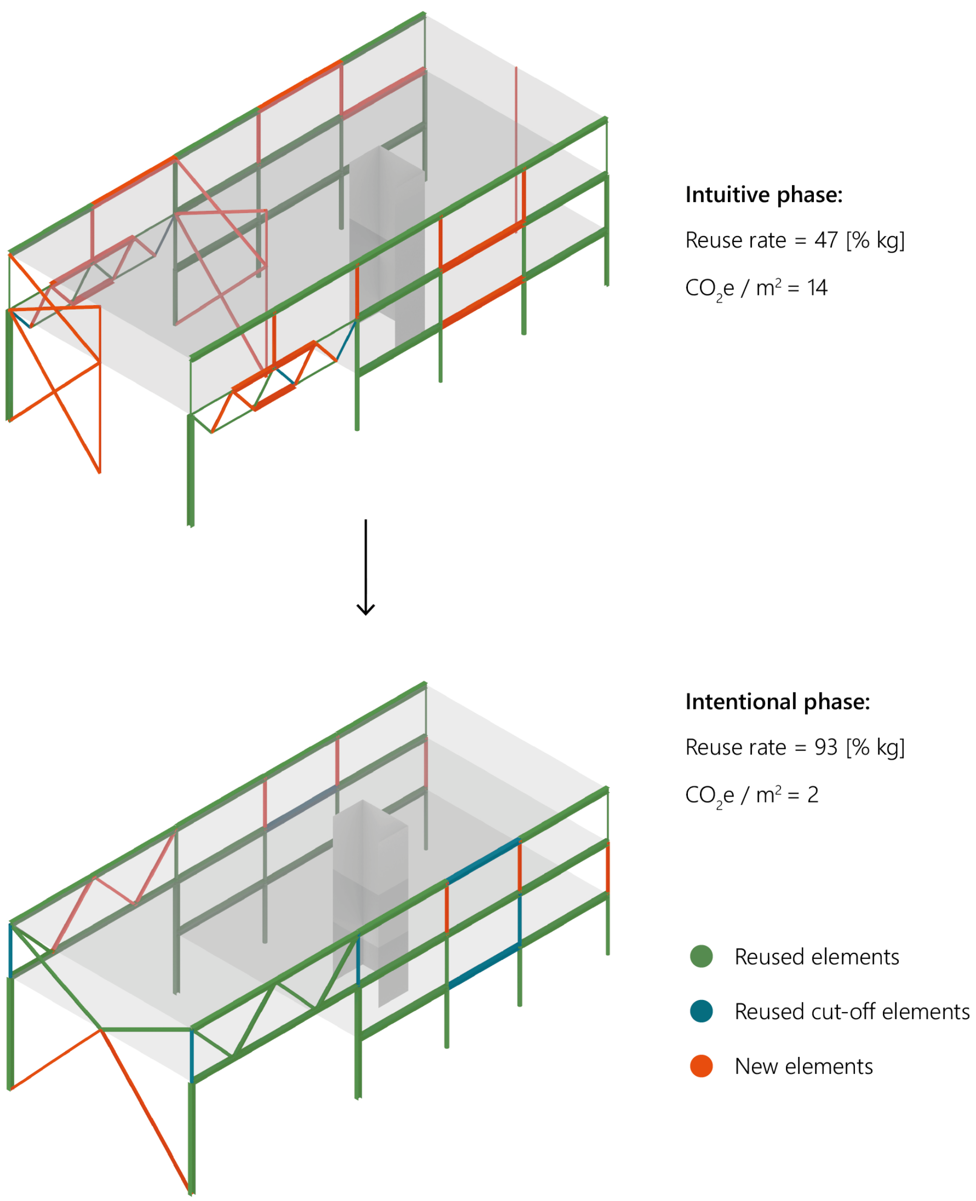

Figure 12.9: Illustration of design sketch 2.

12.7 Non-tested elements

As seen in Figure 8.2–8.5 where the inventory is described, some of the inventory elements are marked in red since they are not tested yet. This means that there are even larger uncertainties concerning these elements. Here, the compatibility matrix can be used to get a quick overview of any other reused elements which are compatible with the affected target elements. By listing those, a replacement for any inventory element which does not pass the testing can be found fast. Such lists are presented in Table 12.6 for design one and in Table 12.7 for design two. For example, it can be seen for both design one and two that there are tested elements which has the same cross section as the elements which are not tested. However, the tested elements are longer than the non-tested elements leading to longer scrap pieces.

Table 12.6: Design one: Other remaining inventory elements which are compatible with the target elements matched with non-tested inventory elements.

Target element id	Matched section	Other compatible elements	Amount
Beam5	HEA360	-	-
Beam11	HEA360	-	-
Column4	CHS219.1x10	CHS219.1x10	8
Column5	CHS219.1x10	CHS219.1x10	8
Column39	CHS219.1x10	CHS219.1x10	8
Column38	CHS219.1x10	CHS219.1x10	8

Table 12.7: Design two: Other remaining inventory elements which are compatible with the target elements matched with non-tested inventory elements.

Target element id	Matched section	Other compatible elements	Amount
Beam6	HEB360	HEA400	10
Beam9	HEB360	HEA400	10
Beam2	HEA360	HEA400	10
Beam5	HEA360	HEA400	10
Beam11	HEA360	HEA400	10
Beam8	HEA360	HEA400	10
Beam15	HEA360	-	-
Beam12	HEA360	-	-
Beam17	HEA360	-	-
Beam14	HEA360	-	-
Column17	CHS219.1x10	CHS219.1x10	10
Column6	CHS219.1x10	CHS219.1x10	10
Column7	CHS219.1x10	CHS219.1x10	10
Column9	CHS219.1x10	CHS219.1x10	10
Column10	CHS219.1x10	CHS219.1x10	10
Column11	CHS219.1x10	CHS219.1x10	10
Column14	CHS219.1x10	CHS219.1x10	10
Column8	CHS219.1x10	CHS219.1x10	10

13
Evaluation phase

The evaluation phase is the final stage of the preliminary design. Here, one of the designs from the intentional phase is chosen for future further development. This is done by a modified evaluation matrix. The chosen design is analysed and verified using a FEM-Design, to confirm that the structure after the matching procedure and design modifications still works as expected.

13.1 Evaluation and selection

The modified evaluation matrix looks slightly different from the original evaluation matrix used in the intentional phase. Although, the categories of sustainability, economy and architecture remains the same. 'Design principle compatibility' has been removed as a criteria and replaced by a criteria evaluating which of the designs that uses the largest amount of cross sections that are common for the reuse inventory. This is because it is now the only design principle that may still differ between the designs. Table 13.1 shows the number of matches that are made using an IPE180, which is the most common cross section, for each phase and design. That this number is increased for design one during the intentional phase may be due to the favouring of common sections which was implemented into the tool.

Table 13.1: Number of matches using an IPE for each design and phase.

