BSc Thesis Civil Engineering

Comparative life cycle assessment (LCA) and life cycle cost (LCC) analysis of a structural design with new steel elements and a structural design with reused steel elements

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Preface

This bachelor thesis titled “Comparative life cycle assessment (LCA) and life cycle cost (LCC) analysis of a structural design with new steel elements and a structural design with reused steel elements” is executed as a final individual assignment in order to obtain the Bachelor of Science degree in Civil Engineering at the University of Twente. The research was commissioned by the global engineering consultancy company Bilfinger Tebodin and was carried out mainly from April until June 2023.

First, I would like to express my sincere gratitude to my external supervisor Thijs Evers and all the colleagues from the Architectural, Structural and Building Services department for the warm welcome at the office in Hengelo and for the opportunity to conduct my research there. Their incessant enthusiasm, friendliness, invitation to the weekly meetings and to not forget the constant coffee support made me feel as a real member of the team and showed me the ways in which work is done in a professional environment. Also, I very much appreciate the nice talks we had during the lunch break walks. Special thanks goes to Maarten Onland and Lei Hendriks whose immense expertise, invaluable help and key insights contributed to my understanding of how structures work in detail and how to model them properly in different structural analysis programs. Complementary to that knowledge, I am very grateful to Thijs for his higher-level suggestions which helped me capture and express the bigger picture of this research in a way that could reach a larger audience.

Furthermore, the exceptional guidance, encouragement and critical feedback from my internal supervisor João Oliveira dos Santos ensured the high quality of the presented information and played a major role in the successful completion of this bachelor thesis. He really made me appreciate the beauty and at the same time the complexity of life cycle assessment. Also, his mentorship has not only enhanced my research skills but also inspired me to strive for excellence.

Last but not least, I am incredibly grateful to my family for their unwavering support and encouragement throughout the challenging journey of writing my bachelor thesis. Their belief in my abilities have made this process much more rewarding and have been instrumental in keeping me motivated.

Finally, I believe that the results of my thesis hold the potential to increase the decision-making capability of the engineering team at Bilfinger Tebodin in terms of the environmental impact of their design choices in future projects. Moreover, I have strived to uncover meaningful insights and practical implications which can offer innovative solutions to the challenges that the construction industry is currently facing.

I hope that the reader will find value in reading my thesis!

Georgi Nikolov
Enschede, June 2023

Executive summary

Objective

The main goal of this research project is to evaluate and compare the environmental and economic sustainability effects of reused steel elements compared to new steel elements for the design of a section through a factory located in the Netherlands by conducting a life cycle assessment (LCA), life cycle cost (LCC) analysis and a structural design analysis.

Methodology

The present study consists of essentially three main parts that are briefly summarised here. The first one is a structural analysis that investigates the necessary procedures and assumptions for the optimisation of the current design and what additional testing and changes are required when considering reclaimed steel elements as compared to new steel elements. This was done via literature research and with the help of the structural modelling program Technosoft Raamwerken V6. The second main component is the LCA that evaluates the environmental impact and provides a calculation of the shadow prices of the original and optimised designs via the Environmental Cost Indicator. In this part, a scenario analysis is performed for four cases that are based on the Environmental Product Declarations (EPDs) created by the steel research organisation Bouwen met Staal and are the following:

- Original design of the structure with 100% new steel in the product stage and 16% reuse of the material in the end-of-life stage based on EPD1
- Optimised design of the structure with 100% new steel in the product stage and 16% reuse of the material in the end-of-life stage based on EPD1
- Optimised design of the structure with 90% reused steel & 10% new steel in the product stage and 16% reuse of the material in the end-of-life stage based on EPD2
- Optimised design of the structure with 100% new steel in the product stage and 80% reuse of the material in the end-of-life stage based on EPD3

Finally, the third part is a parallel and complementary LCC analysis that evaluates the economic performance of the four scenarios over their life span of 50 years including the initial and future costs. Also, a sensitivity analysis of the costs as a function of the discount rate is performed to ensure the robustness of the results.

Results

From the structural analysis part a few destructive and non-destructive tests were identified which serve to ensure that the mechanical properties of the reclaimed steel elements are up to standard. Examples of the tests include tensile tests, hardness tests, Charpy impact test and instrumented indentation testing. This type of testing is necessary because the modelling program that is used for the optimisation of the structure assumes certain default parameters of the steel elements. If there is a mismatch, the results will be incorrect and might cause critical failure once the structure is built. Also, some of the main identified constraints that are associated with reusing steel elements are that the donor building must not be built prior to 1970, no signs of corrosion are present and the elements have not been exposed to extreme loads. In the end, the optimised design had 15.47% less material than the original design when considering only the beams and the columns. However, when the recommendations for reusing steel elements are applied it was found that extra supports are needed to mainly prevent lateral torsional buckling of the bearing beams.

The results from the LCA show that in terms of kgCO_2eq when the original design made with new steel elements is compared to the optimised design with reused steel elements there is a reduction of 83% of the global warming potential of the whole structure. If the same comparison is made only for the optimised design with new and reused steel elements, there is 80% decrease in CO_2 emissions. Regarding the shadow costs expressed by the environmental cost indicator, there is a 73% reduction in the environmental costs from the original design made with new steel elements to the optimised design

made with reused steel elements if the potential savings in module D are included – from € 2301 to €618 for the whole structure. If the same comparison is made for the optimised design modelled with EPD1 and EPD2 the reduction is approximately 69%.

Finally, the LCC analysis shows a 50% reduction in the LCC value between the original design built with new steel elements and the optimised design with reclaimed steel elements at 5% nominal discount rate and 4.4% inflation. If the same comparison is made for optimised design made with new and reused steel elements the reduction is 40% even though in all cases there are extra costs incurred for testing and reconditioning the reclaimed elements.

Conclusion
At present, there is an ever-increasing shift towards more environmentally friendly and economically efficient structural designs in the construction industry due to the climate change phenomenon. Therefore, companies are striving for the development of effective solutions that aim to achieve the targets set by the United Nations in the Sustainable Development Goals (SDGs) in 2015 (UN, 2015) and by their national governments (e.g. the Climate Law in the Netherlands (Klimaatwet, 2019)). Therefore, this report clearly shows and evaluates the environmental and economic trade-offs of reusing structural steel elements with the hope that the insights gained from the LCA and LCC analysis of this case study will facilitate the decision-making process within Bilfinger Tebodin.

Keywords: Life cycle assessment, life cycle cost analysis, structural analysis, reusability of structural steel elements, environmental cost indicator, environmental product declaration, destructive and non-destructive tests for steel elements, new steel vs reused steel trade-offs, sustainability in the construction industry

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Terminology

Consequence class 1 (CC1) - low consequence for loss of human life, and economic, social or environmental consequences small or negligible. (NEN-EN 1990, 2002)

Consequence class 2 (CC2) - medium consequence for loss of human life, economic, social or environmental consequences considerable. (NEN-EN 1990, 2002)

Consequence class 3 (CC3) – high consequence for loss of human life, or economic, social or environmental consequences very great. (NEN-EN 1990, 2002)

Global analysis - determination, in a structure, of a consistent set of either internal forces and moments, or stresses, that are in equilibrium with a particular defined set of actions on the structure, and depend on geometrical, structural and material properties. (NEN-EN 1990, 2002)

Rigid plastic analysis - analysis, performed on the initial geometry of the structure, that uses limit analysis theorems for direct assessment of the ultimate loading. (NEN-EN 1990, 2002)

Elastic analysis - analysis, performed on the initial geometry of the structure, that uses limit analysis theorems for direct assessment of the loading until the yield point of the material. (NEN-EN 1990, 2002)

Buckling length - system length of an otherwise similar member with pinned ends, which has the same buckling resistance as given member or segment of member (NEN-EN 1993-1-1, 2006)

Environmental Product Declaration (EPD) - communicates verifiable, accurate, non-misleading environmental information for products and their applications, thereby supporting scientifically based, fair choices and stimulating the potential for market-driven continuous environmental improvement. (NEN-EN 15804:2012 + A2, 2019)

Environmental Cost Indicator (ECI) – unites all of the relevant environmental impacts into a single score of environmental costs, representing the environmental shadow price of a product or a project. It is expressed in Euro. (Hillege, 2021)

1. Introduction

Nowadays due to the climate crisis, there is an increasing pressure on every sector in the economy to reduce its carbon footprint and thus contributing to limit global warming to 1.5 °C compared to pre-industrial levels as stipulated in the Paris Agreement in 2015 (UNFCCC, 2015). Specifically, the Netherlands has set its goal in the Dutch Climate Act to be a net-zero country by 2050 (Klimaatwet, 2019). There is a market shift that is reinforcing this notion globally. Since the concern of governmental regulatory agencies and clients is growing, an increasing number of companies are trying to incorporate techniques for sustainable design in their projects, as a means of reducing greenhouse gas emissions (GHG) and improving resource efficiency.

Focusing on buildings as a source of GHG emissions, the *Bringing Embodied Carbon Upfront* report from 2019 by the World Green Building Council states that buildings are responsible for 39% of global energy related carbon emissions of which 11% come from materials and construction while the rest 28% come from the operation phase in their life cycle. Moreover, the buildings and infrastructure sector account for more than a half (~52%) of the steel use worldwide (World Steel Association, 2023).

In addition, when the global CO2 emissions are split by economic sector, industry (incl. cement, chemical, petrochemical, aluminium etc.) is responsible for around 27% (~9.4 GtCO2) in 2021 (IEA, 2023), and of that portion around 29% (~2.7 GtCO2) is attributed to iron and steel (IEA, 2022). This means that steel is the biggest emitter in the industrial sector leading by 2% on cement which is the second biggest emitter.

To get a rough idea about the actual quantity of GHG emissions of steel, a study done in 2022 by the World Steel Association gathered data about certain environmental performance indicators from 104 steel companies representing 56% of global crude steel production and reported 1.91 tonnes of CO2 emissions per tonne of crude steel cast only from the production processes. So, there are almost 2 times (1.91 times to be exact) more GHG emissions than actual steel products. Moreover, the steel industry is responsible for 5% of CO2 emissions in the EU (JRC, 2022) and around 7% globally (IEA 2020). This is evidently not sustainable and very harmful to the climate.

Therefore, it can be said that optimizing the design of buildings and considering the reusability of steel elements for their construction have the potential to contribute to the reduction of the GHG emissions and ultimately help in the resolution of the climate crisis.

1.1. Research Context

Currently, there is a projection that the demand for buildings materials is expected to double by 2050, however by then the global carbon emissions must be reduced by at least 50% (Allwood et al., 2010). This, coupled with the fact that steel is considered to be the second most common material used for the construction of buildings (Chen et al., 2022) right after concrete, means that structural engineers and builders should aim to apply methodologies of reducing the use of new steel elements in their designs and try to reuse some of the already produced components elsewhere. However, this is not a popular practice, in fact Gorgolewski et al., (2006) have found that most reclaimed steel elements are used in small amounts for small projects by local builders often requiring individual pieces and not ordering large quantities.

Therefore, certain barriers of reusability of steel elements are present. Tingley et al. (2017) identified the availability of an accurate and properly managed material database as a major concern. Moreover, The Steel Construction Institute (SCI, n.d.) in the UK has classified some more predicaments and has provided a ranking based on the perception of some stakeholders[1] (Figure 1). They give examples such as:

- Availability of reclaimed sections (size, volume, location)
- Quality, certification of reclaimed sections
- Additional time and cost to the design team
- Uncommon practice – not many organizations have the skills/experience to do it

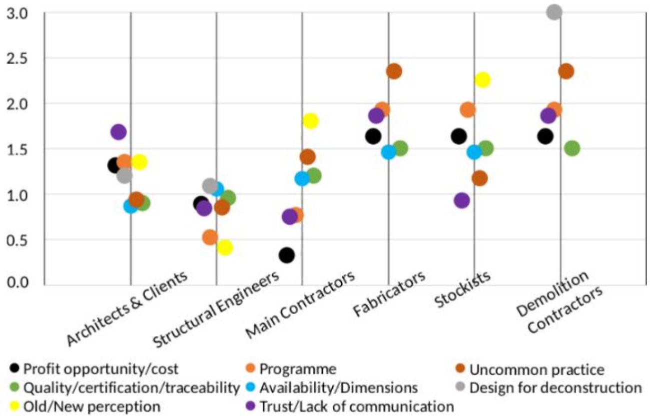

Figure 1: Barrier ranking by actor – the higher the score the higher the perceived importance (Source: SCI, n.d.).

Furthermore, according to Brand (1995) a building is made of 6 layers, namely Stuff, Space Plan, Services, Skin, Structure and Site. The lifespan of each layer is shown in Figure 2. It can be seen that the structure is expected to last a very long time (up to 300 years) as compared to the rest of the layers. Therefore, even when a building loses its functionality after a period of time (e.g. 15-50 years), the structural elements have the potential to be reused elsewhere, either under the same conditions or for different purposes.

Bilfinger Tebodin recognizes this opportunity and at the same time it acknowledges the obligation to reduce the environmental impact of its projects as outlined in the Climate Act by the Dutch government (Klimaatwet, 2019). So, they want to do their part and investigate the possibility of reusing steel in future industrial projects. This could potentially lower the carbon footprint of the structures and thus position the company among the frontrunners of the net-zero transition in the construction sector. In this context, second hand steel might become a very important asset in the future, but as of this moment

[1] "Stockist" means a retailer that stores goods, in this case used structural elements.

the NEN-EN[2] codes do not provide any guidelines on how the calculations should be done or what assumptions should be made for such reclaimed material (Anastasiades et al., 2023).

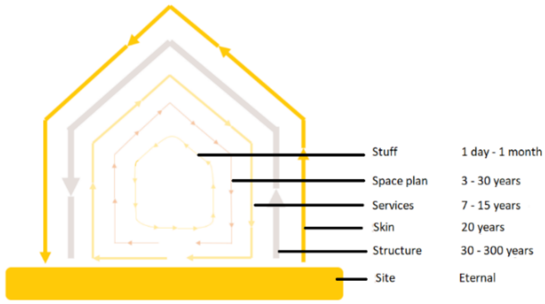

Figure 2: Building layers and their respective lifespans. (Source: Brand, 1995)

1.2. Problem Statement

In the construction industry there is currently an evolving paradigm shift from a more linear way of working (produce-use-demolish) to an approach that has internalized the reusability of structural elements (Van Dijk et al., 2014). Currently, Bilfinger Tebodin is behind this trend since the engineers "consider only new steel elements for their industrial projects" (T.Evers, personal communication, February 23, 2023) whose production is causing high GHG emissions (World Steel Association, 2022). This is a problem since it accelerates the global warming crisis (Ramanathan & Feng, 2009). Moreover, nowadays there is a market shift influenced by regulatory agencies and clients that are demanding more sustainable solutions in the construction sector (Tinker & Burt, 2004) as mentioned in the introduction.

To address these issues, the engineers at the company are aware that certain structural design calculations and practical rules of thumb considering reclaimed steel exist, however they have no experience in how to apply them in their projects. Also, they want to know if such a design will ultimately have less harmful impact on the climate and what will be the economic effect of it.

Therefore, the contribution of this research project is twofold: 1) to address the gap in the structural mechanical knowledge of the company about reusability of steel elements and 2) to evaluate the environmental and economic effects of the two designs in two scenarios *(i) with new steel elements, (ii) new + reused steel elements*. The design of the first alternative is already done and the second one is the optimised version of it. Here the adjective "optimised" refers to the structure that is obtained after selecting the steel profiles in such a way to achieve maximum exploitation[3] under the load combinations described in section 3.3.

Moreover, the results could serve as a reference source for academics in their research on sustainability in the construction industry. This addresses goal number *12: Responsible Consumption and Production* from the Sustainable Development Goals (SDGs) (UN, 2015) and especially target *12.5: By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse*.

1.3. Research Objective

In view of the problem statement the definition of the research objective is: *"to evaluate and compare the environmental and economic sustainability effects of reused steel elements compared to new steel elements for the design of a section through a factory located in the Netherlands by conducting a life cycle assessment (LCA), life cycle cost (LCC) analysis and a structural design analysis"*.

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[2] During the writing of this report on June 6th 2023, a new Dutch Technical Agreement - NTA 8713 (2023) was published by the Royal Dutch Normalisation Institute (Stichting Koninklijk Nederlands Normalisatie Instituut) as a first step towards a standard procedure for reusing structural steel.
[3] Exploitation of a structural profile means that the force it resists is close to its yield strength.

1.4. Research Scope

The study will investigate only the large structural elements such as beams and columns and will disregard the smaller ones, such as connections, tapered haunch segments or flange supports. Also, only local stability checks will be performed, thus excluding global stability checks of the structural design.

1.5. Research Questions

In this section, an overview of the main research questions and their respective sub-questions following the research objective is presented.

1. ***What will be the result for the new structural design of a section through the factory[4]'s production hall with reused steel elements after optimisation?***

1.1 What procedures, standards and norms should be followed when designing an industrial steel structure?

1.2 What destructive and non-destructive tests should be done to verify the mechanical properties of the steel elements?

1.3 What loads should be considered?

1.4 What assumptions have to be made in the structural calculations in order to utilize reused steel elements for the design of the section in the factory?

2. ***What assumptions and limitations should be made and considered for creating an LCA model for both designs?***

2.1 What is the functional unit of the model?

2.2 Which life-cycle phases are included?

2.3 What inputs and outputs can be included in the inventory analysis phase?

2.4 What are the assumptions for the impact of second-hand steel elements?

2.5 Which factors are the most influential based on a sensitivity analysis?

3. ***What assumptions and limitations should be made and considered for creating an LCC model for both designs?***

3.1 Which costs can be identified during the life cycle phases?

3.2 Which factors are the most influential based on a sensitivity analysis?

4. ***What insight can be gained by comparing the results for the LCA and LCC analyses of the two designs?***

4.1 What are the environmental impacts during different life-cycle phases of the two designs?

4.2 What are the environmental impacts of different components of the two designs?

4.3 What are the economic impacts during different life-cycle phases of the two designs?

5. ***What recommendations can be given in terms of the preferable alternative based on its environmental and economic performance?***

5.1 What is the calculated environmental cost indicator (ECI) for both designs?

[4] Due to a confidentiality agreement with Bilfinger Tebodin the exact location and purpose of the factory is not mentioned in this report.

2. Research Design & Methodology

In this chapter, the methods that will be used to answer the research questions and sub-questions are presented and then a research model is shown. Important to note is that desk research and expert elicitation will be most common techniques used in this bachelor thesis. The rationale for this choice is that a lot of information will be necessary both from literature and from the engineers at the company. The advantage of the second technique is that it will significantly accelerate the development of the structural model because it will save a lot of extra empirical work. Whereas, the limitations to the first technique is the availability of up-to-date data and collection of literature that follows a certain confirmation bias.

2.1. Research Methods

For main research question 1, desk research and expert elicitation are the leading strategies. In this way, the necessary information to investigate what assumptions and steps one should follow to make a structural design and tests in order to use reclaimed steel elements (Q1.1-Q1.3) is obtained. Also, the engineers at the company will provide expertise on how to model and optimize the design in the structural analysis software tool – Technosoft Raamwerken V6 (Q1.4). The final output of this part is the optimised design of the structure.

For main research question 2, it is important to gain an in depth understanding of the constituent life cycle phases (Q2.2) of both designs. This can be done via literature research and in consultation with my internal supervisor. The same applies to the determination of the functional unit (Q2.1) and to the compilation of the life cycle inventory phase of the LCA where the relevant inputs and outputs of the system shall be identified (Q.2.3). The subsequent translation of those flows into the environmental impact will be done with the help of the previously developed LCA model. The GaBi software provides access to the ReCiPe method of impact assessment which will be used as a starting point. Any relevant assumptions are included in consultation with the internal supervisor (Q2.4). If there is data availability issues relevant environmental product declarations will be used. Lastly, a sensitivity analysis or scenario analysis will be performed to identify the most and least influential factors to the calculated results or to assess how the results change for each scenario (Q2.5).

For main research question 3, the life cycle cost analysis will be performed in conjunction with a life cycle assessment. Therefore, the characteristics of the latter apply to the former such as system boundary, functional unit, geometrical characteristics of the two designs, life cycle inventory etc. To identify the costs experts, literature and case studies will be consulted (Q3.1). Diversifying the sources will result in a more accurate final calculation. Here a sensitivity analysis will also be performed to see the effects of changing the input variables and provide an insight to the robustness of the model (Q3.2).

For main research question 4, the final results from the LCA and LCC analysis of both structural design will be compared and evaluated (Q4.1 – Q4.3). Therefore, consulting with my internal supervisor and/or other competent experts is very important in order to ensure the validity of the conclusions. Also, a cross check with literature will prove useful for the robustness of the results.

Finally, for main research question 5, recommendations will be given in terms of which design has less environmental impact and which one is cost effective. This will be achieved by considering the answer to main question 4 and by calculating and comparing the environmental cost indicator (Q5.1).

2.2. Research Model

Now a schematic of the steps that will be taken as part of the proposed methodology is presented in Figure 3. The chart is divided into 4 main blocks representing the main research questions. Between the second one (LCA) and the third one (LCC) there is a connecting arrow which is double headed to indicate the mutual dependency and iterations that are expected to take place.