Design	Phase	Number of matches using an IPE180
1	Intuitive	8
1	Intentional	12
2	Intuitive	0
2	Intentional	0

'Risk of extensive coordination' has been divided into two parts where the first part assesses the extent of the changes that has been made compared to the base design, and the other assesses the risk of clashes between the structure and mechanical systems. A new category called 'material utilisation' has been added to give a hint as to how well utilised the structures are. A low degree of utilised weight compared to the total steel weight may indicate a system where a lot of the reused elements have a utilisation of near 50%.

In this phase the value of CO_2e/m^2 that is used for the evaluation matrix is revised to only include the CO_2e embedded in the steel structure, in contrast to the intuitive phase where the CO_2e embedded in the slabs and shafts were included as well. This is due to the fact that also HCF slabs have potential for reuse. For example, the slabs in the reference project Kristian Augusts Gate 13 are reused HCF slabs (Entra ASA, 2021), and there is a section focusing on HCF slabs in the supporting documents for the reuse guide from Boverket (Hansson et al., 2021). In reality, it would be reasonable to assume that a project including steel reuse would also examine the possibility of reusing the HCF slabs. However, this aspect is unknown for this fictitious project, and therefore the environmental impact of the slabs is excluded from the evaluation due to a lack of information.

It is natural that the evaluation matrices vary and look different depending on the stage of the design, since some criteria become irrelevant in later phases. The evaluation matrix for the evaluation phase can be found in Table 13.2.

Table 13.2: Evaluation matrix - Evaluation phase.

Category	Criteria	Importance points	Importance [%]	Design 1	Design 2
Sustainability	Reuse rate	5	16.13	3	5
	CO_2e/m^2	5	16.13	1	5
Management	Risk of extensive coordination	3	9.68	4	2
	Risk of clash with mechanical systems	2	6.45	3	4
	Use of common cross sections	2	6.45	4	1
Economy	Weight/m^2	3	9.68	2	4
Material utilisation	Utilisation · weight / total weight	1	3.23	2	5
Architecture	Aesthetics	3	9.68	4	4
	Floorplan flexibility	4	12.9	2	5
Score				**239**	**371**

There are several other criteria one may consider depending on the project and the level of detail. The following points are some suggestions of such criteria, that would have been relevant to implement in this thesis if more information was known. With respect to the thesis time-frame and limitations they were not included in Table 13.2. Also, aspects and challenges from other disciplines would be considered at this stage.

- Impact on the foundation.
- Slab height and how it impacts ceiling height and the maximum height of the building.
- Total applied load divided by the total material weight to carry the load.
- CO_2e/m^2 including the floor slabs and foundation.

From Table 13.2 it is clear that the best design in this case is Design 2. Which is not surprising when looking at the results from Table 12.5. Design 2 manages to match every single beam, and showed a large increase of reuse rate, from 47% to 93% (Table 11.3, Table 12.5).

Figure 13.1: Physical model zoom in.

13.2 Final FEM analysis and verification

As the matching tool changes the cross sections of the elements after the FEM analysis is run, a final FEM analysis must be performed to ensure that no significant force redistribution has taken place. Therefore, the cross sections of the FEM model for the chosen design are updated, a new analysis is done and the elements are verified using FEM-Design. All utilisation rates from the verification are shown in Appendix A and the maximum and minimum utilisation rates are presented in Table 13.3.

Table 13.3: Maximum and minimum utilisation after running the analysis and verification in FEM-design for the updated sections.

Value	**Element type**	**Utilisation [-]**
Maximum utilisation	Bottom chord	1.01
Minimum utilisation	Column	0.48

Here it is seen that the lower chords of the truss have utilisation rates of 1.01 and 1.00 and is therefore failing the checks. However, only by one percentage point which could both be the result of differences in calculation accuracy between FEM-Design and the matching tool, or of a smaller force redistribution. As the area reduction factor for the imposed load is not accounted for in the calculations, it is reasonable to assume that the elements would pass a more detailed verification and would not need to be replaced. If the increase in utilisation rate is due to a force redistribution, this could may have been avoided by running the FEM analysis again before performing the matching, using the auto designed cross sections. As those cross sections are more similar to those assigned by the matching tool, the sectional forces obtained from running the second FEM analysis are likely to be more similar to those from the final analysis.

It is also seen that some of the columns have a utilisation rate of 0.48 which is below the minimum limit. However, FEM-Design does not take the modified value of γ_{M1} for the buckling verification into account, while the matching tool uses $\gamma_{\mathrm{M1,mod}}$=1.15. The maximum utilisation rate from FEM-Design of all columns where a reused section is used is 0.83, so there is some margin to account for the modified value of γ_{M1}. Also, some of the diagonal elements of the truss have utilisation rates of 0.92 – 0.99. However, these elements are in tension for all load combinations and the compression elements have utilisation rates around 0.7.

Also, the elements included in the stabilising cross are in compression and are affected by FEM-Design not taking the modified value of γ_{M1} for buckling into account. In addition to this, the ignored load reduction factors accounting for the number of floors and the area of the slabs only affects the vertical loads. Therefore, the analysis and verification of the stabilising elements is less conservative than for the other elements.

Initially, reused elements with cross section IPE220 was used for the upper elements of the cross, resulting in a utilisation rate of 0.93. However, when updating all the cross sections of the FEM model and running the analysis again, the utilisation rate of the element is increased to 0.99 for buckling. So, the element would have failed the check by the matching tool including $\gamma_{M1,mod}$. To solve this, a reused IPE240 element is used instead, and the analysis along with the verification is run one more time resulting in a utilisation of 0.76. No significant change of the utilisation rates of the rest of the elements is observed. The lesson from this is that it would have been beneficial to use a larger safety margin for the stabilising elements from the start.

13.3 The design proposal

The final design that is chosen is design two, or design sketch two, as it is called in the intuitive phase. This proposal has the highest reuse rate and the highest CO_2e savings. At the same time, the large span of the slabs and the fact that there are no columns in addition to those along the facade allows for a very flexible and versatile floor plan.

The reason as to why the reuse rate and carbon saving could increase the way it did between the intuitive and the intentional phase, is because every single beam in the design could be reused. This is due to the design modifications that were made. In general, the beam elements are larger than the columns, and so the CO_2e saving from reusing beams is larger than that of reusing columns. The distribution of new and reused elements for each element type is described in more detail in Table 13.4.

Table 13.4: Distribution of reused vs new elements per in the design proposal.

Element type	**Reused**	**New**	**Total**
Beams	22	0	22
Columns	20	6	26
Truss	5	3	8
Stabilisation	2	2	4
Total	49	11	60

When studying Table 12.5 the utilised mass compared to the total mass is worth highlighting. These values are quite similar, which indicates that many of the elements that are matched are quite well utilised.

Figure 13.5 shows which of the inventory elements that are used for the chosen design and how they are cut. All cut-off pieces that are less than 3 m are seen as scrap pieces, as there is a less likelihood that these will be reused in another project. The design proposal uses six such cut-off pieces, meaning that one inventory elements is turned into two reused elements. These parts are marked as blue, both in Figure 13.3 and in Figure 13.5. It is beneficial to use as many cut-offs as possible, if it is possible, since it will minimise the scrap pieces. In addition to the digital model of the design proposal, a physical scale model was built. The purpose of this is to be able to clearly visualise the different cross sections.

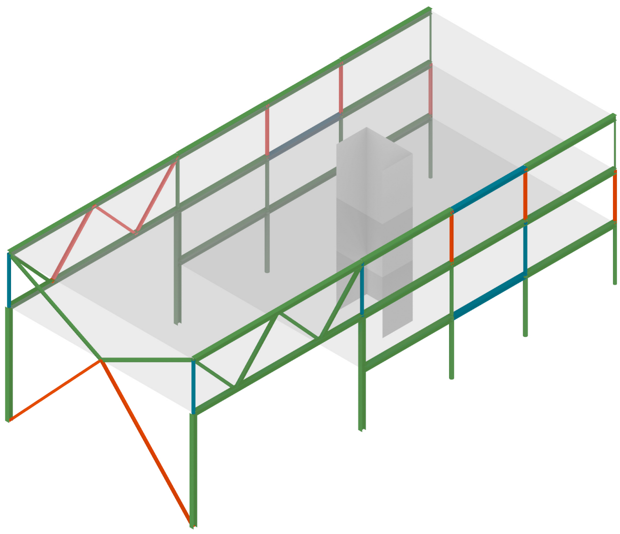

Figure 13.2: Digital model of the design proposal.

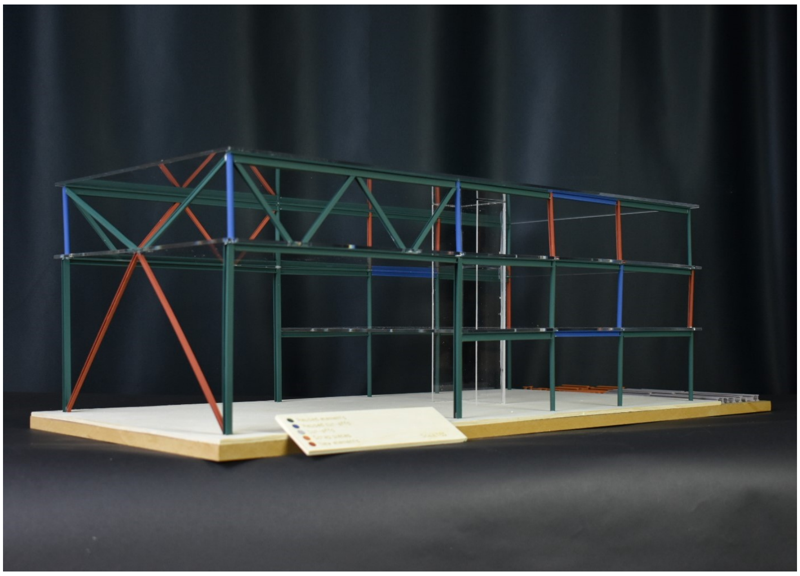

Figure 13.3: Physical scale model of the design proposal.

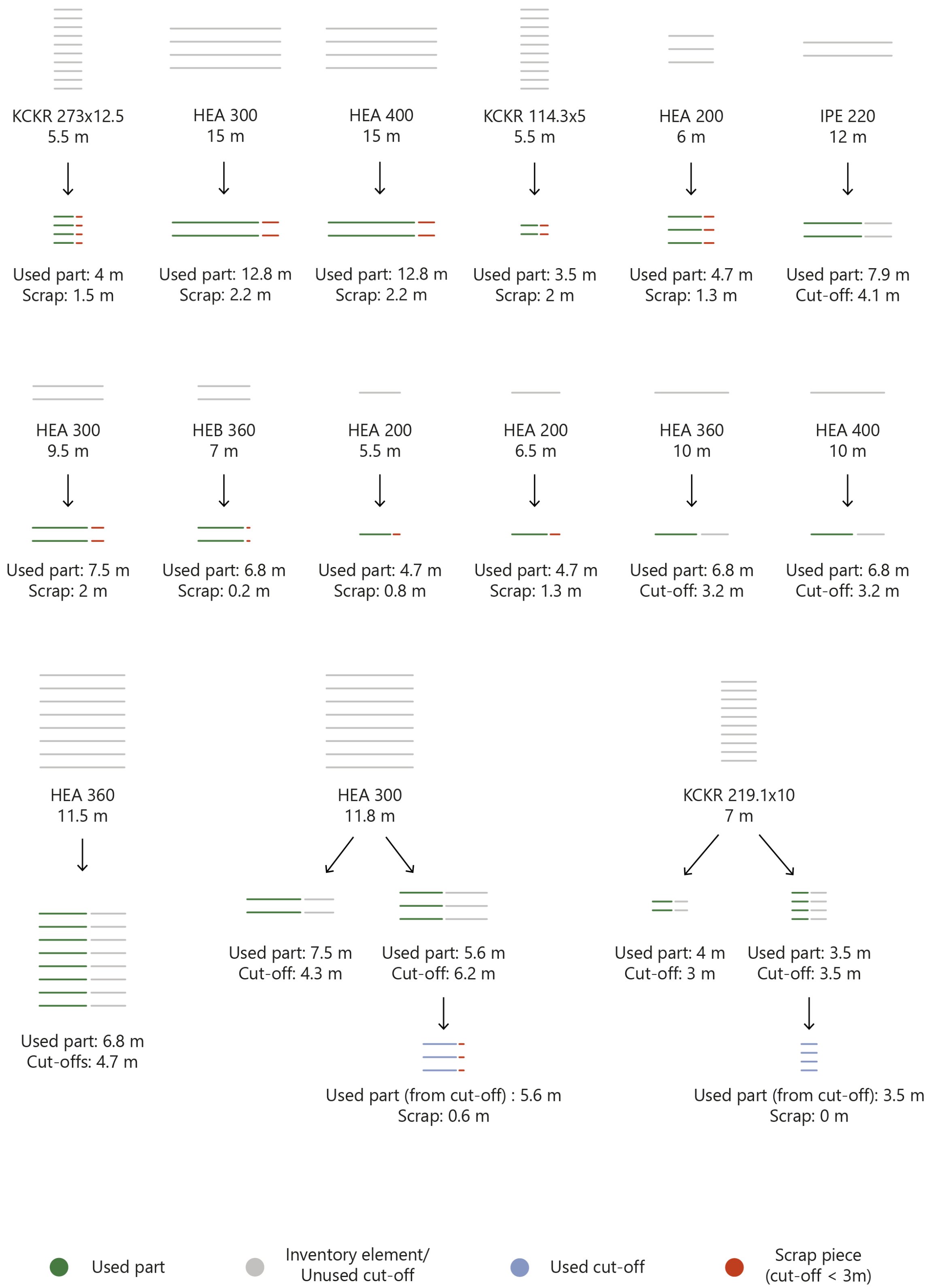

Figure 13.4: Figure showcasing which inventory elements were used, how they were cut, the lengths of the used pieces and their scrap piece, and the lengths of the cut-offs.