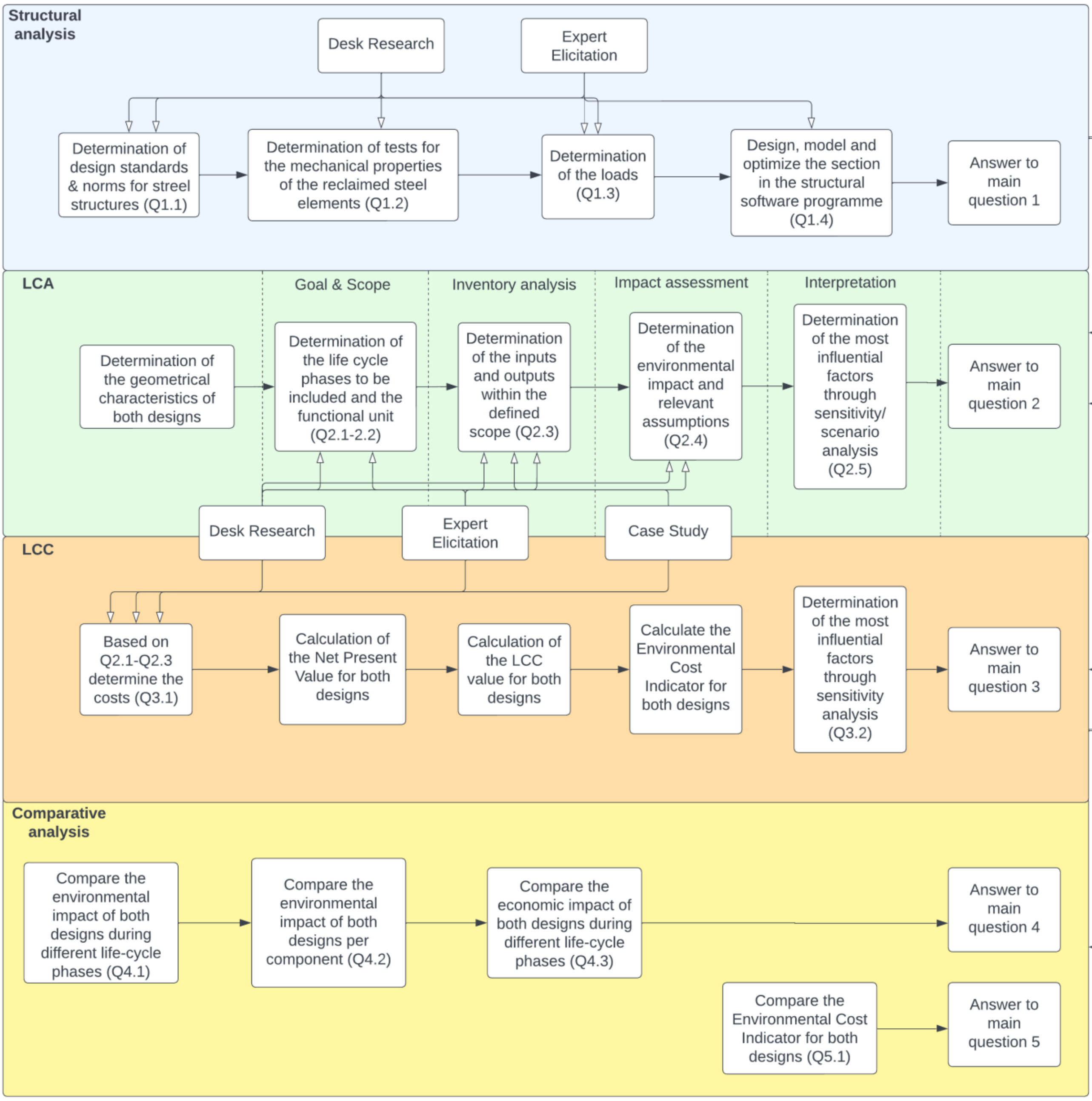

Figure 3: Schematic representation of the methodology.

3. Structural Model

In this chapter, first the destructive and non-destructive tests to determine some of the material properties (e.g., yield strength, cross-sectional dimensions) of the steel elements are outlined in case there is no documentation that states them explicitly. This is done to ensure that the elements fall within the permitted deviations described in NEN-EN 1090-2 (2018) before the structure is modelled in Technosoft Raamwerken V6. Otherwise, the results of the structural calculations might not reflect the real situation because the software assumes certain averaged values for the parameters based on NEN-EN 1993-1-1 (2006). These preliminary tests, could serve as a starting point for any potential refurbishment or additional fabrication processes that have to be performed to guarantee that the steel elements are up to standard prior to reusing them depending on their origin. Next, an overview of the load combinations considered for the structural calculations is presented. Finally, the original and optimised structural models of the section through the factory are described.

3.1. Destructive tests of material properties

Destructive tests are performed in a laboratory and usually samples are taken from the studied element. These are obtained through invasive procedures such as drilling, cutting etc. Further details for sampling are described in NEN-EN 10025-2 (2019). Examples of such tests are given in Table 1.

Table 1: Examples of Destructive Testing techniques for material properties.

Test	Description	Reference standards
Tensile test	The purpose of this test is to determine the yield strength, tensile strength, modulus of elasticity and elongation at failure.	Depending on the temperature at which the test is performed different standards can be followed. For example: • At room temperature – EN ISO 6892-1 (2019) • At elevated temperature - EN ISO 6892-2 (2018)
Chemical composition analysis	This test is important to ensure that the weldability of the steel elements is up to standard as well as the impurity levels. Also, it identifies the chemical elements such as carbon, manganese, phosphorus etc.	For further details on how to conduct the test, EN ISO 14284 (2022) should be consulted. Noteworthy, is that the chemical composition should be as described in sec. 6.6 of EN 10219 (2019).
Charpy impact test	This test enables the engineer to determine the quality of the steel in relation to toughness, i.e. the sub-grade that is commonly expressed as either JR, J0 and J2 (Brown & Iles, 2012).	For the test procedures, EN ISO 148-1 (2017) can be consulted.

The above table should not be considered as exhaustive or complete. There are more destructive tests that exist which include tear test, biaxial test etc. It serves as an example of the procedures that could be followed when the origin and properties of the steel elements are not known.

3.2. Non-destructive tests of material properties

Here, the non-destructive tests for determining material properties such as tensile strength, hardness, stress-strain relationship, steel grade etc. are outlined. These can be performed on the construction site and do not require specific sampling technique. Some examples are included in Table 2.

Table 2: Examples of Non-Destructive Testing techniques for material properties

Test	Description	Reference standards
Hardness test	The accepted definition of this test is the one of Adolf Martens in 1912, which is that hardness is the resistance of a body to indentation by another (harder) body. (Broitman, 2017) Noteworthy, is that the result should be based on at least 3 measurements in the same location and any present coating should be removed from the steel element to be tested. (PROGRESS, 2020, sec A.6.4). In addition, from this test it is possible to derive the yield strength and the tensile strength via equations (1) and (2) as discussed by Fujita and Kuki (2016). This then can be used to estimate the steel grade of the element. An example calculation for such procedure is described in section A.6.4 of PROGRESS report (2020).	There are three potential standards that should be consulted for the details of the test. Those are: • Brinell hardness test (EN ISO 6506-1, 2014) • Vickers hardness test (EN ISO 6507-1, 2018) • Rockwell hardness test (EN ISO 6508-1, 2016)
Instrumented indentation testing	This test resembles the first one, but the difference is that there are loading and unloading cycles.	The results of this test include the elastic modulus and hardness. For more details, consult EN ISO 14577-1 (2015).
Positive metal identification	This test is very cost-effective, quick and portable. It uses X-ray fluorescence for verifying the chemical composition of the steel elements.	Main purpose of this test is to determine the weldability of the steel elements. For the detailed procedures of the test, EN ISO 19272 (2015) can be consulted.
Visual inspection and determination of the remaining life of the element	Based on a "condition score" on the scale of 1-6 (Excellent – Very bad) the relative age of the element can be calculated (NEN-EN 2767-1, 2019, sec. 4.1).	The calculation of the remaining life of the element can be performed according to sec. 5.4, equation (2) in NEN-EN 2767-1 (2019).

Since the yield strength and the tensile strength can be determined by both types of tests, conclusions should be made based on the destructive tests as they are considered more reliable (PROGRESS, 2020, sec A.6.5).

Moreover, important general note is that for the calculation of the cross-sectional properties the measured (actual) dimensions not the expected ones should be used in case they are not within the accepted tolerances. Also, the straightness of each steel element should be checked with EN 1090-2 (2018) and if the deviations are too high appropriate correction techniques should be applied (PROGRESS, 2020, sec A.9.1 & A.9.2).

3.3. Load combinations

In this section, only the governing load combinations of the modelled section are discussed due to space limitations and because there are 119 of them as identified by the Technosoft structural software. The rationale behind this choice is that they are considered to have the most extreme (unfavorable) effect on the structure. Therefore, if the design is proven to be able to resist those loads then it is not necessary to check the capacity of the structure in the other cases.

For this project, two main approaches for the design of the structure are adopted, namely for *strength* or Ultimate Limit State (ULS) and *deflection* or Serviceability Limit State (SLS) according to NEN-EN 1990 (2002). The corresponding combinations in Technosoft that determine the loads for those two states are the *Fundamental* and the *Characteristic* combinations, respectively.

The considered loads are in total 17 (values in kN/m are shown in Figure 43 to Figure 59 in Appendix A) and are the following:

- Permanent loads (self-weight)
- Permanent loads (solar panels)
- Variable loads (installations)
- Variable loads (people q_k)
- Variable loads (people Q_k)
- Wind from left & underpressure A/B
- Wind from left & overpressure A/B
- Wind from right & underpressure A/B
- Wind from right & overpressure A/B
- Wind perpendicular & underpressure
- Wind perpendicular & overpressure
- Snow A
- Snow B

The source information for the solar panels and installations loads is provided in the design brief for the factory and for the rest the relevant Eurocode is followed. The A/B variation of the wind load cases is due to the fact that in NEN-EN 1991-1-4+A1+C2/NB+C2 §7.2.3; Table NB.7 – 7.2 note 3 (2020) mentions that both the negative and the positive value of the external pressure coefficients have to be considered. Also, the reason for the A/B variation of the snow load cases is that since beam 8 is abutted right next to a higher part of the structure it allows for potential snow accumulation growing in a linear fashion(Figure 42 and Figure 59 in Appendix A).

Since the section is 100.8m long and it is located at 75m from the beginning of the building the governing load combinations are not the same for all the elements. An overview of the optimised design is shown in Figure 8 from which it becomes clear that there are 12 steel elements in total of different profiles. The optimisation process of the beams and columns is explained in section 3.5.

The governing load combinations per element for the ULS and SLS are shown in Table 3.

Table 3: Governing load combinations per steel element.

Steel element №[5]	Governing ULS load combination According to eq. 6.10b[6]	Governing SLS load combination According to eq. 6.14b[7]

[5] Figure 63 in Appendix A shows which element is represented by which number.
[6] Source for the coefficients NEN-EN 1990+A1+A1/C2:2019/NB; table NB.4 – A1.2(B) (2019) and Figure 60 in Appendix A provides the equation.
[7] Figure 61 in Appendix A.

1 & 2 (column)	1.20*(Perm.loads) + 1.20*(Solar panels) + 1.50*(Wind from left & underpressure B) + 1.50*(Installations) + 1.50*(Var.l.peop. q_k)	1.00*(Perm.loads) + 1.00*(Solar panels) + 1.00*(Wind from left & underpressure A) + 1.00*(Installations) + 1.00*(Var.l.peop. q_k)
3 (column)	1.20*(Perm.loads) + 1.20*(Solar panels) + 1.50*(Wind from left & overpressure B) + 1.50*(Installations) + 1.50*(Var.l.peop. q_k)	1.00*(Perm.loads) + 1.00*(Solar panels) + 1.00*(Wind from left & underpressure B) + 1.00*(Installations) + 1.00*(Var.l.peop. q_k)
4 (column)	1.20*(Perm.loads) + 1.20*(Solar panels) + 1.50*(Wind from right & underpressure B) + 1.50*(Installations) + 1.50*(Var.l.peop. q_k)	1.00*(Perm.loads) + 1.00*(Solar panels) + 1.00*(Wind from left & underpressure A) + 1.00*(Installations) + 1.00*(Var.l.peop. q_k)
5 (column)	1.20*(Perm.loads) + 1.20*(Solar panels) + 1.50*(Installations) + 1.50*(Var.l.peop. q_k)	1.00*(Perm.loads) + 1.00*(Solar panels) + 1.00*(Wind from left & underpressure A) + 1.00*(Installations) + 1.00*(Var.l.peop. q_k)
6 (column)	1.20*(Perm.loads) + 1.20*(Solar panels) + 1.50*(Wind from right & underpressure B)	1.00*(Perm.loads) + 1.00*(Solar panels) + 1.00*(Wind from right & underpressure B)
7 (column)	1.20*(Perm.loads) + 1.20*(Solar panels) + 1.50*(Wind from right & overpressure A) + 1.50*(Installations) + 1.50*(Var.l.peop. q_k)	1.00*(Perm.loads) + 1.00*(Solar panels) + 1.00*(Wind from left & underpressure A) + 1.00*(Installations) + 1.00*(Var.l.peop. q_k)
8 (beam)	1.20*(Perm.loads) + 1.20*(Solar panels) + 1.50*(Snow B) + 1.50*(Installations) + 1.50*(Var.l.peop. q_k)	1.00*(Perm.loads) + 1.00*(Solar panels) + 1.00*(Snow B) + 1.00*(Installations) + 1.00*(Var.l.peop. q_k)
9 (beam)	1.20*(Perm.loads) + 1.20*(Solar panels) + 1.50*(Snow A) + 1.50*(Installations) + 1.50*(Var.l.peop. q_k)	1.00*(Perm.loads) + 1.00*(Solar panels) + 1.00*(Snow B) + 1.00*(Installations) + 1.00*(Var.l.peop. q_k)
10 (beam)	1.20*(Perm.loads) + 1.20*(Solar panels) + 1.50*(Snow A) + 1.50*(Installations) + 1.50*(Var.l.peop. q_k)	1.20*(Perm.loads) + 1.00*(Solar panels) + 1.00*(Snow A) + 1.00*(Installations) + 1.00*(Var.l.peop. q_k)
11 (beam)	1.20*(Perm.loads) + 1.20*(Solar panels) + 1.50*(Snow A) + 1.50*(Installations) + 1.50*(Var.l.peop. q_k)	1.00*(Perm.loads) + 1.00*(Solar panels) + 1.00*(Snow A) + 1.00*(Installations) + 1.00*(Var.l.peop. q_k)
12 (beam)	1.20*(Perm.loads) + 1.20*(Solar panels) + 1.50*(Snow A) + 1.50*(Installations) + 1.50*(Var.l.peop. q_k)	1.00*(Perm.loads) + 1.00*(Solar panels) + 1.00*(Snow A) + 1.00*(Installations) + 1.00*(Var.l.peop. q_k)

It is important to note that all of the calculations are performed according to the corresponding Eurocodes and their Dutch national annexes (if applicable). Those include:

- NEN-EN-1991-1-1 (2002)
- NEN-EN-1991-1-3 (2002)
- NEN-EN 1991-1-3+C1+A1/NB (2019) (national annex)
- NEN-EN-1991-1-4 (2005)
- NEN-EN 1991-1-4+A1+C2/NB+C2 (2023) (national annex)
- NEN-EN 1990+A1+A1/C2/NB (2020) (national annex)
- NEN-EN-1990 (2002)

3.4. Assumptions and limitations

Here firstly the assumptions for the modelling of the structure are presented below. It is important to mention them as they provide a transparent description of the simplifications that are necessary to represent the real situation in the software. Also, the context in which the structure is modelled and optimised becomes clear. Therefore, the following points are included and a brief explanation of the rationale is provided below each.

- No extra forces from wind bracings is implemented in the calculations

Due to the global stability of the factory wind bracings are present in certain locations in order to resist lateral forces. The structure in this study is such an example. However, the above assumption is made in order to simplify the load cases and combinations.

- Beam to column connections are modelled as hinged connections instead of fixed connections because the latter is more expensive to produce and to practically implement.

This assumption was verified in Technosoft by modelling a simple portal frame in two cases (i) with fixed connections and no horizontal support and (ii) with hinged connections and a horizontal roller support. The former was found to introduce bigger moments in beams that require larger profiles which in turn assuming an average price per kg of steel results in a higher cost.

- The main supports are modelled as hinged supports and the horizontal one is modelled as roller support.
- Bearing beams are made from the IPE profile which was found to be the most economically efficient among all the steel profiles

Since bearing beams must resist mainly vertical loads the moment of inertia (second moment of area) of the strong axis (in this case y-y) has to be sufficiently large. Many profiles meet this criteria, however, because IPE profiles have shorter flanges it means that the total mass expressed in kilograms of steel is reduced thus lowering the cost.

- Columns are made from the HEA profile which was found to be the most economically efficient in terms of €/kg.

Similarly, to the previous assumption, HEA profiles were found to be more efficient as compared to their HEB and HEM counterparts. HEB profiles have equal width and height, whereas HEM profiles have a lot thicker web and flanges. Therefore, in both cases the total mass of steel required to produce these beams is increased which costs more.

- The loading width of the bearing beams (Dutch: *liggers*) and some of the columns is assumed to be 1.1 times or 110% the normal loading width because of the roof deck plates (Figure 4). Note that the 40% reduction is not included since the 3-field roof plates do not start where the structure is, but before it. In the studied section the normal loading width is considered to be 5m so 5.5m is taken (Figure 62 in Appendix A).

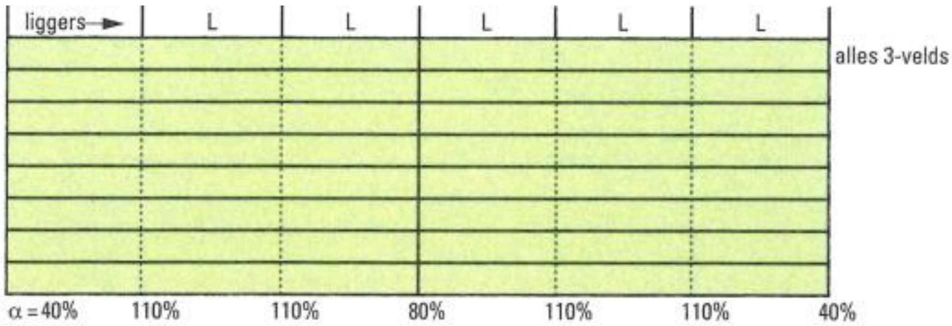

Figure 4: Force transfer steel roofing sheet (Source: Bouwen met staal, 2019)

- An even more optimised design would be one that considers semi-rigid connections instead of fully-hinged connections, because the moments in the middle and the end of the beam would be almost equal thus reducing the amount of required material and lowering the overall cost (Figure 5).

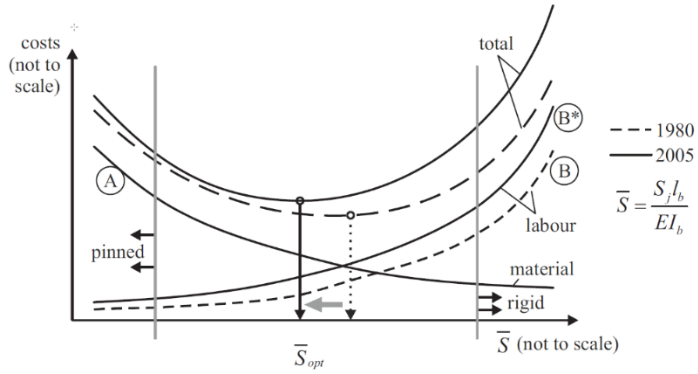

Figure 5: Costs of steel structures depending on the relative joint stiffness. (Source: Velikovic et al., 2015)

- For the majority of the bearing beams there is a camber that is applied in the model in order to reduce the deflections in the characteristic load combinations for the SLS. For the precise values per beam Table 13 in Appendix A is provided. The basic idea behind it is that the beam is "pre-bent" before it is installed in the structure (Figure 6). For more details on cambering consult with Gergess and Sen (2008).

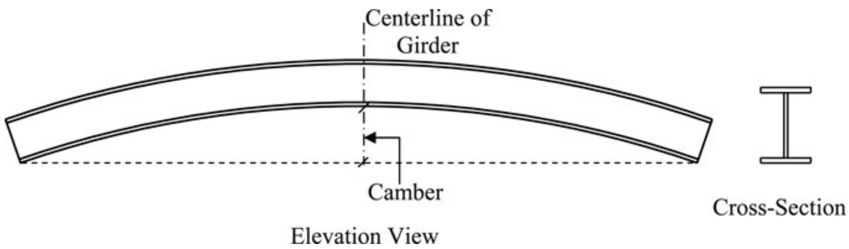

Figure 6: Camber in a structural steel beam. (Source: Gergess and Sen, 2008).

- Finally, the structural calculations are performed with an expected design life of 50 years. Therefore, no reduction in the safety level via lower partial factors is required due to the fact that the design is not considered to be part of an existing building (in situ reuse) or to be relocated elsewhere (PROGRESS, 2020, chapter 8.2.2).

One of the limitations of the structural model is that the connections and the detailing are not done. The reason behind this is that it would add an additional layer of complexity. Even though the produced results might be more accurate, the time required for the implementation would be disproportionate to the potential benefit that might be obtained.

Moreover, as it is explained in the next section a change in a certain calculation parameter is needed in order to design the section with reused structural steel elements. However, the software does not allow the user to amend those. Therefore, the necessary corrected calculations are made manually.

3.5. Final optimised design

In this section, the optimisation of the original design is performed according to standard procedures outlined in NEN-EN 1993-1-1 (2006) and the corresponding Dutch national annex NEN-EN 1993-1-1+C2+A1:2016/NB (2016) with the help of Technosoft Raamwerken V6 structural software. A design is considered optimised in the program when the unity check value for all elements is always below 1, but as close as possible to 1. This means that the profiles are optimally exploited. Figure 64 in Appendix A shows the unity check of all of the used profiles in the optimised design. It can be seen that the most critical effects such as lateral torsional buckling, buckling and displacement are between 0.8 and 1 for all 7 profiles. Figure 65 in Appendix A shows the unity check for all of the used profiles in the original design. It is evident that some of them are not optimised because the values of their critical effects are less than 0.60.

The results will serve for determining the geometrical characteristics and product information necessary to perform the LCA described in the next chapter. Finally, the necessary changes to the optimised design when considering reclaimed steel elements based on the procedures described in the PROGRESS (2020) report are discussed.

In Figure 7, the original design is presented. The height of the structure is 12m and the width is 100.8m. Noteworthy is that the lowest level is set to 10.80m because of the existing higher buildings next to the location of the structure considered in this study. “This causes the designer to choose a greater reference height that in turn results in a more conservative wind load estimation than simply continuing with the height of the structure” (Maarten Onland, personal communication, April, 2023). Also, only the bearing beams have a larger steel grade (S355) due to the large spans of 24m which cause larger moments that need to be resisted by the cross-section. The optimised design is presented in Figure 8.

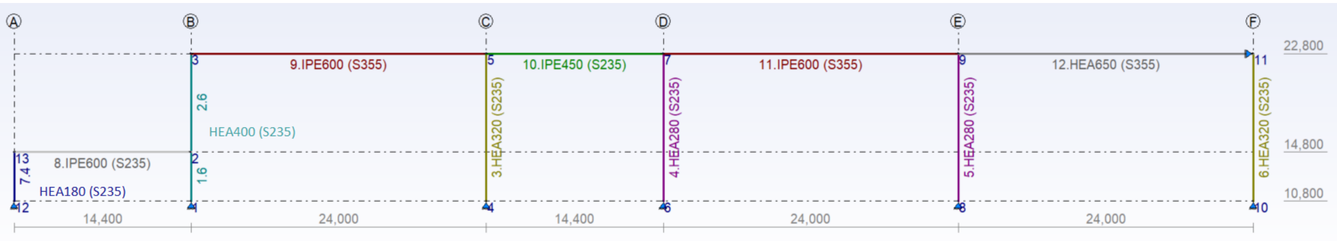

Figure 7: Overview of the original design. Dimensions in m.

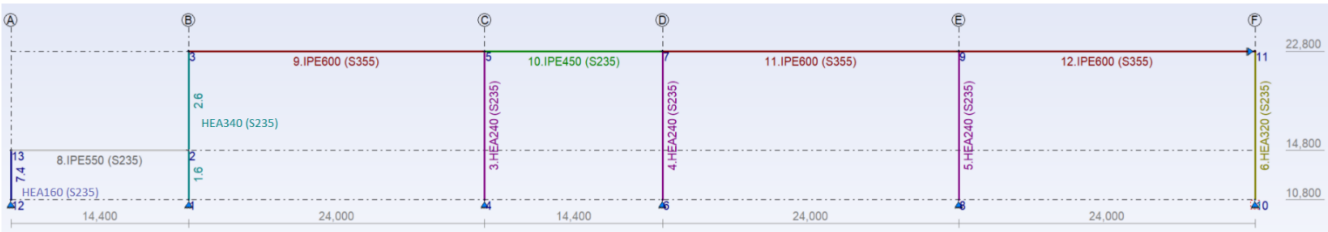

Figure 8: Overview of the optimised design. Dimensions in m.

When comparing the two designs, it is observed that the main differences occur in the column profiles. The original design has bigger profiles which is likely to increase the construction costs and the environmental impact because of their production while the optimised is considered to have more efficient use of the profiles.

In the following subsection, some additional design considerations are applied to the optimised version of the structure in order to see what changes are necessary if reclaimed steel elements are used instead of new ones.

3.5.1. Recommendations for designing with reused steel elements

The main considerations that are included in the scope of this study and that have to be acknowledged by the structural engineer when designing a structure with reused steel elements are the following:

Consideration	Source
Steel elements should be reused only if the source building is not built before 1970, because around this time the ultimate limit state design approach was more widely adopted.	(PROGRESS, 2020) (Brown et al., 2019)

Steel elements should not be reused if they have been exposed to extreme loads such as accidental impact or fire.	(Brown et al., 2019)
Steel elements should not be reused if they come from a structure subject to fatigue. For example, steelwork from bridges.	(Brown et al., 2019)
Steel elements which have been selected for reuse shall be recovered in their original length.	(PROGRESS, 2020)
Steel elements should not have local corrosion or damage.	(PROGRESS, 2020)

Once the elements have been filtered based on the above considerations, they can generally be categorized in 3 classes which are *Class A*, *Class B* and *Class C.* A brief explanation is provided in Figure 9.

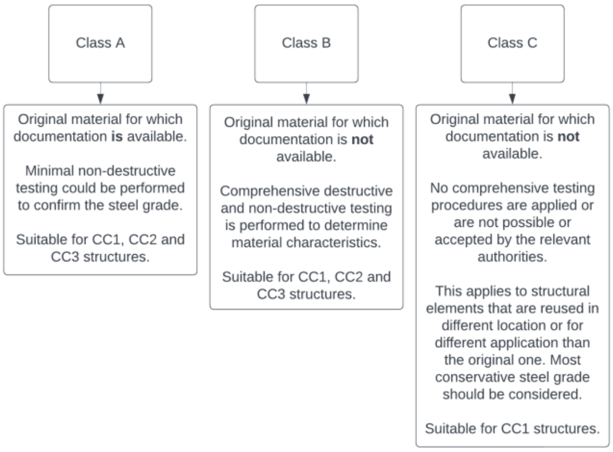

Figure 9: Framework for the classification of reclaimed structural steel elements. (Source: PROGRESS, 2020)

In general, reclaimed steel elements can be expected to perform as intended for new steel, without any material property changes. However, geometric imperfections may affect the member buckling resistance and therefore it may be necessary to increase the relevant partial factor (γ_{M1}) which is normally taken as 1 for new steel elements in the stability calculations. These imperfections can be lack of straightness, accidental load eccentricities, residual stresses from overloading etc., so visual inspection is a good way to assess this (PROGRESS, 2020). The modified coefficient is $\gamma_{M1,mod}$ should be calculated based on the following equation:

$$\gamma_{M1,mod} = K_{\gamma M1} \times \gamma_{M1}$$

where $K_{\gamma M1}$ is a correction factor which serves as a general factor that prevents the partial factor from being changed itself. This is beneficial since γ_{M1} is country-specific (PROGRESS, 2020, Appendix B). The corresponding partial factors that should be used based on the steel grade when designing with reclaimed steel elements are outlined in Table 4.

Table 4: Modified material partial factors based on the identified steel grade. (Source: PROGRESS, 2020, Appendix B)

Steel grade	$\gamma_{M1,mod}$
S235, S275	1.14
S355, S420	1.16
S460	1.18

Therefore, on average $K_{\gamma M1}$ can be taken as equal to 1.15. In other words, additional 15% of safety is added to account for potential uncertainties in the assessment processes of the material properties of the steel elements.

Another important consideration is the design life of the structure as mentioned in section 3.4. Normally for the type of building that this structure is part of, a design life of 50 years is taken according to NEN-EN 1990 (2002). It serves as a reference period for the determination of the reliability index and the corresponding factors for variable actions (e.g. people, equipment). These factors are used to account for the variability of loads which can be greater than anticipated and the possibility of self-weight loads that compensate potential moments being too low. However, when reclaimed steel elements are used a shorter design life can be adopted (15-30 years) which in turn reduces the safety level of the structure to a lower reliability class (PROGRESS, 2020, sec 8.2.1). This assumption requires high degree of quality control/inspection and adaptation of the variable loads such as snow, wind etc. for the structural calculations according to equation NB.1 in section A1.1 of the NEN-EN 1990+A1+A1/C2/NB (2019). Examples of situations where this reduction of the design life can be applied include:

1. In-situ reuse[8]
2. When the whole building is relocated to a different location and re-erected in the same configuration.

Therefore, in the present study a shorter design life is not adopted since the structure is designed as "new" while using reclaimed steel elements for its construction, and thus no adjustments to the variable loads are required. Also, as it is stated in chapter 4.4, since the maintenance phase during the life cycle of the structure is not included in the LCA, the design life will have no influence on the environmental impact calculations.

Finally, when the optimised design is calculated with the abovementioned assumptions for reclaimed steel elements it was found that because of the modified $\gamma_{M1,mod}$ factor extra supports to prevent lateral torsional buckling are needed and the profiles of the beams and columns remain the same. More specifically, in total 8 top flange and 1 bottom flange additional supports for the bearing beams and 1 lateral support in the Z-axis of the HEA160 column are necessary to compensate for the potential geometrical imperfections which causes reduced resisting capacity. Figure 10 and Figure 11 show the optimised design built with "new" steel and with reused steel, respectively. The top flange supports are indicated with an upside down green triangle with respect to the element and the bottom flange supports are indicated with a normal green triangle. The black numbers represent the distance between them. The extra lateral support of HEA160 column is not shown by a symbol but it is expressed in the reduced buckling length for that element in the software (not shown in the figures).

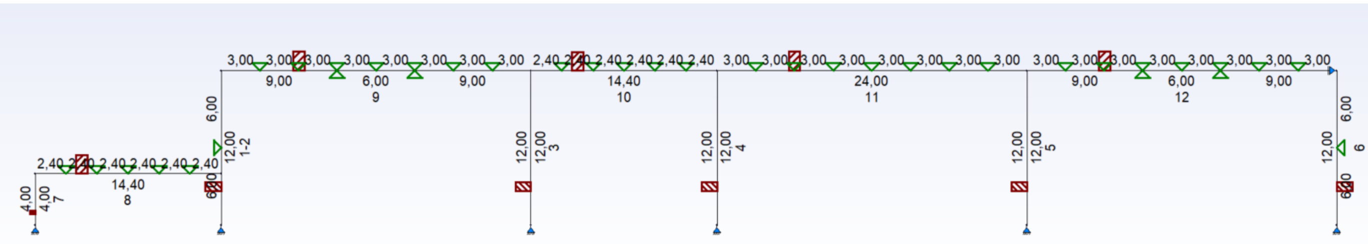

Figure 10: Top and bottom flange supports for the bearing beams of the optimised design built with new steel elements.

[8] The components are preserved and not deconstructed, i.e. the existing structure is just reused. (PROGRESS, 2020, sec 7.4)

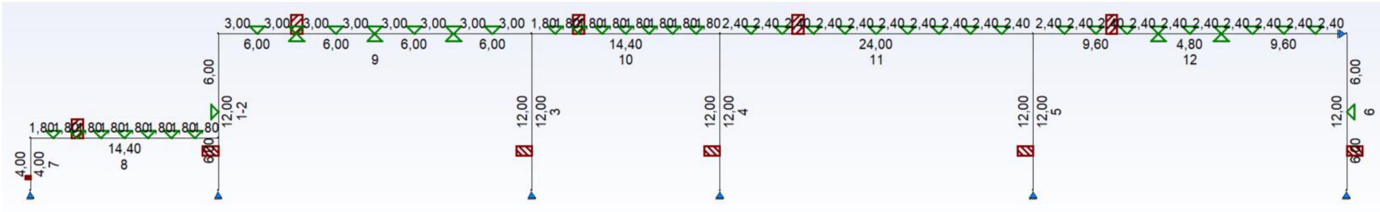

Figure 11: Top and bottom flange supports for the bearing beams of the optimised design built with reclaimed steel elements.

The extra supports are not considered in the life cycle assessment due to their uncertain and relatively small dimensions and because the scope of this study considers only the main structural elements such as beams and columns (section 1.4). Another key conclusion point of this part of the report is that the profiles of the main structural steel elements for this case are not changing depending on whether new or reclaimed steel elements are used.

4. Life cycle assessment

The LCA is a technique to calculate the environmental impacts throughout all the stages of a product's lifespan (Finnveden et al., 2009). Therefore, in this chapter the LCA is performed according to the structure described in ISO 14040 (2006a), ISO 14044 (2006b) (Figure 67 in Appendix B) while the life cycle stages and the system boundaries are determined according to the terminology and nomenclature outlined in the new NEN-EN 15804:2012 + A2:2019 (2019). This is done to ensure that the analysis on the environmental impact of the structure and the following comparison of results have high quality and value to the interested parties.

In addition, to avoid any confusion, Figure 12 can serve as a reference and presents the scenarios that are featured in the report. Note that EPD1, 2 and 3 are introduced in section 4.3.

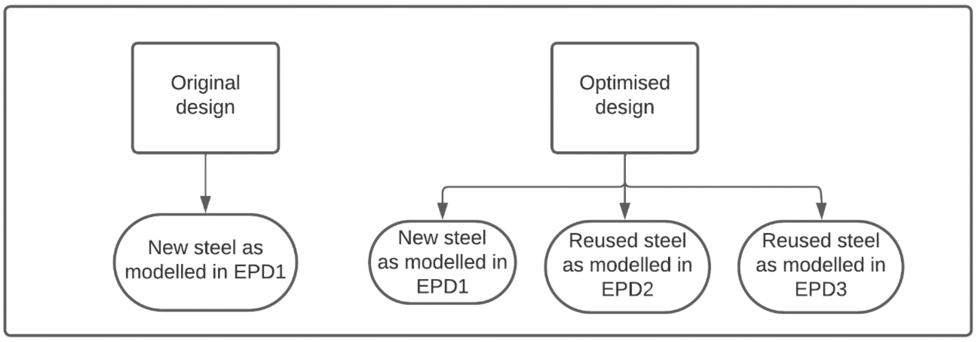

Figure 12: Reference figure for the scenarios featured in the thesis report.

4.1. Goal & Scope

The goal of the current LCA study is to evaluate and compare the environmental impact of the scenarios shown in Figure 12.

Therefore, a functional unit is required. It represents a quantified performance of a product system, which is used as a reference unit (ISO 14040, 2006a). Its importance is expressed in the fact that it enables the objective comparison between different products as long as they have the same final function. In this study the functional unit has been defined as: *"the whole 100.8m long and 12m high section through the factory located in the Netherlands that is able to support the loads determined by the ULS and SLS throughout the building's design life span equal to 50 years"*.

4.1.1. Geometrical characteristics of the designs

The geometrical characteristics represent the main features for each of the designs. They provide the context in which the different alternatives are compared. It includes the location in which they are situated, the construction method and the material used. Table 5 presents the corresponding values.

Table 5: Geometrical characteristics of the two designs.

Type	Original design	Optimised design[9] (New steel elements)	Optimised design (Reused steel elements)
Location	Netherlands	Netherlands	Netherlands
Height [m]	12	12	12
Width [m]	100.8	100.8	100.8
Gross volume [m^3]	1.80	1.13	1.13
Gross surface area [m^2]	118.03	86.56	86.56
Gross weight [kg]	19108,24	16151,44	16151,44
Material	New steel elements	New steel elements	Reused steel elements
Construction method	In-situ construction	In-situ construction	In-situ construction

Next, the classification of the technological system is discussed. In other words, this is the product-based data or in this case, the main features of each of the components of the design which represents a higher level of detail. All this data has to be provided in order to conduct a transparent and objective analysis of the environmental performance of the two designs.

The original design is shown in Figure 7 and the corresponding product characteristics are shown in Table 6. In turn, the optimised design is illustrated in Figure 8 and the corresponding product characteristics are shown in Table 7.

Table 6: Product information for original section design. (Source: Profiel Vinden, n.d.)

Enclosure	Quantity& Type	Material	Width [m]	Height [m]	Length [m]	Cross-sectional area [m^2] x10^{-3}	Surface area[10,11] [m^2]	Volume [m^3]	Weight per m [kg/m]	Amount [kg]
HEA180	1 (column)	Steel (S235)	0,180	0,171	4	4,525	2,90	0,02	35,5	142
HEA 400	1 (column)	Steel (S235)	0,300	0,390	12	15,898	14,40	0,19	125	1500
HEA 320	2 (column)	Steel (S235)	0,300	0,310	12	12,437	14,39	0,15	97,6	2342,4
HEA 280	2 (column)	Steel (S235)	0,280	0,270	12	9,726	13,42	0,12	76,4	1833,6
IPE 450	1 (beam)	Steel (S235)	0,190	0,450	14,4	9,880	10,86	0,14	77,6	1117,44
IPE 600	1 (beam)	Steel (S235)	0,220	0,600	14,4	15,600	12,62	0,22	122	1756,8
IPE 600	2 (beam)	Steel (S355)	0,220	0,600	24	15,600	20,84	0,37	122	5856
HEA 650	1 (beam)	Steel (S355)	0,300	0,640	24	24,164	28,58	0,58	190	4560
									Total:	**19108,24**

[9] The optimized design has two cases – one with new steel elements and one with reused steel elements.
[10] Total surface area of an element is defined by the following formula: $2 \times Cross\ sectional\ area\ +\ 2 \times Top/Bottom\ side\ +\ 2 \times Right/Left\ side\ +\ 2 \times Underside\ of\ the\ flanges.$
[11] Note: To calculate the surface for the underside of the flanges, the following formula is used: $2 \times (Width - Thickness\ of\ web)\ x\ Length$ see Figure 66 in Appendix B.

Table 7: Product information for optimised section design. (Source: Profiel Vinden, n.d.)

Enclosure	Quantity & Type	Material	Width [m]	Height [m]	Length [m]	Cross-sectional area [m^2] x10^{-3}	Surface area [m^2]	Volume [m^3]	Weight per m [kg/m]	Amount [kg]
HEA 160	1 (column)	Steel (S235)	0,160	0,152	4	3,877	0,006	2,57	0,02	30,4
HEA 340	1 (column)	Steel (S235)	0,300	0,330	12	13,347	0,0095	14,40	0,16	105
HEA 240	3 (column)	Steel (S235)	0,240	0,230	12	7,684	0,0075	11,47	0,09	60,3
HEA 320	1 (column)	Steel (S235)	0,300	0,310	12	12,437	0,009	14,39	0,15	97,6
IPE 450	1 (beam)	Steel (S235)	0,160	0,152	4	3,877	0,006	2,57	0,02	30,4
IPE 550	1 (beam)	Steel (S235)	0,300	0,330	12	13,347	0,0095	14,40	0,16	105
IPE 600	3 (beam)	Steel (S355)	0,240	0,230	12	7,684	0,0075	11,47	0,09	60,3
									Total:	**16151,44**

As it can be observed from the two tables, the design with the optimised beam and column profiles contains 15.47% less material as compared to the original design.

4.1.2. Life Cycle Phases

The life cycle phases included in the system boundaries of this study are shown in Figure 13. Therefore, the considered system boundary is defined as "Cradle-to-gate with options, modules C1-C4 and module D" according to the NEN-EN 15804 + A2 (2019) standard.

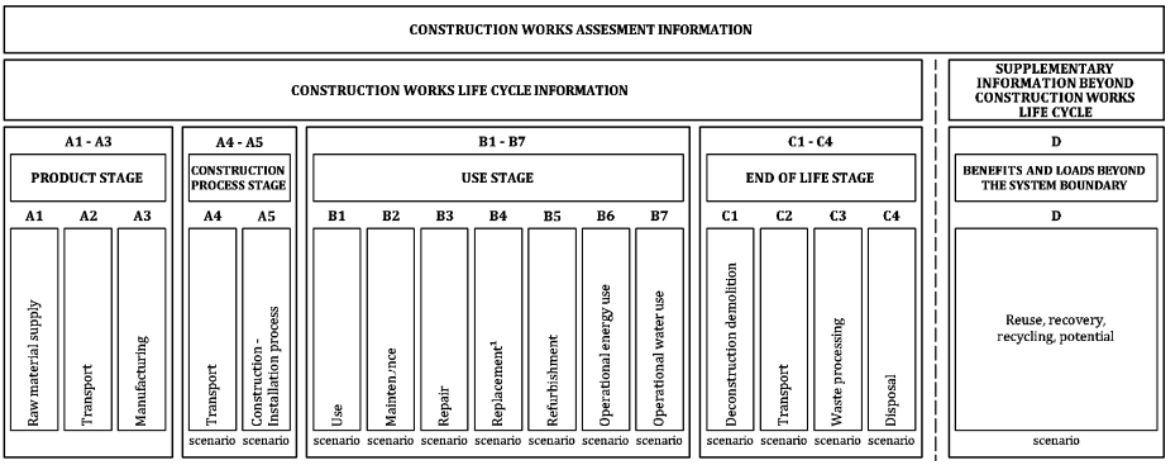

Figure 13: Life cycle stages for the LCA of construction works (Source: NEN-EN 15804 + A2, 2019)

This system boundary means that the product and end-of-life stages must be included, whereas the construction process and use stages are optional.

Module D is special in the sense that it considers the benefits and loads beyond the system boundary. The benefits are related to the potential avoided use of primary material, i.e. virgin material (e.g. iron ore, copper etc.) and primary fuels such as coal, natural gas, biomass etc. While the loads considers potential emissions or other harmful effects to the environment or humans. Therefore, it includes the results from processes such as reusing products and recycling materials.