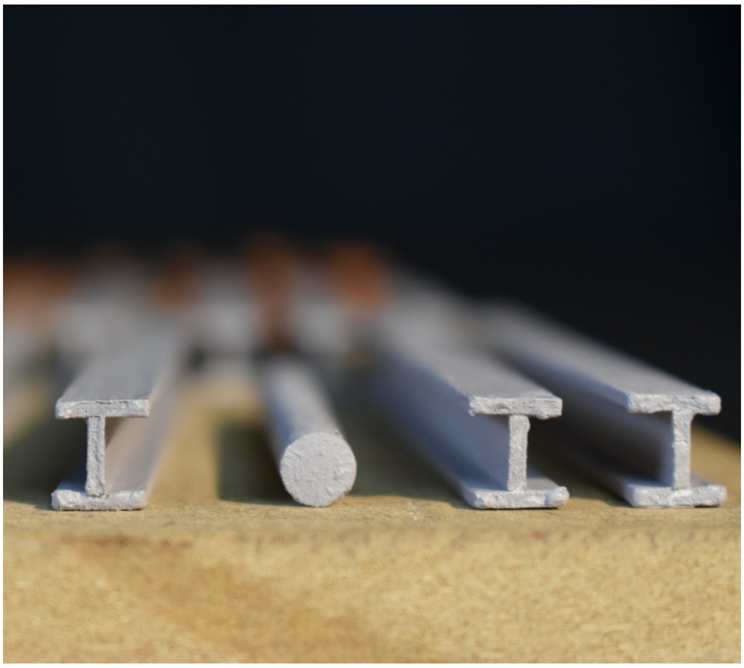

Figure 13.5: Physical scale model of the design proposal zoom in.

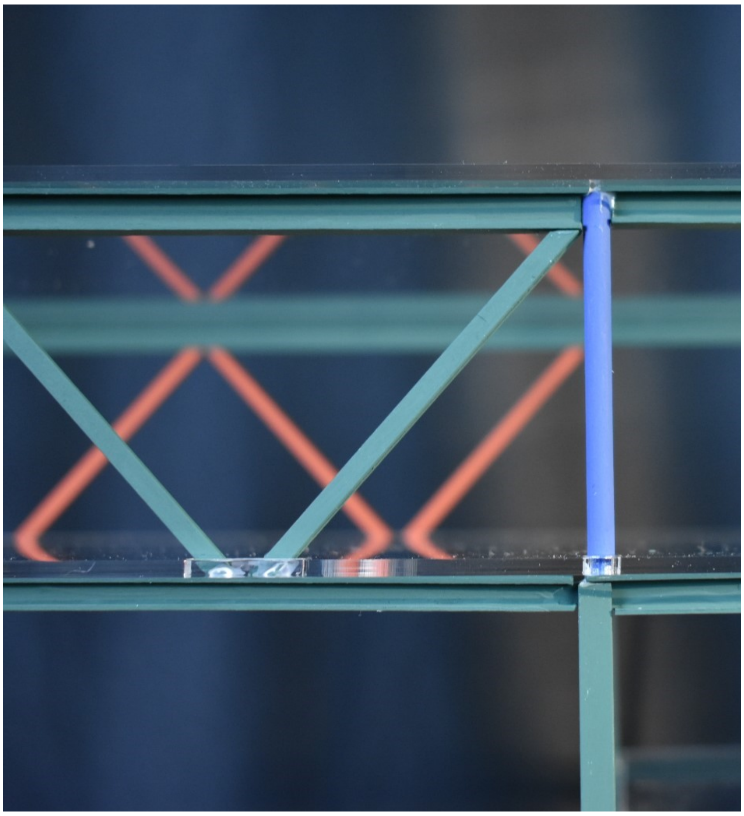

Figure 13.6: Physical scale model of the design proposal zoom in.

Part IV

Reflections

14
Discussion

The reuse of steel is a broad topic, which includes conflicts and uncertainties about its future development. Today, the inventories from steel suppliers in Sweden are small, and the projects that have implemented reuse are few. However, this might change in the years to come which will affect the way one is talking about and working with reuse across multiple disciplines. This discussion focuses on observations and results from the Contextualisation (Part I) and The Design Process (Part III). While also reflecting on further implementations, modifications and improvements of The Design Workflow (Part II). A starting point for the discussions will be taken in the context of today, but reflections on how these aspects might be affected in the future are also included.

14.1 Conflicts of reuse

While it is easy to say that reuse should be prioritised above everything else, one needs to have an overview of what implications incorporating reuse into the mainstream may have. There is a risk that marketing forces will make the reuse rate percentage valued higher than the actual saving of CO_2e. For example, the optimisation objective of a matching tool could instead be defined as the number of reused elements, which does not necessarily mean that the saving of CO_2e is greater.

During the design process performed in the thesis, a minimum allowed utilisation for matched reused elements is set, since it is more sustainable to leave elements having very low utilisation for projects where they are better utilised. However, limiting the allowed range of the utilisation may also cause conflicts and become an ethical question. In the beginning, projects implementing a high degree of reused elements will probably do a lot of marketing to showcase the sustainability of such a building. Naturally, every reuse project will want to reach as high a degree of reused elements as possible. Although, what happens if many elements are outside of the utilisation limits? What if 10% more of the construction could be reused if one allowed as lowly utilised elements as 20%? Though it may sound reasonable to leave elements, as they may be a better fit for another project, it is not certain that this will happen. Clients and the people marketing the buildings strive to make their projects as good as possible, and may not be willing to leave elements for other reuse projects by rivalling companies to grasp. Even if that is the most efficient way of saving CO_2 in total.

The testing procedures and the four categories that the inventory elements are sorted into could also have consequences that can be questioned. Elements that were created before 1971 are the ones that require the most testing, and this will make the prices of the testing procedure go up. So, solely sourcing steel produced after 1971 could be a way of saving money which may cause dilemmas. Will that lead to a pressure to tear down buildings constructed after 1971, even though they are in good shape and could be renovated? Selling steel elements for reuse in new construction should not be seen as a way of motivating or justifying the tearing down of buildings. It should be the last resort. The method with the least climate impact is to maintain the buildings that already exist and not tear down buildings that are still in good shape.

On that topic, another potential danger is the market forces and attitudes towards reuse talked about in the conversation with Musson and Leversha from WSP. Sustainability is being used as a selling point for projects and becomes a way for companies to increase their competitiveness in the market. The thesis student who was supervised by Musson found it difficult to find practitioners willing to talk to them since they did not want to share secrets. Rather than the industry working together to solve the climate crisis, information as to how projects have solved problems related to reuse is hidden.

Leversha additionally mentioned that the steel suppliers used to be able to buy very cheap scrap steel and sell it for a price lower than or comparable to that of new elements, after testing and reconditioning. However, with increased market demands, reused steel becomes more and more expensive. That some buyers are willing to pay more for reused steel is a good thing, but it makes it preferable to buy new elements for the companies that do not have large sustainability budgets, which affects the potential of reuse being implemented on a larger scale. However, in the future, the circularity of building materials will hopefully be more of a standard way of building than something that makes a building stand out. Maybe then, the demand for reused steel can become less driven by the urge to create successful demonstration projects.