4.2. Assumptions & Limitations

A vital part of any LCA study are the assumptions that are considered and limitations that the assessment entails. This is supported by the fact that in the case of steel, there are around 2800 flows that in the life cycle of a kilogram of steel (World Steel Association, 2021) and it is almost impossible to take them all into account for the analysis. Also, it proved very difficult to obtain some specific data on the emissions, fuel and energy consumption for the structure of this research since the contractors do not collect such data.

Moreover, since no access to the professional databases and auxiliary databases of GaBi software was provided, only the educational versions were the available options. This proved to be a very influential limiting factor to the accuracy of results of the assessment of different stages because key processes were often missing or were incomplete.

Therefore, due to the time and data availability constraints it was decided to use the three Environmental Product Declarations (EPDs) published by Bouwen met Staal in 2022 as the source of data for this LCA (SNS & Bouwen met Staal, 2022a,b,c,d). The rationale behind this choice is explained at the end of this section. It should be noted that this is not the ideal way to conduct an LCA because of several limitations that are outlined below.

First, it has been found that the majority (87%) of EPDs do not include all the life cycle stages required by the NEN EN 15804 + A2 (2019) but only a certain "cradle-to-gate with options" system boundary which is unideal if a full LCA is performed (Del Rosario et al., 2021; Schlanbusch et al., 2016). Also, as highlighted by Del Rosario et al. (2021) a lack of comprehensive scenarios is a disadvantage of the current practices in creating EPDs.

Next, Soust-Verdaguer et al. (2023) argue that the development of EPDs within the European Union is still irregular and not evenly distributed giving an example of Germany and France which have many EPDs for various construction products while other countries (e.g. Spain) have a limited number. This causes researchers and analysts to use data that is not geographically representative for their object of study thus leading to potentially unrepresentative results. Therefore, the importance of the local context has been extensively analysed and highlighted by Oztas and Tanaçan (2017).

Lastly, the issue of comparability between the various EPDs is discussed. As Lasvaux et al. (2015) found in their study, there exists a discrepancy in the included life cycle stages between the EPDs of similar products, which renders them incomparable. This is a result of the fact that often EPDs are aggregated and not as explicit as the LCI databases such as Ecoinvent (Morris et al., 2021) and the researcher is not able to change the parameters. Particularly, differences in the technology used, means of transport and the travel distances might have a big influence in the environmental impact of the product (Del Rosario et al., 2021). Also, a major factor could be the grid energy mix which often varies over location and time. Noteworthy is that normally the estimations of avoided emissions are done for the future and those projections might not be accurate because they are based on the current available technology for the production of the assessed product (Morris et al., 2021). Nevertheless, there are increasing efforts for the harmonization and standardisation of EPDs being done to improve the feasibility of comparison (Gelowitz & An, 2017).

However, one of the advantages of using EPDs as a source of data for conducting an LCA is that the data can be accessed and interpreted without the help of a complex software (Morris et al., 2021). This allows for the quick analysis of a given product without the need of various licenses.

Focusing back on the current study and considering the abovementioned points, it can be asserted that the EPDs from Bouwen met Staal have a very good geographical representation, since they rely on aggregated data coming from the members of the Samenwerkende Nederlandse Staalbouw (SNS) organization of the main steel suppliers in the Netherlands. They account for 70% of the Dutch market for heavy structural steel. In addition, all three EPDs were created recently (i.e. 2022) and are hence valid until 2027 (5 year validity). They were developed according to the newest NEN EN 15804 + A2 (2019) and ISO 14025 (2010) standard which ensures the quality and consistency of the declared data.

Therefore, the only drawback is that the results of this LCA study for the section through the factory are calculated as if it is a generic steel structure in the Netherlands because of the lack of case specific data. To compensate for this a scenario analysis is done to investigate to what degree the considered EPDs influence the environmental impact of the structure.

4.3. Life cycle inventory analysis (LCI)

In the inventory analysis the elementary (e.g. product, material and energy) flows that cross the system boundary are considered. Since no comprehensive LCI is performed for this study because of the reasons outlined in the previous section, the assumptions for each of the three EPDs per life cycle module are described below.

EPD1 (SNS & Bouwen met staal, 2022a) – 16% reused steel at the end-of-life

The first EPD is considered to be representative of the current way of producing steel. In this research it is taken as the "New Steel" scenario where all the structural elements are new. The functional unit is defined as *"1 kg heavy structural steel, produced in Netherlands and applied in the Dutch market."* By heavy structural steel the authors mean that the end products made from such steel include I-,H-,U-beams which is suitable for this study since the structure is made of IPE and HEA profiles.

For the A1-A3 modules they have used predefined processes in the Nationale Milieudatabase (National Environmental Database – NMD) which was established to provide unambiguous calculations of the environmental impact of the construction industry in the Netherlands (Stichting Nationale Milieudatabase, n.d.).

For the A4 module they assume a fixed distance of 150km to the construction site.

For the A5 module they assume that 1,5t of heavy structural steel is installed per hour. This is done by a mobile crane which is used for 0.66 hours per ton of steel and 50% of it is electric (a hybrid model). They use a NMD process to model the diesel part of the crane and a modified NMD process for the electric part of it. Also, they note that normally there is a 3% installation waste, but this does not apply to heavy structural steel as the products are pre-fabricated and are hardly damaged, so they assume 0% system loss.

For the use stage (B1-B7) they assume no operating emissions, repair, refurbishment, replacement and maintenance.

For the C1 module assumptions similar as the ones in A5 are made.

For the C2 module the end-of-life scenario shown in Table 8 is assumed.

Table 8: End-of-life scenario for module C2 of EPD1.

Process	Share	Transport distance
Landfilling	0.84%	100 km
Recycling	83.16%	50 km
Reusing	16%	50 km

For the C3 module they have chosen the process provided by the Steel Federation (Koninklijke Staalfederatie, n.d.) for both reuse and recycling which includes sorting and compressing the steel elements. They make the note that this is considered conservative for the reuse process since compression is not needed.

For the C4 module the 1% landfilled steel is modelled by another process provided by the Steel Federation.

For module D Bouwen met Staal identifies two scenarios: reusing and recycling, as it is outlined in the calculation method in sec. D.3.4 in NEN-EN 15804 +A2 (2019). The benefits of reusing are expressed in terms of avoided emissions in the next life cycle. Here, this is a big part of the A1-A3 modules, because reused steel saves 100% of production and 100% of galvanizing the steel elements. However, some of the steel elements may need additional welding, so it is assumed that the reused elements save 50% of the welding and therefore 50% of the energy consumption. The benefits of recycling are based on the 83% end-of-life recycling rate and the avoided raw material equivalents. In practice, it is impossible to reuse 100% of all the released structural steel because of damage during deconstruction (e.g. sawing, obsolete parts). Therefore, a quality factor K of 90% is assumed for reused elements and the rest 10% are recycled. An example calculation of how much material mass is reused and how much of it goes for recycling based on those percentages is included in the document.

EPD2 (SNS & Bouwen met staal, 2022b) – 90% reused steel in product stage and 16% reused steel at the end-of-life

This second EPD is considered as the "90% Reused Steel" scenario in this research where the steel elements of the structure are reclaimed. The functional unit is declared as: "*1 kg heavy structural steel from reuse, (re) produced in the Netherlands and applied in the Dutch market (16% reuse end of life)*".

For the A1-A3 modules they assume 10% new steel and 90% reused steel. The reused steel enters the system without environmental burden and does not receive new coating or galvanisation. Also, as a plausible scenario half of the reclaimed steel elements are refurbished. This means that 45% of the energy consumption and emissions of the welding processes are saved.

All the other modules A4,A5, B, C1, C2, C3, C4 and D are the same as the ones in EPD1. For more details it is recommended to read the document.

EPD3 (SNS & Bouwen met staal, 2022c) –design for reuse, 80% reused steel at the end-of-life, max. 25m

This EPD is included in the scenario analysis in chapter 4.5 to make the assessment more comprehensive. The functional unit for this EPD is defined as: "*1 kg "design for reuse" heavy structural steel with a span of up to 25 meters, produced in the Netherlands and applied in the Dutch market.*" By design for reuse or design for deconstruction (DfD) the authors mean that the following main structural requirements are fulfilled:

- All connections are bolted connections that are specially designed for easy disassembly;
- All (lattice) girders are of the same design to increase interchangeability;
- The disc effect (schijfwerking) of the storey floors has been solved with demountable wind bracing and the columns are boxed making them easy to unscrew;
- Columns are placed storey high, which increases interchangeability
- As little welding as possible is used;
- The steel profiles designed for reuse are widely applicable;

Modules A1-A3, A4, A5, B, C1, C3 and C4 are modelled the same as the ones in EPD1.

For module C2 the assumed end-of-life scenario is shown in Table 9.

Table 9: End-of-life scenario for module C2 of EPD3.

Process	Share	Transport distance
Landfilling	0.20%	100 km
Recycling	19.80%	50 km
Reusing	80%	50 km

The same assumptions for module D as EPD1 are made as well.

All of the above EPDs use the “Cradle-to-Grave and Module D” system boundary shown in Figure 14 with the corresponding inputs and outputs.

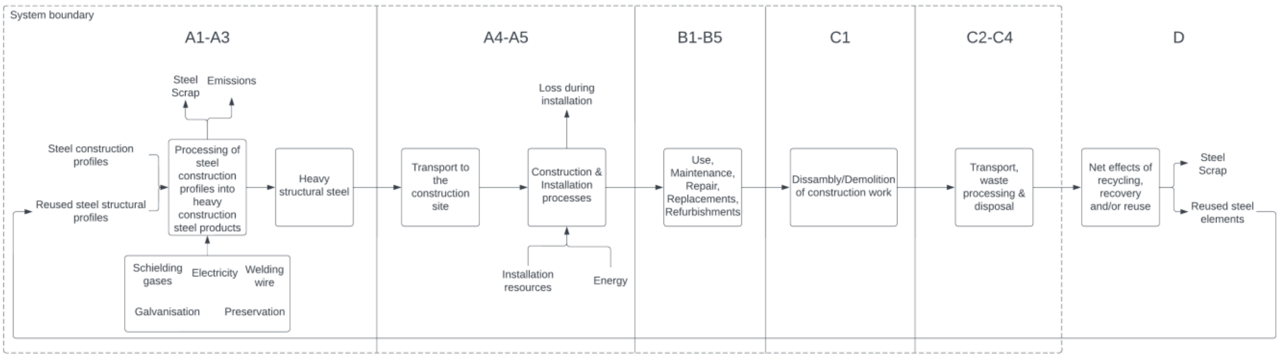

Figure 14: System boundary of the three EPDs provided by Bouwen met Staal.

4.4. Life cycle impact assessment (LCIA)

In this section, the assessment of the environmental impact throughout the life cycle of the structure is discussed. The following impact categories were considered (Hillege, 2023):

- **Global warming potential (GWP)** [kg CO2-eq] – indicator of potential global warming due to emissions of greenhouse gases to the air.
- **Acidification potential of land and water (AP)** [kg SO_2-eq] – indicator of the potential acidification of soils and water due to the release of gases such as nitrogen oxides and sulphur oxides.
- **Eutrophication potential (EP)** [kg PO_4^{3}-eq] - indicator of the enrichment of the aquatic ecosystem with nutritional elements, due to the emission of nitrogen or phosphor-containing compounds
- **Ozone depletion (ODP)** [kg CFC11-eq] - indicator of emissions to air that causes the destruction of the stratospheric ozone layer
- **Formation potential of tropospheric ozone photochemical oxidants (POCP)** [kg C_2H_4 (ethene) eq.] - indicators of emissions of gases that affect the creation of photochemical ozone in the lower atmosphere (smog) catalysed by sunlight.
- **Human Toxicity Potential (HTP)** [kg DCB eq.] - impact on humans of toxic substances emitted to the environment.
- **Fresh water aquatic ecotoxicity potential (FAETP)** [kg DCB eq.] - impact on freshwater organisms of toxic substances emitted to the environment.
- **Marine aquatic ecotoxicity potential (MAETP)** [kg DCB eq.] – impact on seawater organisms of toxic substances emitted to the environment.
- **Terrestrial ecotoxicity potential (TETP)** [kg DCB eq.] – impact on land organisms of toxic substances emitted to the environment.

- **Abiotic depletion potential for non-fossil resources (ADPE)** [kg Sb-eq.] – indicator of the depletion of natural non-fossil resources
- **Abiotic Depletion Potential for fossil resources (ADPF)** [kg Sb-eq.] – indicator of the depletion of natural fossil resources

Due to space limitations only the results of the impact categories global warming, acidification and eutrophication are presented in detail in this section. The results for the full set of impact categories for the two designs per life cycle module based on the three EPDs can be found in Table 14, Table 15, Table 16 and Table 17 in Appendix B.

Figure 15 shows the GWP score for the original design. It is evident that the highest quantity of emissions occurs in the product stage (A1-A3) – 21.4 tCO_2eq which is expected because of the carbon intensive processes and high number of inputs and outputs involved in the constituent modules. Also, CO_2eq emissions have a long atmospheric residence time so they have a more long-term impact on climate change. It is worth mentioning that in module D the emissions are considered with negative sign in order to indicate the amount of potentially avoided $kgCO_2eq$ in the next life cycle of the product which in this study is the whole structure. This interpretation of module D applies for all graphs presented in this report. The avoided 4.2tCO_2eq is a reasonable measurement since in EPD1 16% of the material is reused and 83% of it is recycled. Refer to the equations outlined in section D.3.4 in NEN-EN 15804 + A2 (2019) for more details.

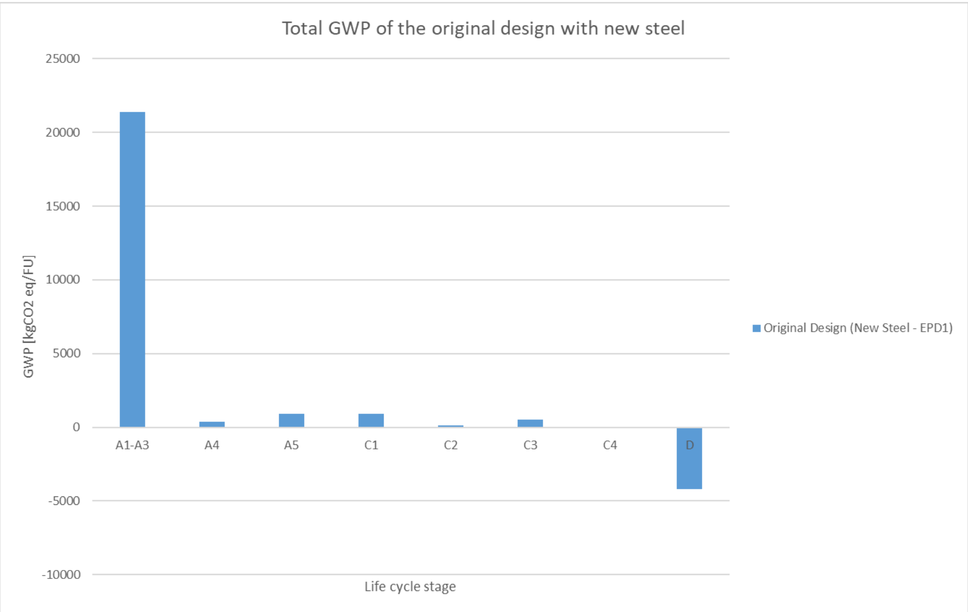

Figure 15: GWP of the entire original design made with new steel elements.

In Figure 16 , the AP score of the original design is shown. This impact category shows emissions of 75 $kgSO_2eq$ again during the product stage (A1-A3). The avoided emissions for the next life cycle of the product calculated in module D are 14.1 $kgSO_2eq$.

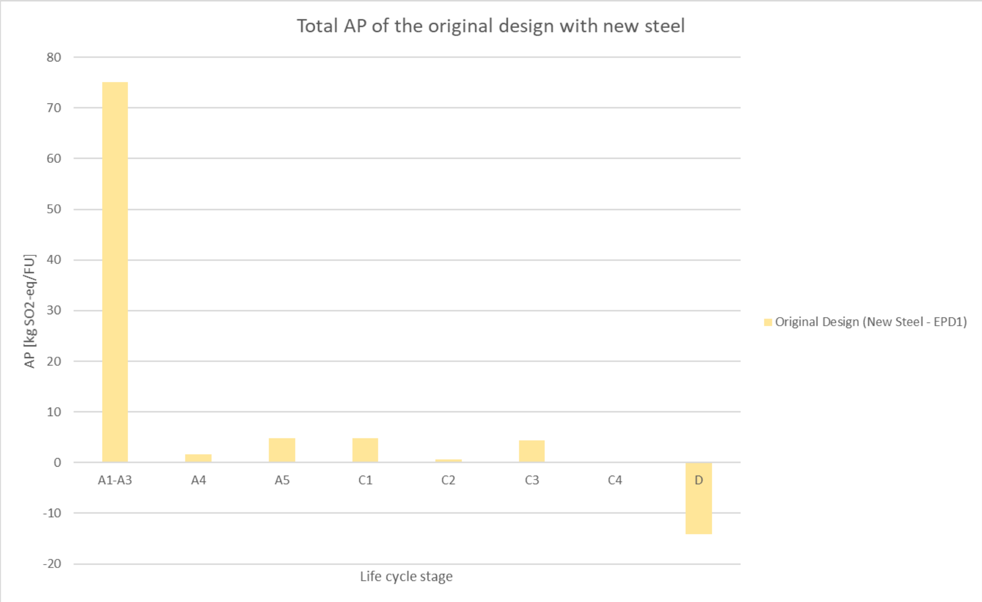

Figure 16: AP of the entire original design made with new steel elements.

Lastly, in Figure 17 the EP score of the original design is shown. Only 14 $kgPO_4^3eq$ are calculated in the product stage. This could be explained by the fact that while the released nutrients can cause an excessive growth of algae in water bodies the effect is very localised and thus causes limited damage. The avoided benefits in module D are 2.7 $kgPO_4^3eq$.

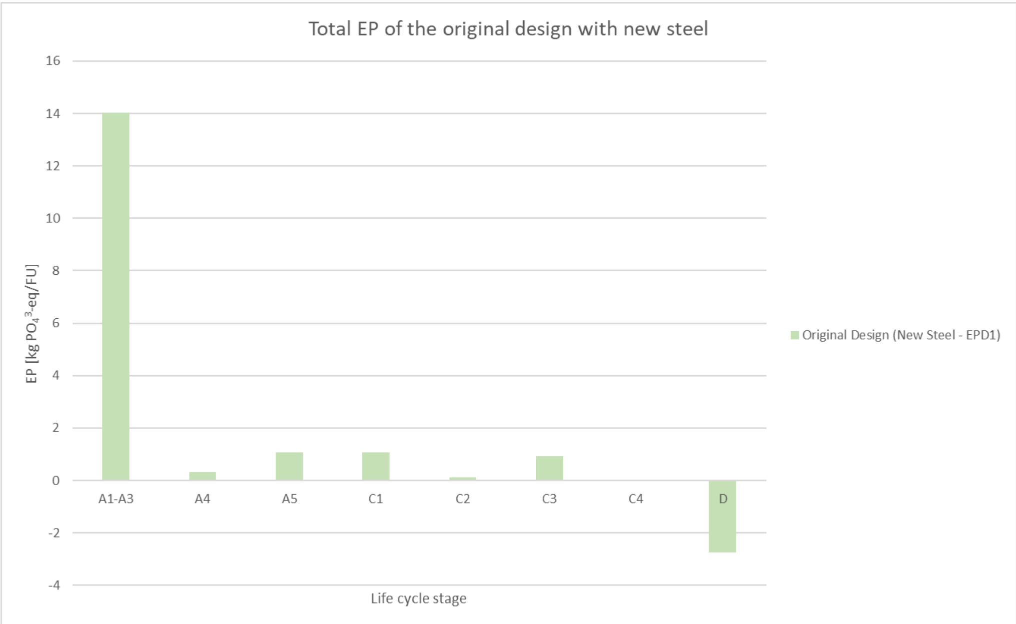

Figure 17: EP of the entire original design made with new steel elements.

Next, the environmental impact for the same three impact categories but now for the optimised design made of new and reused steel elements is discussed considering the 3 EPDs. Firstly, the GWP of the whole structure is shown in Figure 18. Again, the largest amount of emissions occur in the product stage for both EPD1 and EPD3 – 18.1 tCO_2eq, while the GWP for EPD2 is only 3.2 tCO_2eq. This is nearly a 5.66 times reduction in emissions in the case when the structure is made out of 90% reused steel elements. In module D, a big spike of avoided emissions –12.3 tCO_2eq for EPD3 is observed. This is due to the fact that in EPD 3 the 80% reused steel elements are modelled in the end-of-life stage instead of the product stage. This indicates the net material flow is positive – there is more output material in the system than input. Therefore, based on the equations outlined in section D.3.4 in NEN-EN 15804 + A2 (2019) a larger benefit is calculated. Whereas, in the case of EPD2 only 0.28 tCO_2eq are avoided. This reduction or penalty is caused by the fact that the incoming material flow is higher (90%) than the outgoing material (16%) which results in lower avoided emissions.

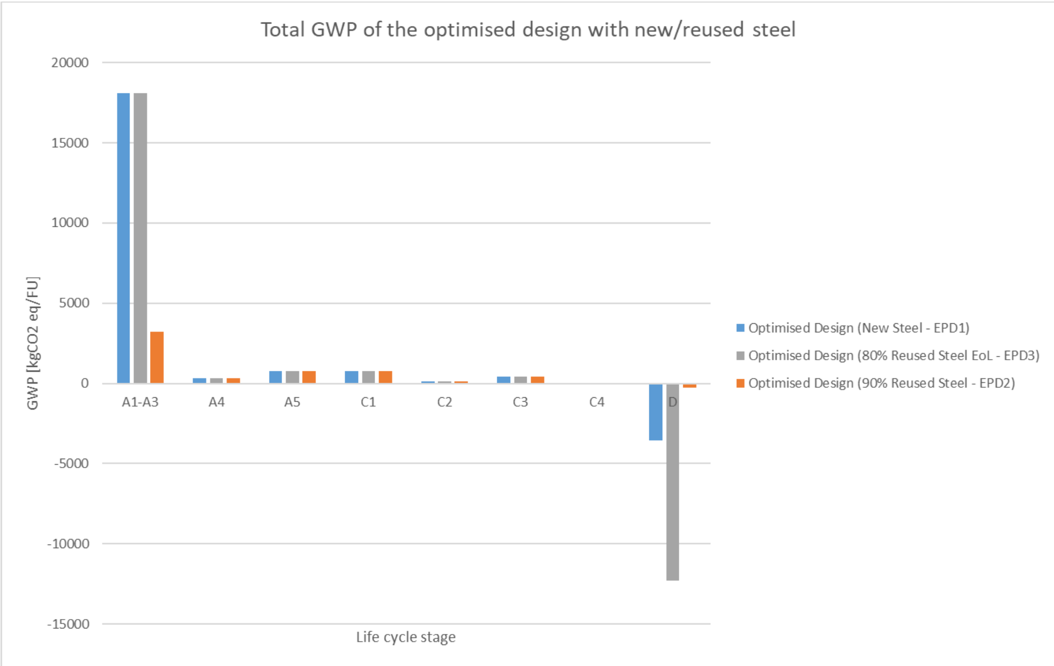

Figure 18: GWP of the entire optimised design made with new and reused steel elements based on EPD1,2,3.

Next, the AP score of the optimised design based on the 3 EPDs is shown in Figure 19. The total emissions during the A1-A3 modules amounts to 63.5 kgSO_2eq for both EPD1 and EPD3, while it is reduced to 10.8 kgSO_2eq for EPD2. The avoided emissions in module D are 12 kgSO_2eq for EPD1, 43.4 kgSO_2eq for EPD3 and 1.2 kgSO_2eq for EPD2.

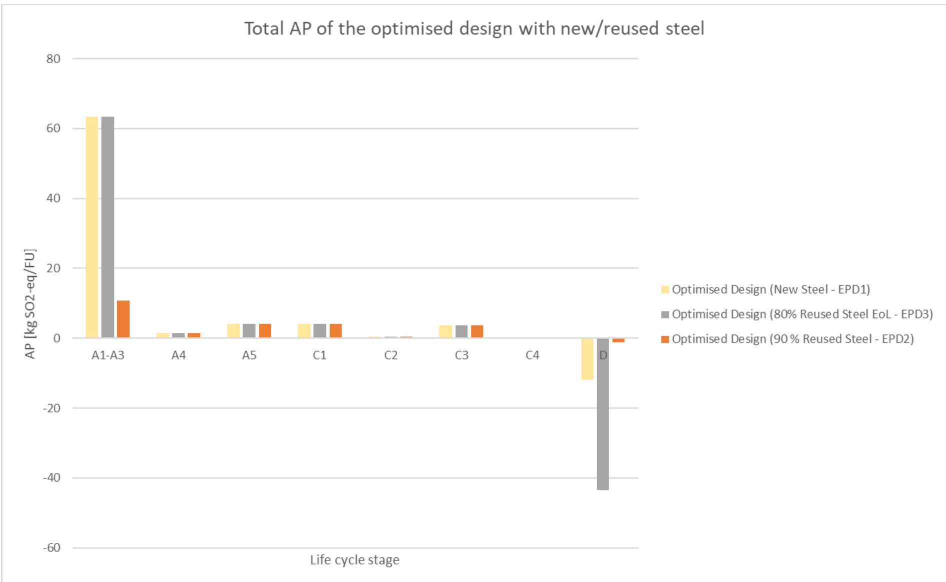

Figure 19: AP of the entire optimised design made with new and reused steel elements based on EPD1,2,3.

Finally, the EP score of the whole optimised structure in the 3 studied cases is shown in Figure 20. For EPD1 and EPD3 the total emissions during the product stage are 11.8 kgPO_4^{3}eq while it is reduced to

1.9 $kgPO_4^3eq$ for EPD2. The calculated potentially avoided emissions (benefits) in module D amount to 2.3 $kgPO_4^3eq$ for EPD1, 8.2 $kgPO_4^3eq$ for EPD3 and 0.2 $kgPO_4^3eq$ for EPD2.

Figure 20: EP of the entire optimised design made with new and reused steel elements based on EPD1,2,3.

4.5. Interpretation

In this section, an interpretation of the environmental impact results of the optimised design per EPD and per structural component (bearing beams and columns) is made only for GWP because of time limitations. Noteworthy, is that the proportions are applicable for the rest of the impact categories – AP, EP. In Figure 21, the contribution analysis of each of the life cycle modules to GWP for EPD1 is shown.

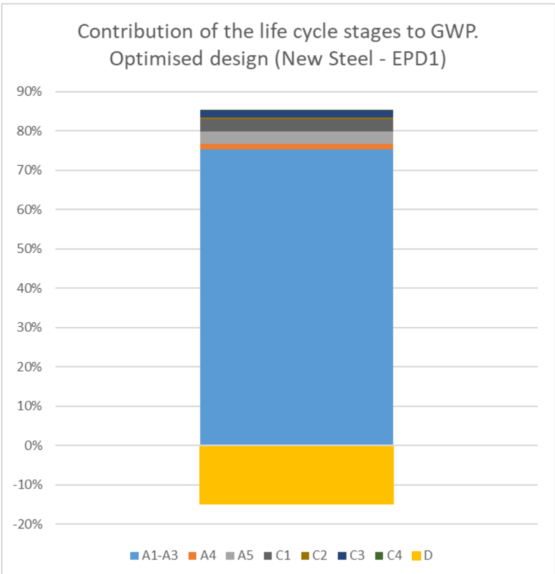

Figure 21: Contribution analysis of all the life cycle modules to GWP of the optimised design - EPD1.

It is evident that biggest part of almost 75% of the CO_2eq emissions comes from the product stage (A1-A3) while the all the other stages combined account for around 10%. Module D is included with its negative sign which indicates the potential of avoided emissions in the next life cycle. It is calculated that 15% of CO2eq can be saved by reusing 16% of the steel elements and recycling 83% the steel scrap as mentioned in the inventory analysis section 4.3.

Next, from Figure 22 it can be concluded as the recovery rate at the end-of-life increases – from 16% to 80% in EPD3, the potentially avoided emissions increase from 15% to almost 40% of total absolute impact. This means that in the next life cycle instead of having 18.1 tCO_2eq (Figure 18) in the product stage the released amount would be reduced to 5.8 tCO_2eq or by 12.3 tCO_2eq (the grey bar).

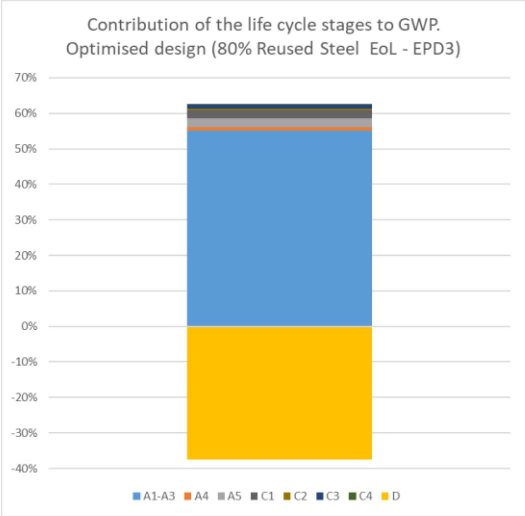

Figure 22: Contribution analysis of all the life cycle modules to GWP of the optimised design - EPD3.

The final contribution analysis of the life cycle stages to GWP for EPD2 is shown in Figure 23. Here the share of the product stage (A1-A3) is around 55% of the total absolute emissions while the rest of the stages account for 40%. The percentage of module D is the smallest (~5%) out of all the EPDs in this study because of the net outflow of material being negative which results in a reduction in the benefits after the end-of-life.

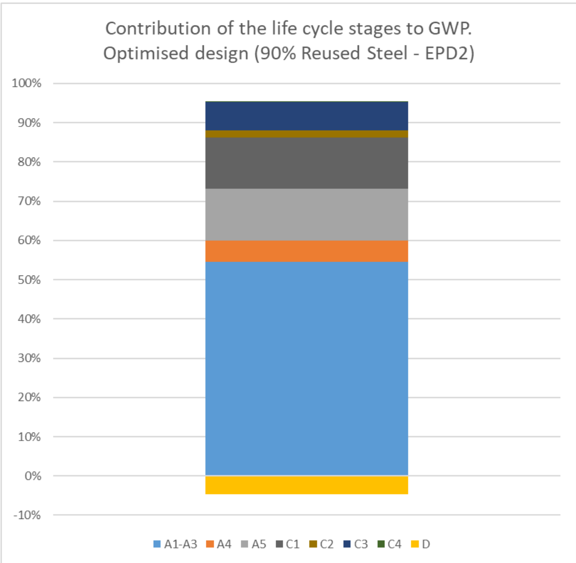

Figure 23: Contribution analysis of all the life cycle modules to GWP of the optimised design - EPD2.

Now a brief analysis is made on the share of emissions per structural component of the optimised design considering the two extreme EPDs, namely EPD1 (New steel) and EPD 2 (90% Reused steel). From Table 7 the total material mass of the bearing beams and the columns can be calculated as 11427.8 kg and 4723.6 kg, respectively. This means that the needed material for the former is 2.42 times larger than the latter due to the bigger profiles used to resist the vertical loads.

In Figure 24, the ratio for the CO_2eq emission between the bearing beams and the columns confirms the expectation that it follows the ratio of the material masses of the components. Noteworthy is that there is a reduction in the environmental impact in the product stage (A1-A3) of 82.32% between the same component made from new steel and the reused one. For module D the penalty that is introduced due to the higher input material in EPD2 is reflected in the 92.2% decrease in avoided emissions. The GWP score of the two scenarios for the whole optimised structure can be seen in Figure 18.

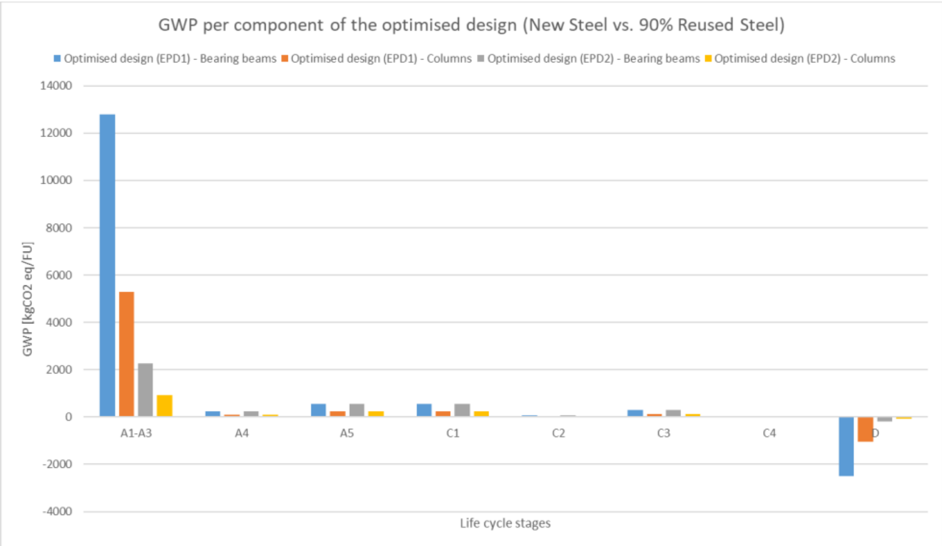

Figure 24: Total GWP per component of the optimised design made from new and reused steel elements.

Since for this study EPDs are used as the source of data for the LCA, a comprehensive sensitivity analysis is not feasible because the parameters in the models such as transport distances, fuel/electricity consumption are not modifiable. Therefore, a scenario analysis is performed based on all three of the EPDs as mentioned in the assumptions and limitations section. Here only an overview is presented for the relative change in GWP per life cycle stage per EPD due to space constraints. In Figure 25, the kgCO_2eq can be seen per life cycle stage with the benefits (avoided emissions) in module D.

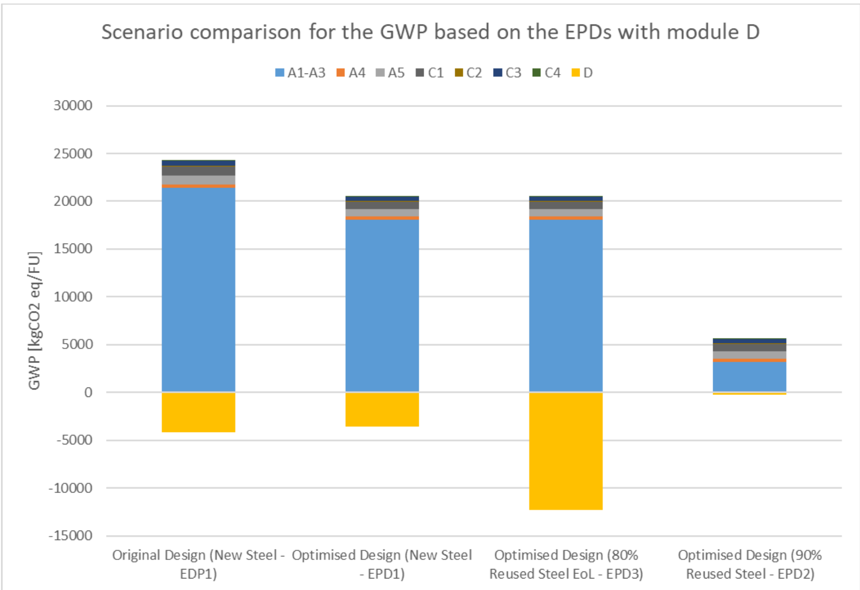

Figure 25: Scenario analysis for the GWP of the two designs based on the three EPDs with module D.

Whereas, in Figure 26 the same overview is presented, but this time the benefits of module D are calculated in the product stage (A1-A3) as if the structure is in its next life cycle – cumulative GWP.

This results in a graph that shows the potential of CO_2eq reduction after the design is optimised and when the proportion of reused material increases – from 17.2 tCO_2eq (original design – EPD1) to 2.9 tCO_2eq (optimised design – EPD2) or an 83% reduction in emissions. In addition, if the optimised design is made from new steel elements (EPD1) and from reused steel elements (EPD2) the reduction in CO_2eq emissions is 80%.

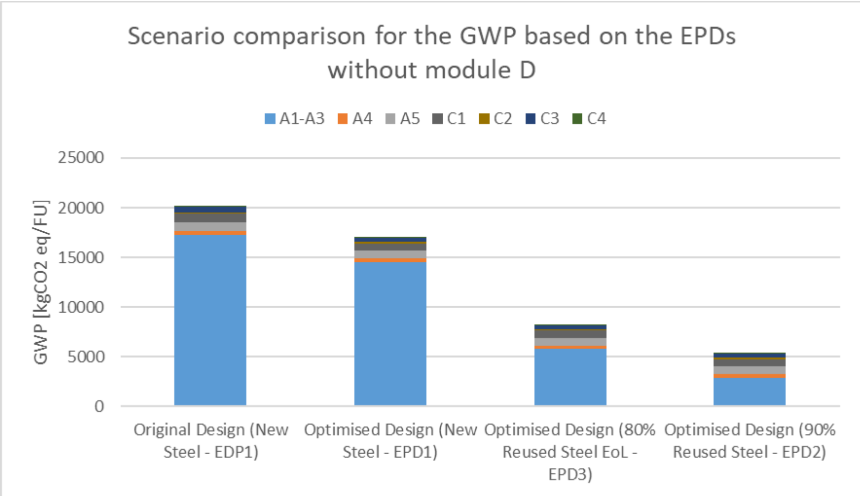

Figure 26: Scenario analysis for the cumulative GWP of the two designs based on the three EPDs without module D.

4.6. Environmental Cost Indicator of the two designs

This section focuses on the calculation of the Environmental Cost Indicator (ECI) or Milieukostenindicator (MKI) in Dutch of the two designs per life cycle module. In addition to the definition in the Terminology section, it is worth mentioning that this is the cost to the government for neutralising the environmental impact of the construction product. The calculation of the shadow price is done by first multiplying the environmental scores for the 11 impact categories with the weight factors (expressed in €/unit) shown in Table 10 and then the results are added together to obtain the ECI. An overview of the calculation is presented in Figure 27. Finally, a comparison is done to ascertain to what extend the final shadow price of the whole structure (functional unit) is influenced by the three different EPDs.

Table 10: Weight factors per impact category for the ECI calculation. (Stichting Nationale Milieudatabase, 2022)

Impact category	Unit	Weight factor [€/unit]
Abiotic Depletion Potential for non-fossil resources - ADPE	kg Sb eq.	0,16
Abiotic Depletion Potential for fossil resources - ADPF	kg Sb eq.	0,16
Global Warming Potential - GWP	kg CO2 eq.	0,05
Depletion potential of the stratospheric ozone layer - ODP	kg CFC11 eq.	30
Formation potential of tropospheric ozone photochemical oxidants - POCP	kg C_2H_4 (ethene) eq.	2
Acidification Potential of land and water - AP	kg SO2 eq.	4

Table 10: Weight factors per impact category for the ECI calculation. (Stichting Nationale Milieudatabase, 2022)

Eutrophication Potential - EP	kg PO_4^{3} eq	9
Human Toxicity Potential - HTP	kg DCB eq.	0,09
Fresh water aquatic ecotoxicity potential - FAETP	kg DCB eq.	0,03
Marine aquatic ecotoxicity potential - MAETP	kg DCB eq.	0,0001
Terrestrial ecotoxicity potential - TETP	kg DCB eq.	0,06

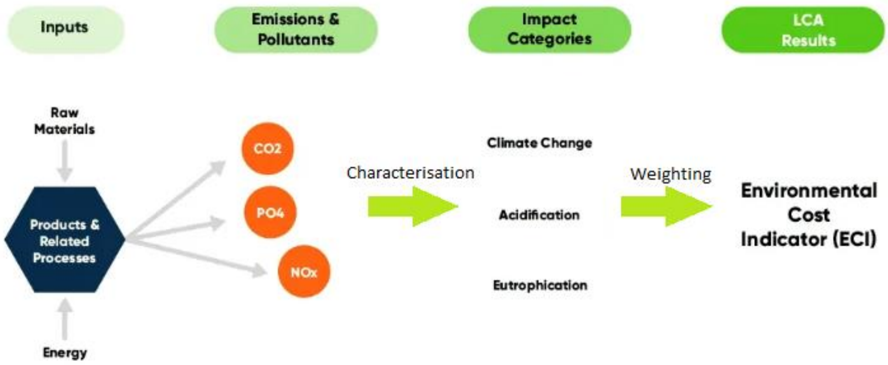

Figure 27: Overview of the Environmental Cost Indicator (ECI) calculation (Adapted from Hillege, 2021)

Noteworthy is the fact the ECI calculation is perform according to the set of 11 categories outlined in NEN EN 15804 + A1 (2013) instead of according the set of 19 categories described in the newest appendix of the same norm - NEN EN 15804 + A2 (2019). The reason for this is that the weight factors for the larger set are still under development as of the writing of this report (Stichting Nationale Milieudatabase, n.d.).

As was mentioned in section 4.4, the impact assessment of the 11 categories for the two designs per life cycle module based on the three EPDs is included in Table 14, Table 15, Table 16 and Table 17 in Appendix B. Also, the shadow prices per impact category of the life cycle modules based on the three EPDs are shown in Table 18, Table 19, Table 20 and Table 21 in Appendix B.

Next, the contribution of each life cycle module to the total shadow price of the original design made from new steel elements (EPD1) is shown in Figure 28. The total cost of the functional unit is 2301 €/FU including module D with a negative sign which indicates potential savings of production costs in the next life cycle. It is evident that the majority (75%) of the cost is allocated in the product stage which is explained by the fact that the same stage has the majority of the environmental impact as well (Figure 15, Figure 16 and Figure 17).

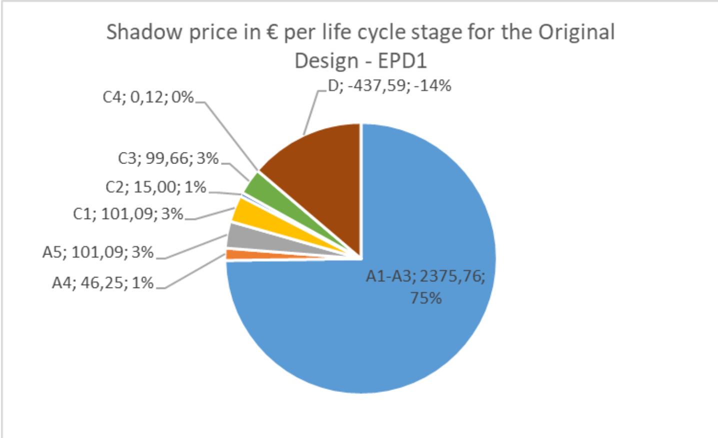

Figure 28: Relative shadow price in € per life cycle stage for the original design made with new steel elements - EDP1.