14.2 Differences in workflow for reused steel from a stockist and from a donor building

In Sweden today, very few structural elements are reused and the stocks of reused elements at steel suppliers are relatively small and limited. Therefore, one could argue that if one can reuse any element, even with a very low utilisation, it is worth it since the element is not likely to be used in another project. This leads to a discussion about the intervals of utilisation that one should accept when working with reused elements in a new construction. The projects in London have set a limit, elements must have a utilisation between 70–100%, else the reused element can be used more efficiently in another project. This is not regulated in any way but is more a rule of thumb used in the industry. However, in a donor building, it is likely that the client already owns the elements, in that case, one can argue that all utilisation rates below 1.0 could be used, as it is not as likely that someone else will use the elements.

The design project of the thesis is made with an accepted utilisation between 50–100%. Unlike England, with their large stocks and several reuse projects, Sweden has different preconditions. It is not as likely that an element with a utilisation of 50% will be used more efficiently in another building. Also, with the current distrust against reuse that exists within the field, there is a point in showcasing that it is possible to construct a building with a large quantity of reused elements. However, in the future, if reuse becomes more mainstream, one should consider using a higher lowest limit depending on the preconditions of the project.

The utilisation interval could also be determined by whether the elements are taken from the inventory from Stena Stål, or if they are taken from the inventory inspired by the donor building. In the case of a steel supplier stock, there is a larger chance that another project might have use for the elements. In the case of a donor building, those elements may not be as likely to be picked up by other projects, as they may be harder to find. They may also already be bought by the client. Therefore, there may be grounds for not having a minimum limit on the utilisation, or at least for having a more generous span, when using a donor building.

It is not only the range of allowed utilisation rates that is affected by the type of inventory. Parameters such as the minimum reusable length for a cut-off part, and whether to include reusable cut-off parts in the cost for the optimization algorithm to minimise could differ depending on the stock. When using a steel supplier, the minimum reusable length must be long enough for it to be likely that use is found for the element in other projects, which may not yet be known. When the steel is already owned by the client, it may be easier to know alternative projects for which the steel could be used, and therefore be more specific concerning the reusable cut-off length. During the design process of the thesis, reusable cut-off parts are included in the cost of matching a reused element when using the optimisation algorithm. This comes from the reasoning that long and large elements are those having the largest environmental impact, and if the algorithm favours cutting long elements while there are shorter compatible elements available, the chances of a project needing a long reused element to find one are reduced. If a donor building is used and it is uncertain whether unused cut-off parts will be used in other projects, there may be reason to not include reusable cut-off parts in the cost.

14.3 Suitability for reuse

Even though one may wish that reuse could be implemented everywhere, there are several factors to consider. Firstly, the inventory elements have to be tested and evaluated. If they have been subjected to fire or cyclic loading, the elements should not be considered for reuse at all. Secondly, it is important to look into what type of structure the elements could be implemented into. Is it an office building, or a housing project? Thirdly, one has to look into on what scale it is possible to implement reused elements. Are we talking about isolated rooms with low aesthetic requirements, or does the client want to construct the entire building with reused elements?

14.3.1 Reuse on a smaller scale

A reuse project such as an office building will have aesthetic requirements, and in the future, there may have to be an aesthetic as well as a structural analysis of the inventory elements. But reuse might be more realistic to be implemented on a smaller scale first, where the elements can be hidden. Or in places with lower aesthetic requirements like storage rooms, bike sheds, sheet piles, temporary structures, or technical rooms for ventilation or technology that can be found in offices.

14.3.2 The type of structural element

When performing the Eurocode verification within the matching tool, quite many simplifications and limitations are applied to the truss elements, while not as many limitations are needed for the beams and columns. For example, the buckling lengths for the elements are taken as the lengths between the nodes, instead of performing a global buckling analysis which would be dependent on the stiffness distribution of the truss. Also, the truss calculations according to Section 6.4 in SS-EN 1993-1-1 are excluded as several elements need to be verified simultaneously, which is not supported by the tool. This means that the result from the tool is more reliable for the columns and beams, and it may indicate that truss elements are not the best type of elements to start with when implementing reuse.

Aesthetically, a truss is often more visible than columns and beams. Using the variety of cross sections that the reuse inventories offer today may lead to a fun expression that could be used to make reuse attractive. However, there is also a risk that the look of the truss becomes messy and chaotic instead.

14.4 Dependency on inventories

The inventory that is mainly used in the design project, coming from Stena Stål, has a large variation of elements where most of the sections are either quite small or quite large. This made the matching quite tricky, and many of the design sketches got low reuse rates since the larger inventory elements were too lowly utilised and the smaller elements failed the checks by being utilised too high or having too large deflections. As a consequence, this could lead to very few matches when working with a form-focused design approach, where the structure is not flexible to design changes.

The final design proposal has the highest reuse rate of all the initial sketches and is characterised by long spans and hollow core slabs that significantly increase the self-weight. Thanks to this, many of the larger inventory sections such as HEA360 and HEA400 have utilisation rates within the allowed range, as seen in figure 13.5. Also, it proved beneficial to have varying span lengths within the structure as there are not large quantities of identical elements in the inventory. So, to reach a high reuse rate with the investigated inventory, there is a need for either designing with a material-driven design approach, or allowing for design modifications after an initial matching is performed. The design modifications which proved most efficient for increasing the reuse rate for the investigated design and specific inventories are:

- Check the statistics as to why inventory elements were not matched and make changes accordingly.
- Manually check if parts of the horizontal stabilising system can be reused.
- Could a row of columns be moved to allow for a larger variation of spans and elements?
- Can elements such as truss elements be adjusted to enhance the reuse rate? For example, can the amount of truss spans be adjusted?
- Could the heights between the floors be adjusted to allow for a larger variation of elements?

However, the approach of designing with reused steel elements which is the most feasible will change as the steel suppliers' inventories become larger, and when reuse becomes more common. This can be seen when comparing the stocks and design process in England to Sweden. English steel suppliers have thousands of tonnes of steel elements, and statistics of the most common cross sections that they almost always have in stock. This means that English engineers have larger design freedom and a larger potential to achieve high reuse rates even when following a more form-focused design approach.

From the perspective of improving the environmental impact, it can be questioned whether it is beneficial to have an inventory that favours concrete slabs, as they have a large amount of embedded CO_2e (unless they are also reused). As CLT-slabs have a much lower carbon footprint, it can be argued that it is better to use CLT-slabs combined with fewer reused steel elements, compared to using concrete slabs combined with more reused steel elements. For the examined design, Table 11.3 shows the value of embedded CO_2e for the sketches when including the slabs and elevator shaft, while Table 12.5 shows the value of embedded CO_2e for only the steel elements. Here, it can be seen that the result of evaluating the design alternatives differs significantly depending on which of these values are studied. Table 11.3 highlights how much lower the climate impact of the structure as a whole is in Sketch one and four, where CLT slabs are used. Table 12.5 highlights how much lower the environmental impact of the steel structure is for sketch two, where HCF-slabs are used. So, for the specific inventory used in the project, there is a greater pay-off to use reused elements in projects which does not have the right preconditions for using timber slabs. This could be the case for projects requiring large spans or have strict acoustic requirements.

For this thesis, the value of embedded CO_2e which is used as a base for the evaluation matrix is for the final selection revised to only include the steel elements. This since it would be reasonable to assume that a project using reused steel would also investigate reusing the slabs, but this is unknown for the fictitious project. Also, as the main focus of the thesis is steel reuse, the evaluation of the sketches should focus on that. In a real project, the entire structure must be considered to get an idea of the climate impact as a whole.

14.5 Was the matching tool necessary?

It can be concluded that there is a need for some type of automatised workflow and matching procedure for structural engineers to work with reuse efficiently. This is important since the suggested method is very iterative, and it would be very time-consuming to do all calculations and matching by hand. The two discussed existing tools (Phoenix3d and Stockmatcher) help solve more isolated problems, as only a limited set of load effects and cross sectional properties are taken into consideration. These tools could have been applied if the elements in the design were analysed more separately. The columns and diagonal truss elements could have been matched by using Phoenix3d, and the beams by using Stockmatcher. For elements with combined bending moment and normal force, for example, the top and bottom chords of the truss, none of these tools would give an accurate result. So, an added value of using the self-scripted tool is to be able to match the entire structure in one run (with one pre-processing and one post-processing) and get accurate results for a larger variety of structural elements.

As already mentioned, the values of CO_2e for reused and recycled steel used for the design are taken from the climate database by Boverket (Boverket, 2023b). However, in a real project when there is more specific information concerning the climate impact of the reconditioning of the reused elements, distance of the transports, and which producer makes the recycled elements, these values might need to be adjusted. This is not possible in either Phoenix3d nor Stockmatcher, but it can be controlled by updating a parameter for the self-scripted matching tool. Other values that can be controlled by the user for the matching tool but are hard-coded for the existing tools are the minimum allowed cut-off length and allowed range of utilisation rates. As seen during the intentional phase, it is also beneficial that more compatibility checks can be added and that the cost of the matches can be adjusted to favour certain elements as more information about the project is gained.

14.5.1 Who should do the matching?

That there are more parameters to control for the matching tool compared to the existing tools means that there is a larger freedom to adjust it to project specific conditions, but it also requires more knowledge of the user. Time needs to be spent to understand the different parameters and experience in both FEM-Design and Rhino/Grasshopper is needed. To understand how the algorithm works and be able to adjust the compatibility checks and matching costs, some experience with the concept of optimisation and with C# programming is necessary. Sorting and grouping the parameters logically and creating thorough explanations and user instructions would be a way to make the tool more user-friendly.

In reality, there may be different structural engineering companies involved during different phases of the project, while the steel supplier remains constant. So, it may be more beneficial for some projects to have such a tool being used by the steel supplier instead. In that case, the tool may need to be adjusted for the software experience which is common for those who work there. Another option would be if a similar mainstream tool was developed and could be used by multiple companies.

15 Future works

This thesis has set limitations and made simplifications to account for the time frame of the thesis. However, the principal workflow and matching tool may have the potential of being applied to different projects and even other materials than steel. Some aspects that are not considered in this thesis would be of great importance if such a design project were to be built in reality, such as the connections between the elements.

15.1 Implementation beyond steel

Although this thesis is limited to focusing on steel elements, the principal workflow, matching tool, and the method of working with reuse can be implemented on other materials, such as hollow core slabs or timber beams. This would require a modification of the parameterised FEM model to include shell elements and the Excel lists of inventories would need to be updated. The Eurocode verification performed by the matching tool would need to be expanded to also include relevant checks according to SS-EN 1992 and SS-EN 1995, and the remaining compatibility checks may need adjustments. For example, a check ensuring that the widths of the slabs are large enough would need to be included, in addition to the check of their lengths.

15.2 Defining alternative optimization objectives

As already mentioned, the motivation behind reusing steel should mainly be to improve the environmental impact of a project. Therefore, a suitable optimization objective for a reuse project is to minimise the total amount of embedded CO_2e, including the scrap pieces. However, there may be project-specific reasons for defining other optimisation objectives. For example, in Phoenix3d the user can choose between minimising the amount of embedded CO_2e, minimising the amount of waste, and minimising the total weight of the structure, both while including the scrap pieces and while not including them.

Modifying the matching tool to minimise the total weight of the structure would be rather easy. To do this, the weight of the elements would need to be taken as input instead of the CO_2e, and whether or not to include the scrap pieces would need to be specified in the function defining the cost of performing an assignment. Another compatibility check would also need to be added to make sure that an inventory element is not heavier than the target element which it is replacing.

For minimising the waste there are two alternative approaches. For the first approach, the optimisation objective would be to minimise the volume of the cut-off material. To do this, the cross section area would need to be taken as input instead of the CO_2e, and the cost of performing an assignment would need to be taken as the cut-off length multiplied by the cross section area. The second approach is applicable when there are existing bolt holes intended to be used for the new construction. Then, the optimisation objective would be to maximise the number of elements with a cut-off length equal to zero. Since the A* algorithm is developed to minimise cost paths, this modification is not as straightforward as the first approach. One way to do it would be to set the cost of making an assignment that does not lead to a cut-off to zero, and the cost of making an assignment that leads to a cut-off to one.

Another possible optimization objective would be to maximise the utilisation rates of elements in the structure. To do this, the cost of performing an assignment would need to be equal to one divided by the utilisation rate of the inventory element, as the task of the algorithm is it minimise the total cost.

Finally, another possible optimization objective would be to maximise the number of matches. This could be done in a similar way as when maximising the number of matches leading to a cut-off length equal to zero. The cost of performing an assignment would need to be equal to zero, and for all target elements where no assignment can be made a cost of one is added.

15.3 Computational efficiency vs quality of the solution

Figure 10.16 illustrates the speed of the algorithm and shows that the run time very fast becomes unreasonably long for a larger number of matches than eleven. To solve this problem, the target elements are sorted according to their amount of embedded CO_2e, and the optimization is performed for separate sub-groups. As seen in Table 10.4, this results in a slightly higher value of the total amount of embedded CO_2e of the structure. One way to further develop the matching tool would be to continue investigating how the algorithm can give a better result within a reasonable run time.

As seen in the example presented in Section 10.6, the heuristic estimate is important for guiding the algorithm towards the optimal solution without investigating bad candidates. The estimate used for the final iteration of the tool does not consider the cut-off parts of the inventory elements, which could both misdirect the algorithm and possibly make it dismiss candidates finding efficient ways to use them. So, making a more precise estimate which includes the cut-off parts could be one way of both making the algorithm faster and possibly making it find a better solution. There are also examples in literature where the A* algorithm has been made faster by running the calculations of the heuristic estimate on the graphics processing unit (GPU).

(Zhou and Zeng, 2015; Weinstock and Holladay, nd).

For elements in the inventory, there are typically several identical elements. Giving all identical inventory elements the same index and keeping track of how many of them have been used proved to be an efficient way of making the algorithm faster, compared to giving each individual inventory element its own unique index. This is because it reduces the branching factor b. It may also be possible to make similar groupings of target elements which have almost the same geometry and load effect, and give them the same index. This could reduce the depth d of the problem making the algorithm even faster.