The results for the optimised design made with new steel elements have a similar distribution with a total shadow cost of the functional unit equal to 1945 €/FU including module D (Figure 29). Noteworthy, is the fact that in Figure 21 the kgCO_2eq emitted in the product stage (A1-A3) account for 75% of the total GWP as well.

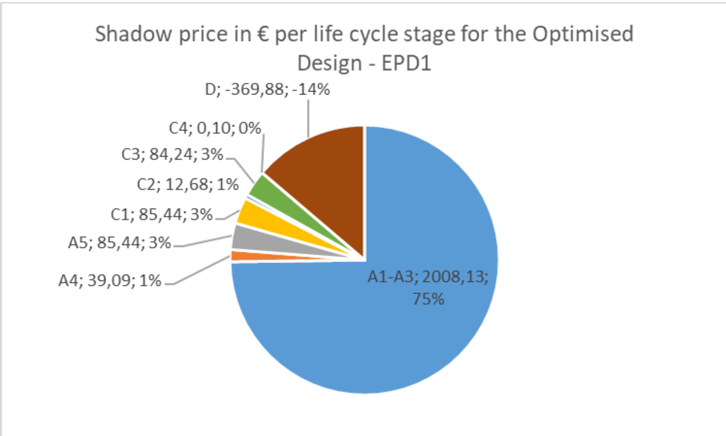

Figure 29: Relative shadow price in € per life cycle stage for the optimised design made with new steel elements - EDP1.

Next, the contribution of the life cycle modules to the shadow cost in the case of the optimised design made with 90% reused steel elements is shown in Figure 30. The total cost is 618 €/FU including module D. Notable is the fact that in Figure 23 the contribution of the A1-A3 modules is slightly higher – 55% than the 50% of the same modules to the total shadow cost of the structure. This might indicate that other effects apart from the CO_2 emissions in the other stages might have a relatively high contribution to the environmental cost.

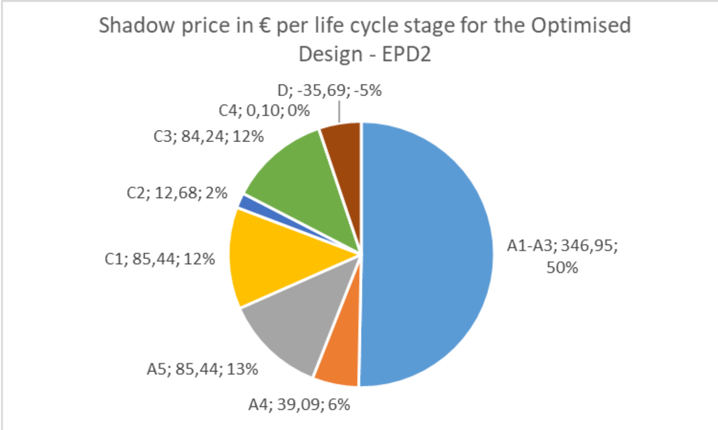

Figure 30: Relative shadow price in € per life cycle stage for the optimised design made with 90% reused steel elements - EDP2.

The results of the last analysed scenario are shown in Figure 31. Here the increase in the savings in Module D to 37% is expected since the recovery rate is 80% meaning that the outgoing material is larger than the input material. Similar proportions can be seen in Figure 22. Also, the contribution of the product stage (A1-A3) is between other two scenarios amounting to 55%.

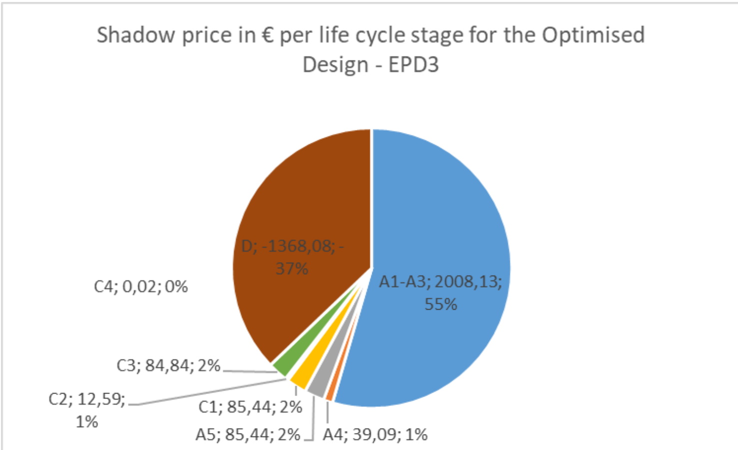

Figure 31: Relative shadow price in € per life cycle stage for the optimised design made with 80% reused steel in the EoL - EDP3.

Finally, an overview of the influence of the three EDPs on the final total shadow price of the structure per scenario is shown in Figure 32. Notable is that the negative value of module D is both included and excluded in the graph for all the cases. Therefore, the reduction in environmental cost when module D is included in the cumulative price, starting from the original design made with new steel elements to the optimised design made with 90% reused steel elements is calculated to be 73%. When considering the optimised design made from new steel elements (EPD1) and from reused steel elements (EPD2) the cost reduction is approx. 69% (incl. module D). Therefore, the optimised design built with reclaimed steel elements is recommended since it has the least environmental costs. The influence of module D is most evident in EPD3 which is logical because the potential savings of reusing 80% of steel result in a 59% reduction in the environmental cost.

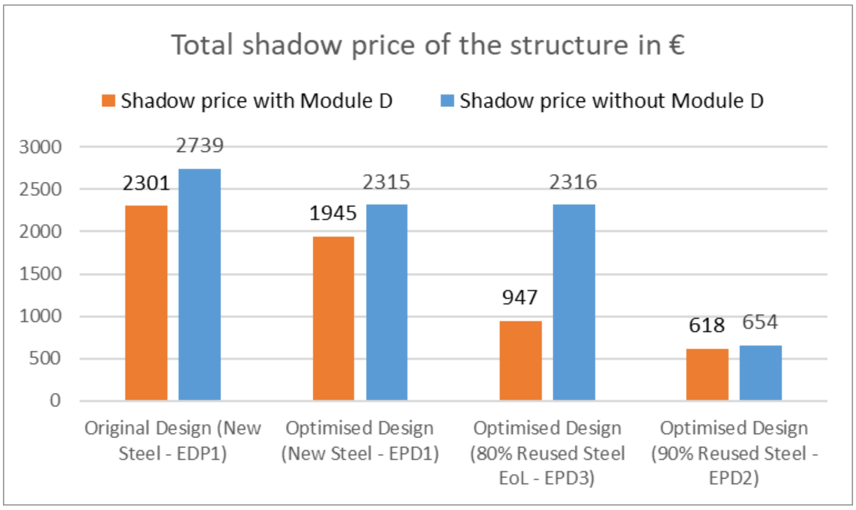

Figure 32: Total cumulative shadow price expressed in €/FU based on the four scenarios shown in Figure 12.

5. Life cycle cost analysis

Life cycle cost analysis is a tool to calculate the total cost of a product over its lifespan (Rebitzer & Hunkeler, 2003). More precisely, it is a technique used for the assessment and prediction of the cost performance of constructed assets over a predetermined period of time (ISO 15686-5, 2017). Therefore, an emphasis is placed on the initial and future costs, which usually are considered on an annual basis in the construction industry since projects are expected to last for a long time (e.g. 50 years). Noteworthy is the fact that since this study conducts both LCA and LCC analysis it is recommended in the code of practice by Swarr et al. (2011) that the two assessments share the same parameters defined in the four stage of ISO 14040 (2006a) (Figure 67 in Appendix B). This means that the same system boundaries and functional unit are assumed in the LCC as in the LCA described in chapter 4. Therefore, the use stage (B1-B7) is excluded in the LCC.

5.1. Assumptions & Limitations

As with every life cycle analysis, it is important to state the relevant assumptions and limitations in order to ensure the transparency and quality of the obtained results. Similar to the LCA in chapter 4 gathering the costs during all of the considered life cycle stages proved to be a difficult and time-consuming process. Most of the data was either out-dated and/or representative of a different geographical location than the one of the structure in this study. Some of the modules in the life cycle of similar product system were missing or their sources were not explicitly mentioned. Moreover, for some of the processes an attempt was made to obtain the costs directly from the construction contractors but they offer such information only to commercial clients via requests and do not have it publicly available.

Therefore, the assumptions below are made based on two main sources namely the PROGRESS report, sec. 7.2 (2020) and the paper of Vares et al. (2020) which have been chosen as a reference for the costs because of their transparency and their recent publication and geographical vicinity. The actual cost values are shown in Table 11 (sec. 5.2) in € per ton of new or reused steel. There the applied assumptions to a particular cost are referenced with a number between brackets (e.g. *(1)*, *(2)* etc.)

First, the described costs in the PROGRESS report are converted from £ to € using a factor of 1.16 as of June 13th 2023 (*British Pound to Euro Exchange Rate Chart*, 2023). Therefore, the following assumptions are made:

1. A 25% increase is added to the minimum costs for new steel to obtain the maximum ones in order to account for the variability of section sizes, etc.

2. Reclaimed section costs are based on a 26% scrap value of the new steel cost plus a flat rate margin for 128€ per tonne.

Next, the assumptions taken and deduced from the paper by Vares et al. (2020) are originally made based on the construction market in Finland and not in the Netherlands. Therefore, they should be considered as indicative and not precise. Notable is that the ratios between prices are taken as a guide instead of the absolute costs except for the reuse and recycling revenue values. The reason is that prices can vary in time but ratios are relevantly constant as suggested in the publication *Cost Components* by Bouwen met Staal. The assumptions are the following:

3. Revenue of 984 €/t from the sold recovered structure, but 166 €/t additional cost for deconstruction. In Table 12 the savings are indicated with a negative sign.
4. Revenue of 200 €/t from sold steel scrap. In Table 12 it is shown with a negative sign.
5. Demolition costs are 74% of Deconstruction costs.
6. Demolition audit costs are 50% of the deconstruction audit costs.

It is important to mention a few general limitations related to LCC as a technique. One of them is the fact that the estimation of the discounting rate, potential costs in the use stage of the product and future revenues is very difficult due to the dynamic nature of levels of the economy and social movements (Rebitzer & Hunkeler, 2003). This is accompanied by the inherently limiting fact that current technology is used for the evaluation of the future costs.

In addition to the time and location dependency, most of the costs are aggregated which leads to the issue of mapping them in a one-to-one relationship with a particular unit process identified in the LCA. Therefore, every project should be assessed individually.

5.2. Costs per life cycle phase

Overview of cost ranges of various operations that occur during the different life cycle modules of new and reused structural steel elements are presented in Table 11. The potential savings from the sold steel scrap via recycling and from the revenue of selling the elements via recovery are shown in Table 12.

Table 11: Overview of cost ranges for both new and reused steel of the various processes included in the life cycle modules of the product system.

Element (life cycle module)	New Steel (€/t)			Reused Steel (€/t)		
	Min	Avg	Max	Min	Avg	Max
Raw material (A1)	945[12]	1063	1181 *(1)*	374 *(2)*	404	435*(2)*
Deconstruction (C1)	-	-	-	140	166	192
Reconditioning (A3)	-	-	-	116,5	175	233
Fabrication (A3)	379	454	530	379	454	530
Construction (A5)	140	167	195	140	167	195
Fire protection coating (A3)	210	262	315	210	262	315
Engineering (A3)	65	79	92	65	79	92
Demolition (C1) *(5)*	103	123	142	-	-	-
Demolition audit costs (C1) *(6)*	68	81	94	-	-	-
Deconstruction audit costs (C1)	-	-	-	136	162	188
Transport (A2-4 & C2)	26	27	29	77	82	87
Testing (A3)	-	-	-	169	186	204

[12] The new steel price is calculated based on the steel price index value of 180 on 06.06.2023 (*StaalPrijsIndex*, n.d.) provided from Brink Staalbouw. The base price of steel when the index was set in 2016 was about € 500-550 per ton (Jurgen van Gils, personal communication, June 13 2023).

Table 12: Potential savings in module D depending on the method of recovery.

Potential Savings in D	
Recycling (€/t) *(4)*	Reuse (€/t) *(3)*
-200	-818

5.3. NPV & LCC value

In this section, the Net Present Value (NPV) and the LCC value are presented for the original and for the optimised design. For the latter the three EPDs are considered since they model different scenarios in the product stage (A1-A3) and the end-of-life stage (C1-C2). An arbitrary value for the nominal discount rate of 5% is chosen and an inflation rate of 4.4% (CBS, 2023) is used to obtain the real discount rate. The discount rate is defined as the "time value of money" and the difference between the nominal and real discount rate is that the former includes the inflation rate and the latter does not (Mearig et al., 1999). Noteworthy is that the NPV is calculated according to Eq. 1 and the LCC according to Eq. 2 below

$$NPV = \sum_{t=0}^{T} \frac{C_t}{(1+i-j)^t} \quad (Mearig\ et\ al., 1999) \qquad (Eq. 1)$$

$$LCC = C_0 + \sum_{t=1}^{T} \frac{C_t}{(1+i-j)^t} \quad (Mearig\ et\ al., 1999) \qquad (Eq. 2)$$

where,

C_o – initial capital cost;

C_t – present value of all recurring costs, incl. operation costs, maintenance and replacement costs, disposal costs) at year t;

t – year of cash flow;

i – discount rate;

j – inflation rate;

Module D is included separately to indicate the potential savings that potentially can be achieved through recycling and recovery of the elements.

Notable for the NPV and LCC calculations is that only the demolition/deconstruction and transport costs at year 50 are included since the costs in use stage (B1-B7) of the structure are assumed to be zero. This causes the NPV values to be 10 times lower on average than the initial costs because they consider only recurring costs. The actual cost values considered per life cycle stage per EPD at 5% discount rate and an inflation rate of 4.4% can be seen in Table 22, Table 23, Table 24 and Table 25 in Appendix C.

In Figure 33, the NPV and LCC values for the whole structure per design and per EPD can be seen. It is evident that the reduction in cost from the optimised design made with new steel (EPD1) to the one made with 90% reused steel is 40% even though there are extra costs incurred for testing and reconditioning the reclaimed elements (Table 24). However, they are not as big as the costs for fabrication and coating of the new steel elements (Table 23). If the same comparison is made with the original design made with new steel the reduction is almost 50%. Moreover, it is interesting to note that the scenario in which the optimised design is 80% reused in the end-of-life an increase in the LCC of

3.7% is observed. This is because the costs for the deconstruction audit and the deconstruction process are slightly greater than the ones for demolishing most of the structure (84%) as modelled in EPD1.

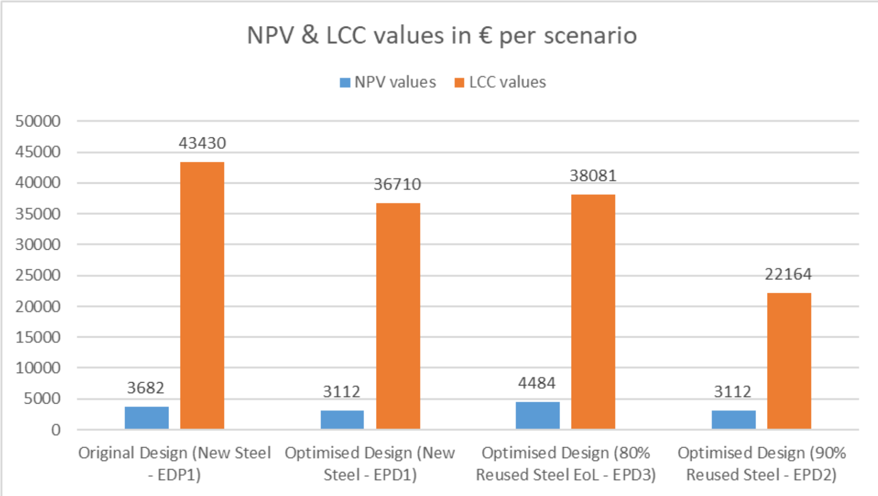

Figure 33: Average NPV & LCC values for the original and optimised design per EPD at 5% discount rate and 4.4% inflation rate.

Next, the main observation that is made from Figure 34 is that there are 55% more potential savings in recovering and reusing the steel elements at the end-of-life stage than there are if 83.16% are recycled and only 16% are reused as modelled in EPD1. Section 4.3 - Life cycle inventory analysis (LCI) explains this.

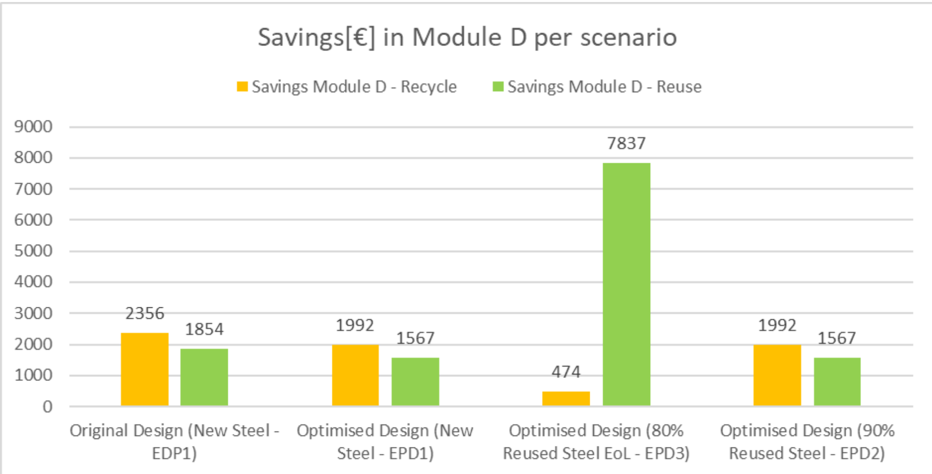

Figure 34: Average potential savings in module D of the two designs per EPD.

5.4. Interpretation

In order to ensure the robustness of the results, in following graphs the nominal discount rate is varied between 0% and 10% to see the extent to which the average LCC values for the A-C life cycle modules change per scenario. In Figure 35, a clear increase in the LCC values is observed in all cases when the discount rate is less than 5% which means that the structure is valued more in the present. This change is most extreme when the discount rate equals 0% resulting in an increase by 50% for EPD1, by 62% for EPD2 and by 58% for EPD3. In contrast, when the discount rate is greater than 5% the LCC value is becoming lower at a decreasing rate. At 10% discount rate the LCC value is reduced by 7.7% for EPD1, by 12.8% for EPD2 and by 10.7% for EPD3. This means that as the discount rate increases the structure is valued less and less in the present.

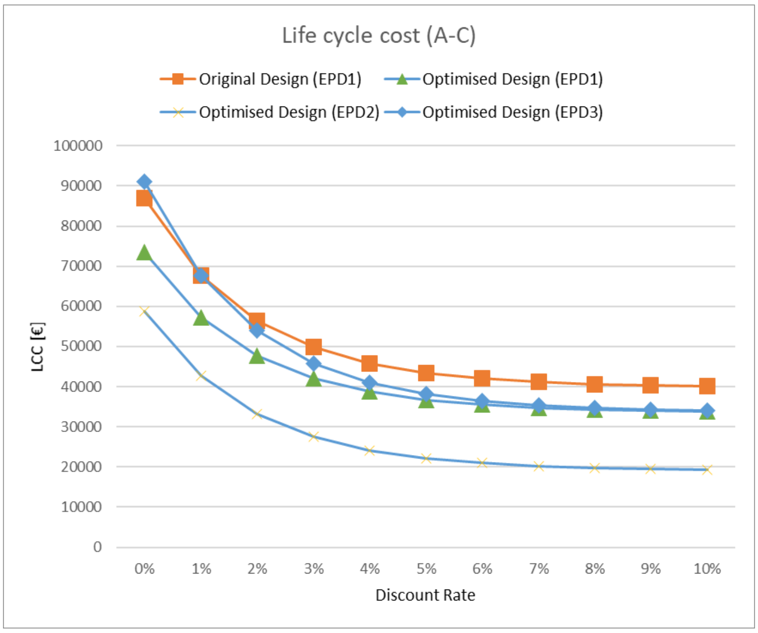

Figure 35: LCC values per scenario based on the variability of the nominal discount rate.

Next, in Figure 36 the potential savings from recycling per scenario are shown. It is logical that the original design made with new steel (EPD1) has the highest score in this graph since it also has the largest amount of material. Whereas, the optimised design modelled in EPD3 has the lowest value for recycling but it has the largest potential savings in Figure 37. Therefore, from those two graphs, it can be concluded that the benefits of reusing the steel elements are much greater than recycling them – 80% are reused in EPD3 which yields €100k at 0% discount as compared to only € 30k if 83.16% are recycled at 0% discount rate as modelled in EPD1.

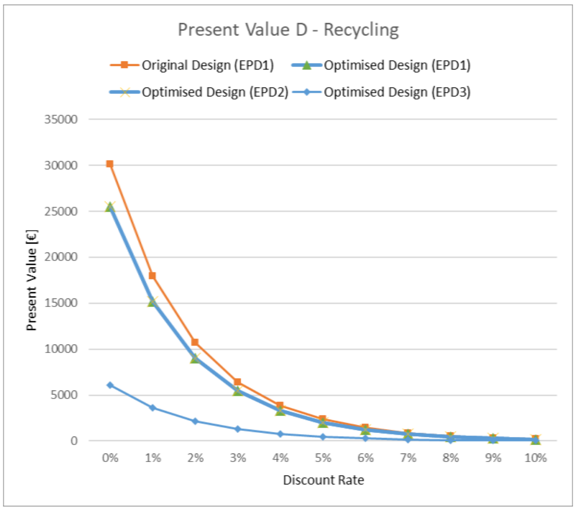

Figure 36: Present value of the benefits calculated for recycling with varied discount rate in module D after 50 years.

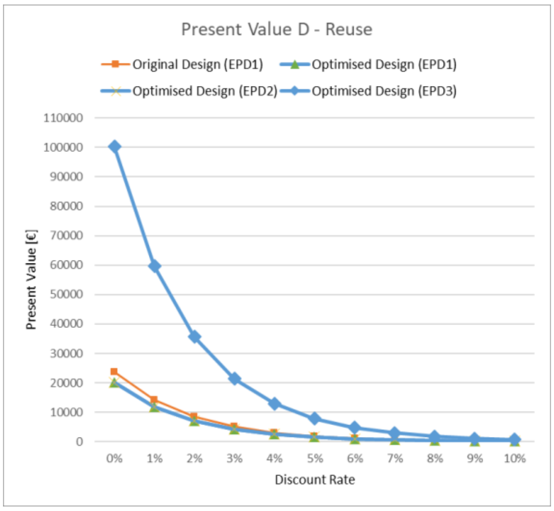

Figure 37: Present value of the benefits calculated for reuse with varied discount rate in module D after 50 years.

5.4.1. Sensitivity analysis

For the sensitivity analysis of the life cycle cost assessment a variation in the discount rate for the life cycle modules from A-C are discussed. Noteworthy is that an analysis on the results obtained by a hyperbolic discounting function is not included due to time constraints. A simple explanation of the difference between the two approaches is that hyperbolic discounting places less value on the near future than the exponential one and greater value on the more distant future (Green & Myerson, 1996). Figure 68 in Appendix C provides a visual representation of both functions.

Moreover, an analysis on the effect of the time horizon(e.g. 10, 15, 25 years) for the NPV calculation is not included in this section due to the omission of the use stage of the product system as stated in section 5.3. Therefore, only a fixed period of 50 years is included and the inflation rate is kept constant at 4.4%.

In Figure 38, the sensitivity of the LCC value to the change in nominal discount rate is shown for the original design with new steel elements. The exponential behaviour of the function is clearly visible as it starts with a very high valuation (€~87k) and it decreases at a slowing rate to around € 40k. The error bars show that the range of values is the biggest (+/- €12k) when the discount rate is lower than 5% and it is almost constant when it is larger than 5% (+/- €5.5k). Table 26 in Appendix C provides more details.

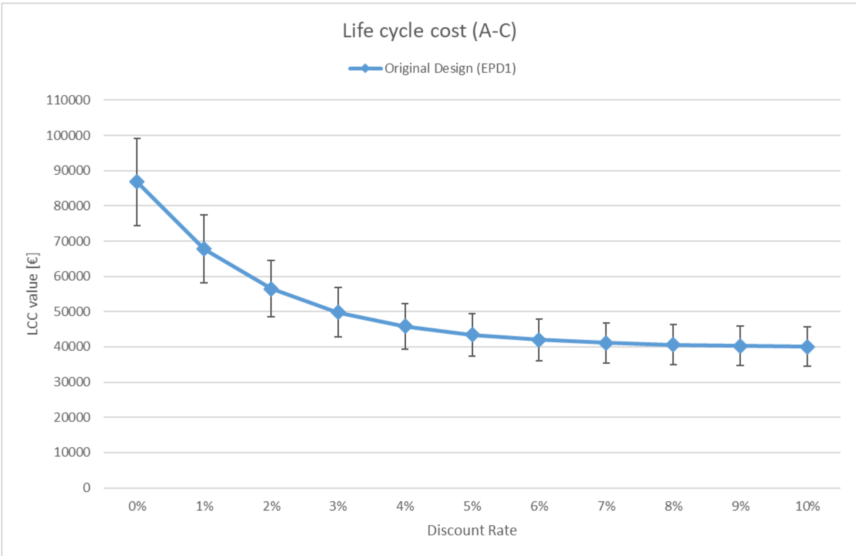

Figure 38: Sensitivity of the life cycle cost of the A-C modules to the change in discount rate for the original design with new steel elements (EPD1).

The same observations can be made for the optimised design with new steel elements shown in Figure 39. However, the values are a bit less than the original design which is expected since the optimised design needs less materials than the original one. At 0% discount rate the LCC value is on average € 73k and it decreases gradually to € 34k at 10% discount rate. This is a reduction of 15% from the original design with new steel. Moreover, the error bars show a maximum change of +/- €10k at 0% and +/- €4.7k. Table 27 in Appendix C provides more details.

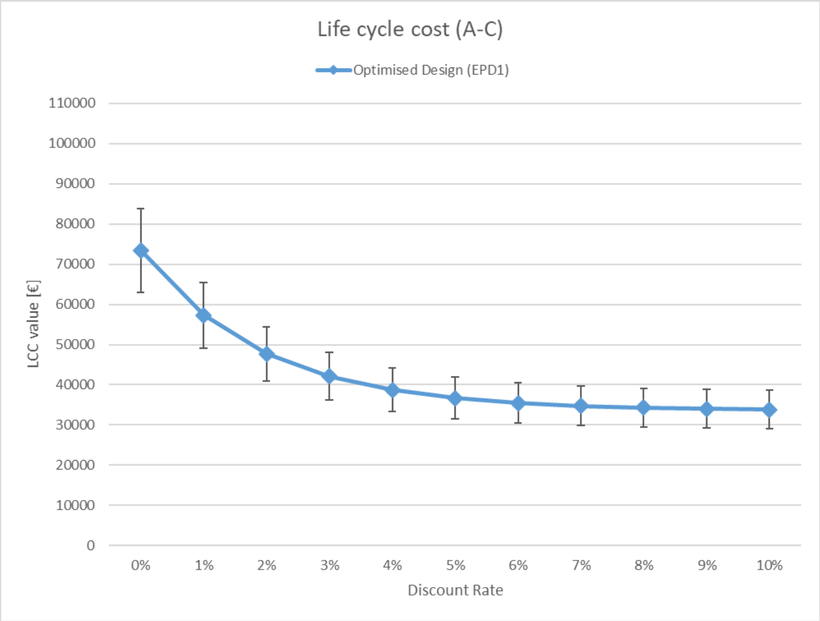

Figure 39: Sensitivity of the life cycle cost of the A-C modules to the change in discount rate for the optimised design with new steel elements (EPD1).

Next in Figure 40, the LCC value for the optimised design with reused steel elements as a function of the discount rate is shown. It is evident that there is a big reduction in the LCC due to the different scenario modelled in EPD2. The extreme value at 0% discount rate is 20% less than the scenario modelled with EPD1 for the same design – from € 73k to € 59k – and when the discount rate is 10% the reduction is 43% - from € 34k to € 19k. In addition, the error bars show a change of +/- € 8k for the former case and +/- €2k for the latter case. Table 28 in Appendix C provides more details.

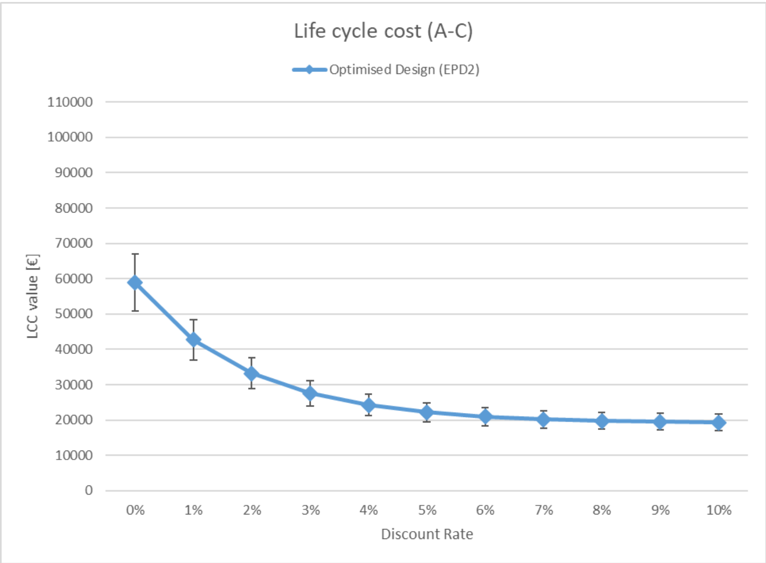

Figure 40: Sensitivity of the life cycle cost of the A-C modules to the change in discount rate for the optimised design (EPD2).

Finally, Figure 41 shows the scenario in which the optimised design is modelled according to EPD3 with 80% reuse at the end-of-life stage of the product system. The highest value occurring at 0% discount rate is € 90k and it plateaus around € 33k at 10% discount rate. This scenario is on par with the case of the original design as can be seen from Figure 35 as well. This is due to the extra costs in the end-of-life stage for deconstruction. Also, the error bars indicate a change in range of values of +/- €12.7k at 0% discount rate which decreases to +/- €4.7k at 10% discount rate. Table 29 in Appendix C provides more details.

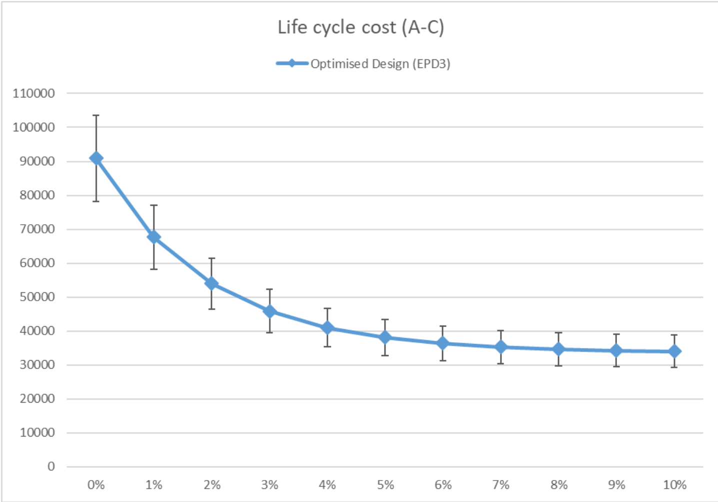

Figure 41: Sensitivity of the life cycle cost of the A-C modules to the change in discount rate for the optimised design (EPD3).

To summarise, the reduction in LCC value for the A-C stages is between 20-43% when the optimised design is modelled in EPD1 as compared to EPD2 depending on the discount rate considered for the calculation. Moreover, this proportion increases to 32-52% when the original design with new steel elements (EPD1) and the optimised design with reused steel elements (EPD2) are compared.

6. Conclusion

At present, there is an ever-increasing shift towards more environmentally friendly and economically efficient structural designs in the construction industry due to the climate change phenomenon. Therefore, companies are striving for the development of effective solutions that aim to achieve the targets set by the United Nations in the Sustainable Development Goals (SDGs) in 2015 (UN, 2015) and by their national governments (e.g. the Climate Law in the Netherlands (Klimaatwet, 2019)). In order to aid the decision-making process, comprehensive life cycle models are required which provide valuable information about the studied product system.

The aim of this study was to evaluate the environmental and economic sustainability effects of reused steel elements compared to new steel elements for the design of a section through a factory located in the Netherlands by conducting a LCA and a complementary LCC. Since the design with new steel elements was already done, an investigation of the necessary procedures and assumptions for the design with reclaimed steel elements was performed via a literature review in order to create a guideline with the steps that need to be considered. Based on the results a few destructive and non-destructive tests were identified which serve to ensure that the mechanical properties of the elements are up to standard. This is necessary because the structural program that is used for the optimisation of the section assumes certain default parameters of the steel elements. If there is a mismatch, the results will be incorrect and might cause critical failure once the structure is built on site. Examples of the tests include tensile tests, hardness tests, Charpy impact test etc.

After that, the original design was optimised via Technosoft Raamwerken V6 software with the help of the experts at Bilfinger Tebodin. The optimised design had 15.47% less material than the original design when considering only the beams and the columns. Furthermore, a few main assumptions were identified in the literature that influence the choice of which reclaimed steel elements are suitable to be used for the design of the structure and which are not. Some of the main constraints are that the steel elements can be reused if the source building is not older than 1970, if they are not corroded and have not been exposed to extreme loads. Also, due to potential geometric imperfections that might influence the stability check of the elements, a new and modified partial factor $\gamma_{M1,mod}$ is suggested by the literature to be implemented. It essentially adds 15% of safety margin that accounts for any uncertainties in the assessment of the steel elements. Therefore, it was found that in total 10 extra supports are necessary to prevent buckling in one column and lateral torsional buckling in a few bearing beams.

Once the geometrical characteristics of the two designs were known, a "cradle-to-gate with options, modules C1-C4 and module D" LCA was conducted. Unfortunately, there were two major limiting factors. The first one is the fact that there was limited access to comprehensive databases that contain information on the environmental impact of specific processes that occur during the product, use and end-of-life stage of the structure. The second one was due the fact that the contractor that builds it does not gather data on the fuel and electricity of relevant equipment. Therefore, it was decided to use three Environmental Product Declarations (EPDs) from Bouwen met Staal that were a good match for the structure because of their representativeness of the Dutch steel market and their functional units. They provided data for all of the life cycle stages except the use stage since no maintenance was expected for the particular product systems that were analysed. The three cases modelled in the EPDs based on which the environmental impact was investigated for the two designs are the following:

- 100% new steel in the product stage and 16% reuse of the material in the end-of-life stage based on EPD1
- 90% reused steel & 10% new steel in the product stage and 16% reuse of the material in the end-of-life stage based on EPD2
- 100% new steel in the product stage and 80% reuse of the material in the end-of-life stage based on EPD3

The main findings of the LCA in terms of kgCO_2eq were that when the original design made with new steel elements is compared to the optimised design with reused steel elements there is a reduction of 83% of the global warming potential of the whole structure. If the same comparison is made only for the optimised design with new and reused steel elements there is 80% decrease in CO_2 emissions. Some similar studies have been conducted in the past such as the ones outlined in the PROGRESS (2020), Vares et al. (2020) and Gervasio & Dimova (2018). However, their results are hardly comparable due to the different geometrical characteristics, inventory analysis and time/geographic location dependency.

Next, the Environmental Cost Indicator for the two designs was calculated per scenario. It essentially shows the potential cost that government has to pay to neutralize the environmental impact of the structure or the cost of direct environmental damage. In order to ensure the correctness of the results the environmental impact of all the 11 categories according to EN 15804 + A1 (2013) are calculated for the whole structure. Those include human toxicity, acidification of land and water, eutrophication potential etc. The results show that there is a 73% reduction in the environmental costs from the original design made with new steel elements to the optimised design made with 90% reused steel elements if the potential savings in module D are included – from € 2301 to €618 for the whole structure. If the same comparison is made for the optimised design modelled with EPD1 and EPD2 the reduction is approximately 69%.

Finally, a life cycle costing (LCC) analysis was made for the two designs per life cycle stage based on the available cost data found from literature and was modelled with the same parameters as the LCA. Noteworthy, is the fact that real time cost data for the construction processes involved in the life cycle of the structure can hardly be obtained since companies that perform these activities only offer them to commercial clients via a request. Therefore, even though the cost data used in this study was not representative of the time or geographical location of the analysed system the results are considered indicative. Namely it was found that the LCC value – composed of the initial costs and the net present value of all recurring future costs – at a 5% nominal discount rate and 4.4% inflation for the original design equals to €43k. Whereas under the same conditions the optimised design with reused steel elements equals €22k or there is almost a 50% reduction. If the same comparison is made for optimised design made with new and reused steel elements the reduction is 40% even though there are extra costs incurred for testing and reconditioning the reclaimed elements. In addition, a sensitivity analysis of the LCC value as a function of the discount rate was made to ensure the robustness of the results. The variation was between 0% and 10%. The LCC was on average higher by €57-47k at 0% depending on the considered scenario.

Of course, this thesis project will not solve directly the problem of reusing structural steel elements in the construction of buildings, however, the insights gained from the LCA and LCC analysis of this case study can certainly contribute to the better understanding of the environmental and economic trade-offs and facilitate the decision-making process.

In addition, it is noteworthy that the results for this optimised section can be extrapolated for all the sections throughout the factory that share the same geometrical characteristics and thus calculate the total benefits of reusing structural steel elements. However, even though the Waste Framework Directive (European Commission, 2008) ranks the reuse method of recovery to be environmentally superior to recycling, it should be verified via a comprehensive LCA due to the variability of building practices and specifics of each construction project.

7. Discussion & Recommendations for future research

The goal of this study was to evaluate and compare the environmental and economic impact of two section designs built with new and reused steel elements. Even though it achieved this target, as was emphasized throughout the report, there are numerous assumptions that influence the results of the LCA and LCC analysis. Therefore, in this section a few main points for future research based on the research questions are discussed.

First, in terms of the LCA it would be useful to visit the construction site to gather all the relevant data for a more comprehensive analysis instead of relying on the general EPDs modelled by Bouwen met Staal. Examples of such data include liters per hour for any self-propelled cranes, energy per hour for any professional equipment that is used during the construction/installation stage of the structure. This would yield specific results for the impact assessment of the product system and thus allow for a more accurate calculation of the environmental cost indicator. Therefore, it would be interesting to research if a larger dataset would have any influence on the outcome of the study.

Furthermore, regarding the LCC analysis an investigation of the effect of hyperbolic discounting as compared to the exponential one on the net present value would offer a clearer overview of the short and long-term benefits of the designs. Also, the extent to which the time horizon (e.g. 15, 25 years) influences the net present value would be interesting to study.

In this research project in total four scenarios were analysed (refer to Figure 12 in chapter 4), however modelling more scenarios in which different proportions of the new and reused material are assigned in the product and end-of-life stages might provide additional insight into the distribution of the benefits as a function of the recycled or reused quantities.

Moreover, since the social dimension of sustainability is not considered in this thesis it would be useful to assess all of the stakeholders' interests including Bilfinger Tebodin, the steel manufacturers, the environment etc. and provide conclusions on the trade-offs of all scenarios. One way to achieve this is with the help of a multi-criteria decision analysis that can be implemented in a comprehensive and automated software tool that follows the methodology and assessments discussed in this report. It can provide informative graphs for the emissions and costs per life cycle stage and per component of the studied system.

8. Recommendations on the reusability of reclaimed steel elements

From the results of this study, the benefits of the optimised design made with reused steel elements are clear both in the environmental and economic aspect. However, as it was outlined in the research context there are certain barriers that are preventing the reusability of steel elements to become common practice. One of them is that designers are used to working with standardized elements that are available at a moment's notice and have guaranteed mechanical characteristics such as steel grade, camber values etc. Also, there is a common perception that older standards are of lower quality than the present ones so often elements are oversized to account for any uncertainties in the steel properties.

Therefore, next to the design recommendations in chapter 3.5.1 a few points to facilitate the reusability of steel elements partly based on Gorgolewski et al. (2006) and the thesis of Varghese K. Z. (2022) are given as recommendations to the practicing structural engineers at the company:

- Adopt a material-driven design instead of a form-focused design whenever possible. This means that the available materials should be identified first and then the design should be adjusted accordingly instead of vice versa.

- Designing for adaptability and deconstruction should be prioritized as often as possible to maximise the usefulness and value of the different components at the end-of-life stage of the structure.
- Establish a “log book” for the building that would serve as a deconstruction manual in order to ensure maximum reusability of the structural elements.
- Consult with the new NTA 8713 (2023) for the reuse of structural steelwork.
- Preserve and store all the detailed documentation of the project until the end of its design life in order to avoid the lack of information about the performance of reclaimed structural steel elements. This ensures the traceability of the elements as well.

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Appendices

Appendix A Structural Model

In this appendix, some of the details regarding the structural model are outlined in order to provide context and ensure the transparency of the data.

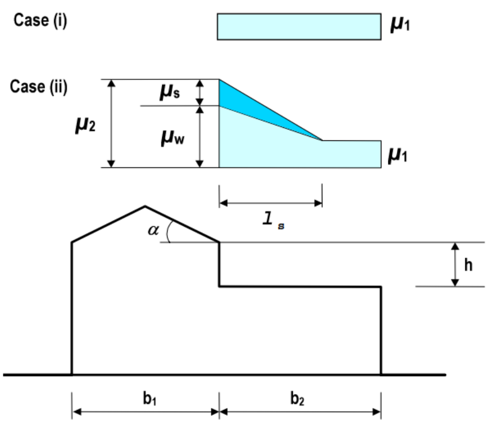

Figure 42: Snow load shape for roofs abutting to taller construction works.(Source: NEN-EN 1991-1-3, 2002)

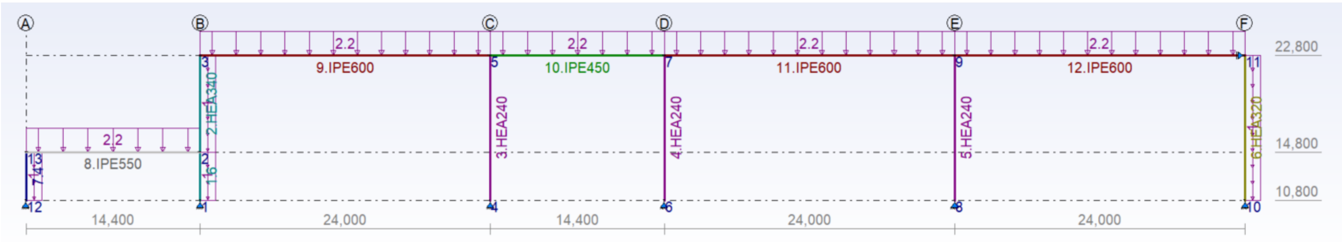

Figure 43: Load case: Permanent loads from self-weight.