In the code, all candidates are placed in a list and the new candidates which are generated from the already started candidates are always put last in it. This means that the candidates that are at the end of the list are closer to being finalised and their weights are therefore more realistic. So, even though a candidate at the beginning of the list has a low weight, its weight is probably more optimistic than the weights of the candidates placed at the end of the list. One way to make the algorithm faster could be to make a few candidate expansions, and then initially only search at the end of the list for candidates to continue expanding. Then, only when enough candidates have been discarded and the list is shorter, the beginning of the list is searched. This approach is more consistent with a 'depth-first' search as the algorithm prioritises to increase the depth of started candidates before expanding more candidates, and it could be a way of reducing complexity (Russel and Norvig, 2010). How large parts of the list that is searched at a time, and when to start examine the beginning of the list would need to be further examined.

A common way to increase computational speed is to run algorithms using several parallel threads. Due to the sequential nature of the A* algorithm, it is difficult to make an efficient parallel A* search (Zhou and Zeng, 2015). However, there are examples in literature where the nodes of the graph (matches) are divided to be handled by different processors (Weinstock and Holladay, nd) which has increased the computational efficiency. This could also be something to investigate to be able to increase the group sizes when running the algorithm, and possibly run the whole set of target elements at once.

According to (Hart et al., 1968), who first published the A* search algorithm, the heuristic estimate must be lower than or equal to what is achieved in reality to be able to guarantee that a globally optimal solution is found. However, in the same article it is stated that the computational speed can be increased by increasing the heuristic estimate. This will however mean that the found solution is not necessarily globally optimal. This could be examined as an alternative to using the sub groups for the optimisation and it could be compared which approach that achieves the best result in the shortest time.

15.4 Eurocode verification

The Eurocode verification in the design workflow is self-scripted in C# and performed in the same Grasshopper component as the optimization algorithm. Due to time constraints, the verification is very specific for the design project and only the checks relevant to the chosen geometry and types of cross sections are included. This also means that the information concerning material grades and cross sectional properties of the inventory elements need to be input into the matching tool together with the parameters related to the optimisation algorithm. In total 47 values are input into the matching tool which makes it difficult for the user to get an overview of the relevant parameters. Therefore, one way of making the workflow more user-friendly would be to separate the Eurocode verification from the algorithm, and possibly produce the entire compatibility matrix in a different Grasshopper component. The workflow would also become more general and it would be faster to apply it to other projects if the verification calculations were not self-scripted but could be performed within FEM-Design.

In a meeting with Marco Pellegrino from Strusoft, who are the developers of FEM-Design, it was discussed that it would be beneficial to perform a larger part of the workflow in C# using Visual Studio and the FEM-Design API, instead of Grasshopper. It is also discussed that a simpler way to perform the structural verification could be to use interaction volumes. Interaction volumes are graphical representations of the combinations of moments and axial forces for which the capacity of a member is great enough (StruSoft, 2023). FEM-Design currently only supports creating interaction volumes for concrete members. But, if there is support for creating interaction volumes for steel in the future, they could be used for performing the structural checks used for creating the compatibility matrix.

During the meeting, it was also questioned whether it is necessary to perform a full Eurocode verification for the matching tool. As already discussed in Section 9.4.3.3, an alternative approach would be to compare the cross sectional properties of the target elements and the inventory elements, and perform a verification after the matching has been performed. This would make the matching process more simple but with a greater risk of elements failing the final verification check. This would need to be further examined by performing the matching using the two different approaches and comparing the results.

15.5 Connection design

Almost every steel structure has critical connection points that require a thought-out design. The proposal in this thesis is no exception. Detailed design of the connections would be necessary if this project was to be built or further developed. This may also become additionally challenging due to the large variety of cross sections that are available in the reuse inventory. For example, there are some nodes in the truss system where many different elements of different sizes and different types of cross sections meet. If it is not practically possible to design these connections in such a way that all centre lines meet at the same point, some additional moments due to eccentricities might need to be considered in the Eurocode verification of the members. There might also be some local variations in cross section resistance due to the detailing of the members that should be accounted for. It is important to map any effect that the detailing has on the member verification and account for it in the design workflow to make the design more realistic.

One example of centre lines not meeting at the same point is the connection between a column and two beams of different depths. As the upper flanges of the beams need to be at the same level to support the slab, the centre lines of the beams cannot meet the centre line of the column at the same point (see figure 15.1). To limit this problem, one idea would be to introduce a condition to the matching tool, setting a maximum depth difference between two adjacent beams. Another example could be the case where two columns of different sizes are placed on top of each other (see figure 15.1). Where this happens for columns along the facade (assuming that the columns are offset from the walls), it is reasonable that it is preferred to have all columns aligning with the outer wall, as it saves space and makes it easier to attach the facade. This would mean that the centre lines of the columns are not meeting at the same point causing a moment in the lower column. This moment would then need to be accounted for by the matching tool. Alternatively, eccentricities and local strength reductions could be accounted for by reducing the maximum allowed utilisation.

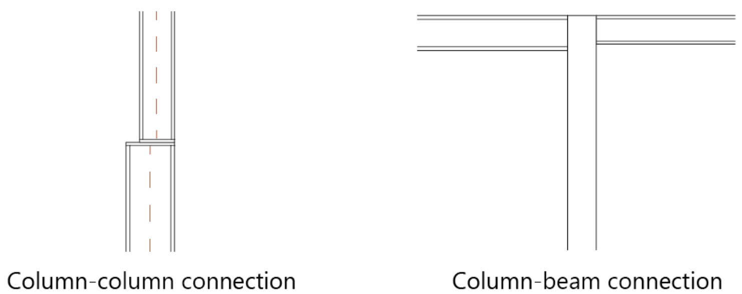

Figure 15.1: Sketches of connections with different sized elements.

The inventory elements built up from L sections already have bolt holes at the ends. If a design where these elements are used would have been chosen, it would also be relevant to examine if the existing bolt holes could be used again. This would additionally constrain the geometry of the truss as no cut-offs can then be allowed, or only cuts at the locations of any intermediate bolt holes. The maximum load effect of the members could then also be limited by the resistance of the bolts fitting in the holes. To account for this checks that consider the type of connection and type of bolts would need to be included in the matching tool.

15.6 Common cross sections

During the intentional phase, the tool is modified to favour cross sections that are common in the inventories. This means that if the inventory has a large amount of the same cross section, the tool should aim to use as many of those elements as possible. The reasoning behind this is that these elements are less sensitive to changes. If the inventory is updated and three of the inventory elements of that section disappear, there are still elements with the same cross section left that can be used instead. Although, one can question if this favouring will help at this stage, and the answer is that it probably will not. It may even be a disadvantage, as there might be a higher demand for large amounts of identical elements. However, in the future, if the inventories become larger and the demand for reused elements rises, the common cross sections can provide important data. Statistics of historical inventories can map common sections that are likely to appear in the inventory. In that case, a favoring of common sections can be beneficial.

15.7 Changing the inventory

Having longer and varying span lengths, larger self-weights and larger spacing is not guaranteed to increase the reuse rate in every design project. It just reflects the specific inventory at the time of receiving the lists from Stena Stål. Tibnor is another steel supplier in Sweden that has recently started to offer reused steel as well. Also, in the future, there may be records of historic inventories from both Stena Stål and Tibnor where it can be seen how much the availability of elements varies over time. To further understand which design modifications are most beneficial depending on the specific inventory, the design process using the digital workflow could be performed for several inventories from different suppliers and at different times. This could also be done to further test the workflow, and discover any changes needed to make it more general.

During the intuitive phase, some preventive design principles are defined to reduce the structure's vulnerability to changes in the inventory that may occur between the preliminary design phase and the time of constructing the building. Also, some actions are mapped that could be made to solve the problem when a reused element planned to be used in the design disappears from the inventory. However, no actual inventory changes are made in the later design phases which could have been a way to test and evaluate the effectiveness of the principles and actions. It would also be relevant to examine how much the inventory can change without considerably changing the reuse rate of a design.

16
Conclusion

What key tasks included in the reuse workflow directly affect the work of the structural engineer?
There are many different workflows one can apply when working with reused steel, depending on the project. For example, a project that aims to reuse elements from a donor building is different from a project that only uses steel supplier inventories. Some alternative workflows are presented in Figure 6.2, Figure 6.3 and Figure 6.4 where the tasks performed by the structural engineer are highlighted. The main task of the structural engineer is to explore how a structural system can be matched to reused elements and how to account for changing inventories. As all suggested workflows are repetitive, an important task of the structural engineer is to find efficient ways to repeat the same calculations. If the preconditions of the project allows for it, another task is to find which design modifications that enable a higher reuse rate.

What could an inventory of reused steel elements look like and which uncertainties could be associated with such inventories?
Reuse inventories in Sweden today are relatively small, with limited amounts of different cross sections, and limited quantities of the same cross section. When working with a steel supplier, there is a risk that elements are sold to other projects and a chance of new elements being added to the inventories. Elements from a donor building are likely already owned by the client, which makes such inventories more stable. However, if the design process and testing of the elements are performed in parallel, there is the risk of elements not passing the quality assurance.

What characterises an optimized structure in the context of reuse, and how can this be translated into an optimization objective?
In general, an optimized structure is characterised by a low environmental impact. A suitable optimization objective would then be to minimise the total amount of embedded CO_2e. It is also important to consider scrap material in the numbers. There may be project-specific requirements motivating other optimisation objectives, but it is important to note that a large number of reused elements does not always equal the largest saving in CO_2e. Ultimately, the saving in CO_2e should be prioritised to avoid greenwashing.

How can an inventory of reused structural steel elements be used in a new structure in an optimized way and what tools can aid this process?
Reused elements can be matched to a new structure using optimization algorithms. The A* search algorithm is an example of such an algorithm, but several alternative

algorithms can be used. As inventories might change and several design options might need to be investigated, it is also of great help to have an automatised matching workflow to save time. To account for project specific requirements the tool need to be flexible, and may need to be combined with some manual work as well. Today, access to such tools is quite limited as the ones open to the public are simplified and hard to implement on more complex structural systems. More advanced tools are often developed internally by companies and are not open for everyone to use.

The process also benefits from having an iterative design approach. When many different design sketches are generated in the preliminary design phase, the design team could get an idea of which type of structure would lead to the smallest amount of embedded CO_2e. Through iterations, refinements, and small design modifications, the CO_2e saving can be increased even more. This requires openness and flexibility from all involved disciplines.

What design verifications according to Eurocode are directly affected by the fact that the elements are reused?
Since the testing of the elements ensures that they are equivalent to new elements, almost no Eurocode checks are affected by reuse at all. The only check that is affected is the buckling verification where it is recommended to slightly reduce the resistance to account for any imperfections not detected during the testing.

How can reuse influence the design of the structural system, and what qualities and compromises can this lead to?
Reuse can influence the design by allowing for a larger variety of cross sections and by adjusting parameters such as span lengths to enable a high reuse rate. This could have consequences for the aesthetics and functionality of a building as adjusted span lengths could limit the floor plan. The varying cross sections could look motley and playful, but they could also look miss-placed. However, based on the results in the Design Process, small changes in the design can lead to large savings in CO_2e. The CO_2e savings is the largest quality of reusing steel and, when applied appropriately, reuse have the potential of being one of the strategies ensuring that sustainability goals within the construction industry are reached.

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A
Appendix 1

Max. of load combinations, Steel bar, Utilization - for selected objects

Member	**Section**	**Maximum utilisation**
[-]	[-]	[%]
Beam 0	HE-A 400	61
Beam 1	HE-A 300	78
Beam 2	HE-A 360	73
Beam 3	HE-B 360	71
Beam 4	HE-A 300	73
Beam 5	HE-A 360	70
Beam 6	HE-A 360	69
Beam 7	HE-A 300	71
Beam 8	HE-A 360	69
Beam 9	HE-B 360	70
Beam 10	HE-A 300	71
Beam 11	HE-A 360	69
Beam 12	HE-A 360	51
Beam 13	HE-A 300	57
Beam 14	HE-A 360	51
Beam 15	HE-A 360	51
Beam 16	HE-A 300	57
Beam 17	HE-A 360	51
Column 0	HE-A 300	62
Column 1	HE-A 300	63
Column 2	KCKR 273-12.5	48
Column 3	KCKR 273-12.5	48
Column 4	KCKR 273-12.5	49
Column 5	KCKR 273-12.5	49
Column 6	KCKR 219.1-10	50
Column 7	KCKR 219.1-10	50
Column 8	KCKR 219.1-10	49
Column 9	KCKR 219.1-10	49
Column 10	KCKR 219.1-10	50
Column 11	KCKR 219.1-10	50
Column 12	HE-A 160	92
Column 13	HE-A 160	92
Column 14	KCKR 219.1-10	48
Column 15	KCKR 219.1-10	48
Column 16	KCKR 219.1-10	60
Column 17	KCKR 219.1-10	60
Column 18	HE-A 160	71
Column 19	HE-A 160	71
Column 20	HE-A 160	71
Column 21	HE-A 160	71
Column 22	KCKR 114.3-5	83
Column 23	KCKR 114.3-5	83
Columncont 0	HE-A 300	71
Columncont 1	HE-A 300	65
Cross 0	HE-A 160	96
Cross 1	IPE 240	75

Cross 2	HE-A 160	95
Cross 3	IPE 240	76
Trussbot 0	HE-A 300	101
Trussbot 1	HE-A 300	100
Trussdiag 0	HE-A 200	99
Trussdiag 1	HE-A 200	56
Trussdiag 2	HE-A 200	55
Trussdiag 3	HE-A 200	71
Trussdiag 4	HE-A 200	93
Trussdiag 5	HE-A 180	67
Trussdiag 6	HE-A 160	92
Trussdiag 7	HE-A 160	94
Trusstop 0	HE-A 400	61
Trusstop 1	HE-A 400	60

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