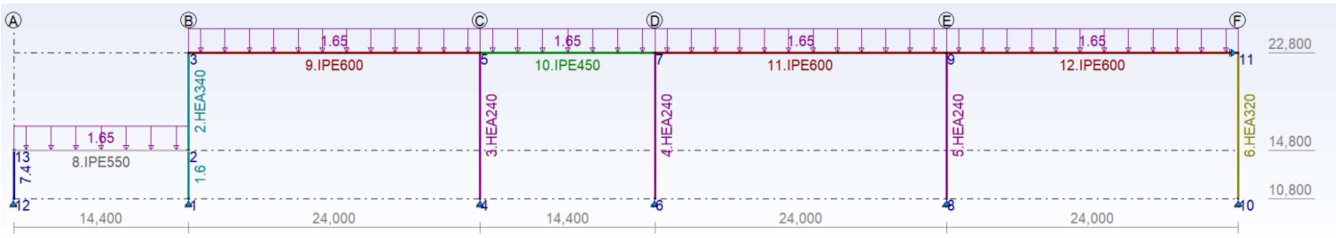

Figure 44: Load case: Solar panels.

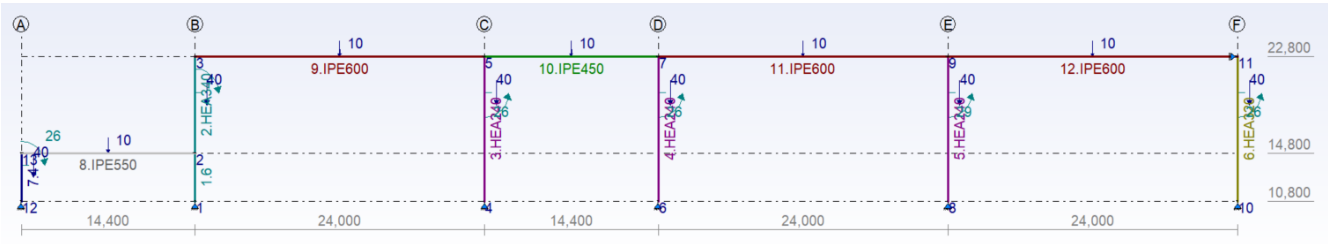

Figure 45: Load case: Installations.

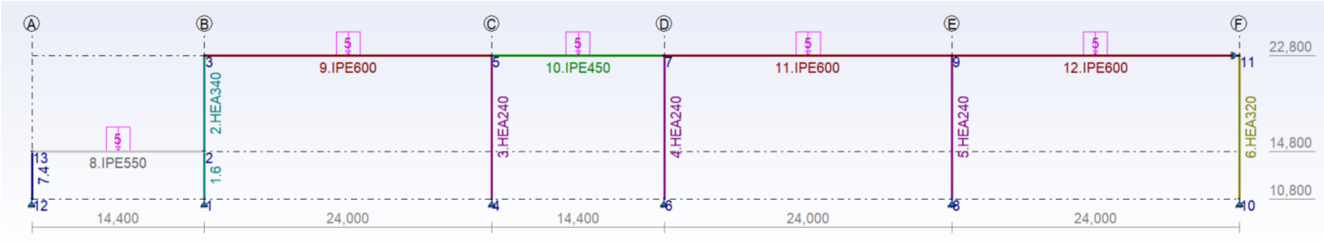

Figure 46: Load case: Variable loads - people q_k.

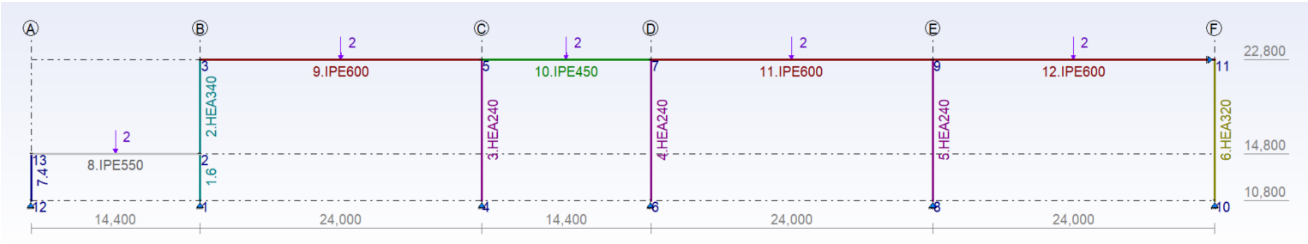

Figure 47: Load case: Variable loads - people Q_k.

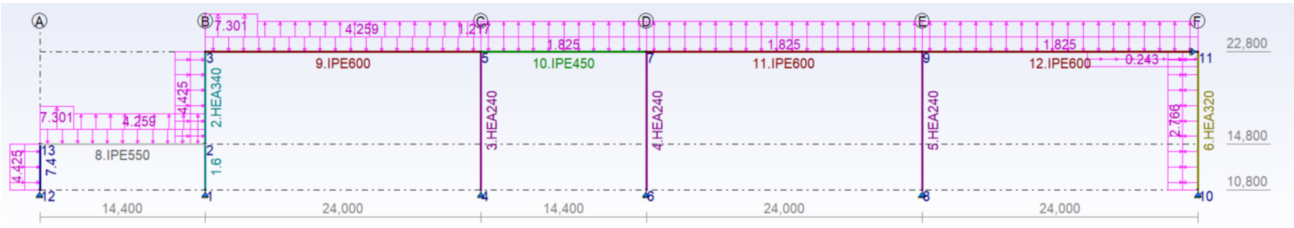

Figure 48: Load case: Wind from left & underpressure A.

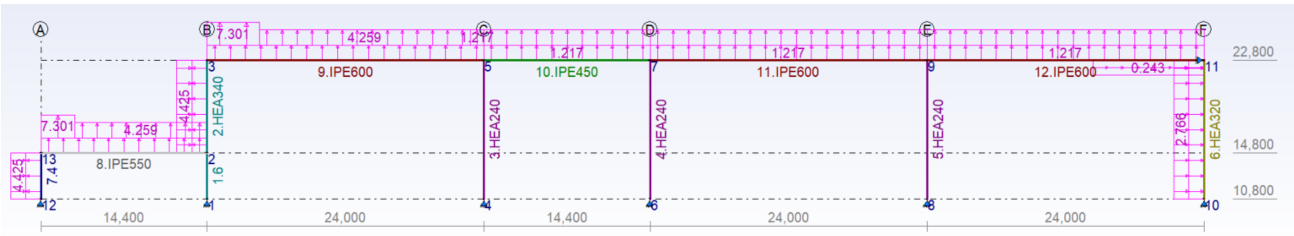

Figure 49: Load case: Wind from left & overpressure A.

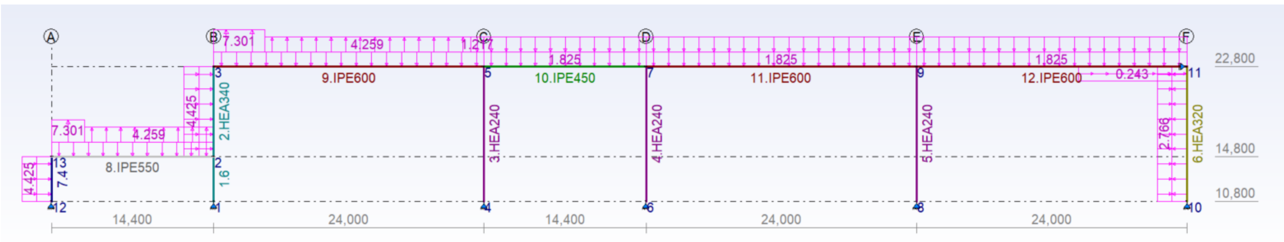

Figure 50: Load case: Wind from left & underpressure B.

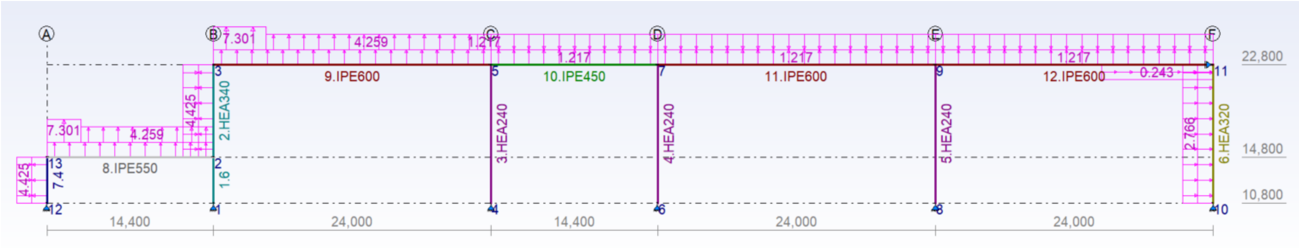

Figure 51: Load case: Wind from left & overpressure B.

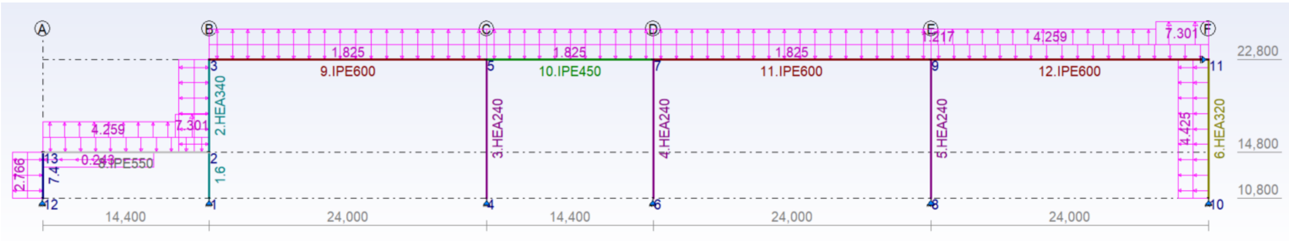

Figure 52: Load case: Wind from right & underpressure A.

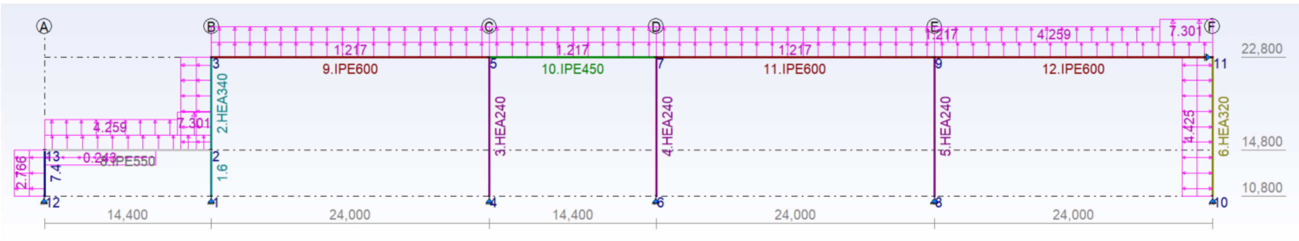

Figure 53: Load case: Wind from right & overpressure A.

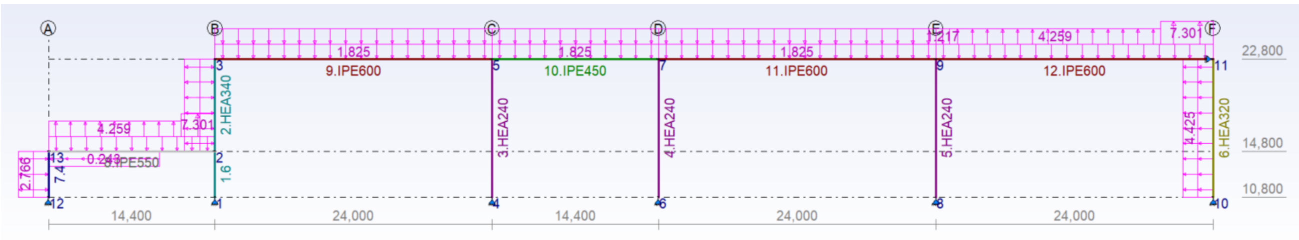

Figure 54: Load case: Wind from right & underpressure B.

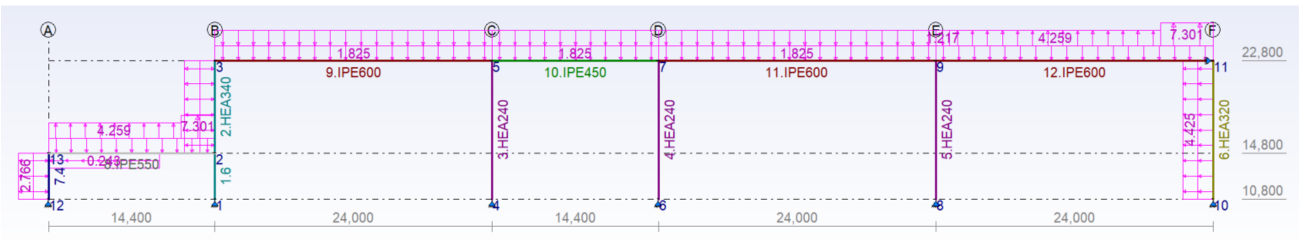

Figure 55: Load case: Wind from right & overpressure B.

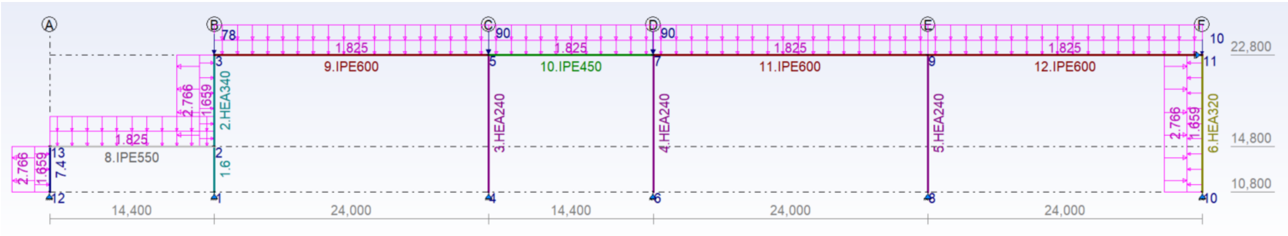

Figure 56: Load case: Wind perpendicular & underpressure.

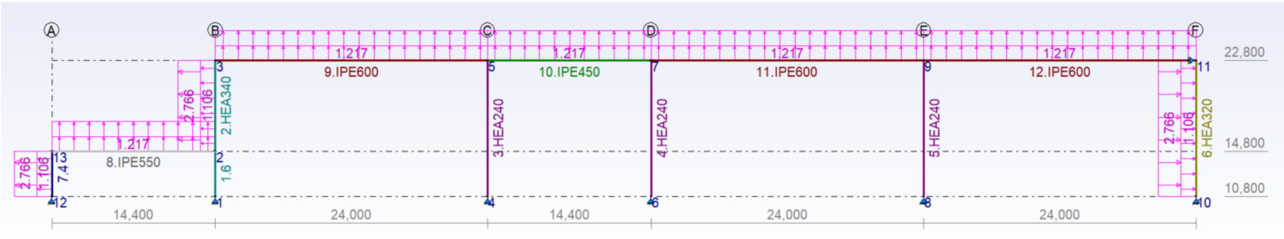

Figure 57: Load case: Wind perpendicular & overpressure.

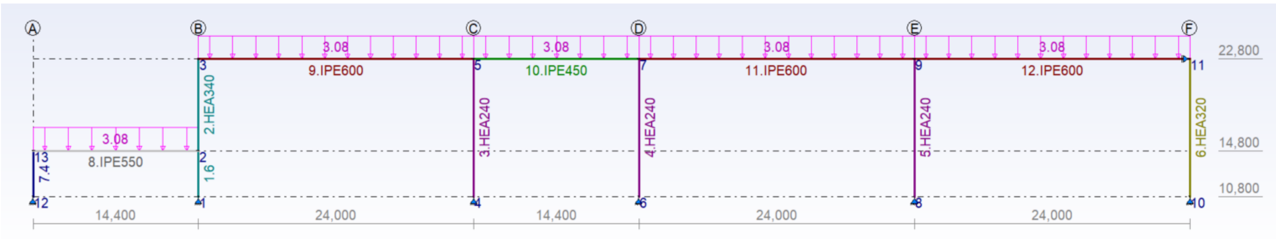

Figure 58: Load case: Snow A.

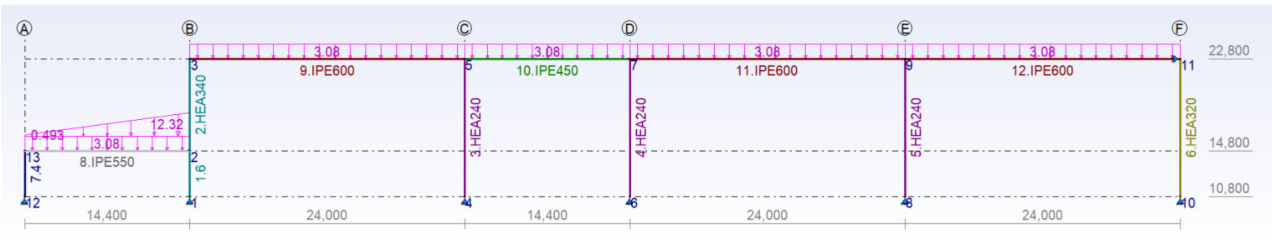

Figure 59: Load case: Snow B.

$$\begin{cases} \sum_{j\geq 1} \gamma_{G,j} G_{k,j} \text{"+"} \gamma_P P \text{"+"} \gamma_{Q,1} \psi_{0,1} Q_{k,1} \text{"+"} \sum_{i>1} \gamma_{Q,i} \psi_{0,i} Q_{k,i} & (6.10a) \\ \sum_{j\geq 1} \xi_j \gamma_{G,j} G_{k,j} \text{"+"} \gamma_P P \text{"+"} \gamma_{Q,1} Q_{k,1} \text{"+"} \sum_{i>1} \gamma_{Q,i} \psi_{0,i} Q_{k,i} & (6.10b) \end{cases}$$

Figure 60: Expressions for the combination of actions on a structure for the ULS.(Source: NEN-EN 1990 §6.4.3.2 (3),2002)

In Figure 60, where some of the symbols mean:

"+ " implies "to be combined with"

$\sum$ implies "the combined effect of"

ξ is a reduction factor for unfavourable permanent actions G

$$\sum_{j\geq 1} G_{k,j} \text{"+"} P \text{"+"} Q_{k,1} \text{"+"} \sum_{i>1} \psi_{0,i} Q_{k,i} \qquad (6.14b)$$

Figure 61: Expressions for the combination of actions on a structure for the SLS. (Source: NEN-EN 1990 § 6.5.3 a), 2002)

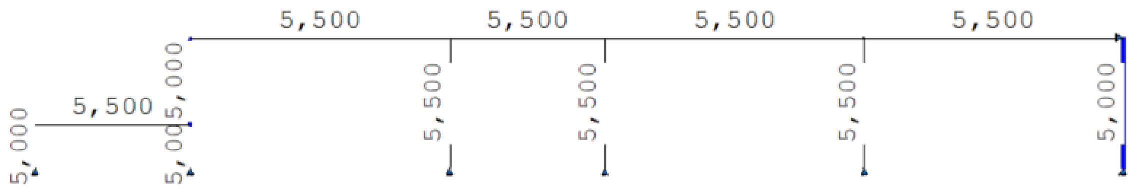

Figure 62: Loading widths of the analysed section.

The identifiers of the columns and bearing beams are visualized in Figure 63.

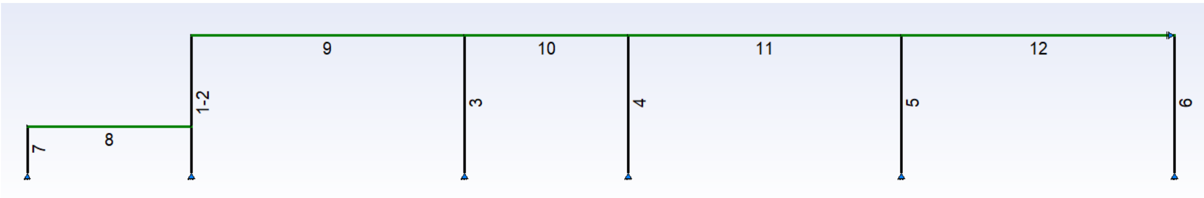

Figure 63: Enumeration of the bearing beams and columns.

In the following table, the camber values for the bearing beams of the structure are shown.

Table 13: Camber values in mm for each of the bearing beams.

Bar number	Camber [mm]
8	15
9	110
10	15
11	110
12	110

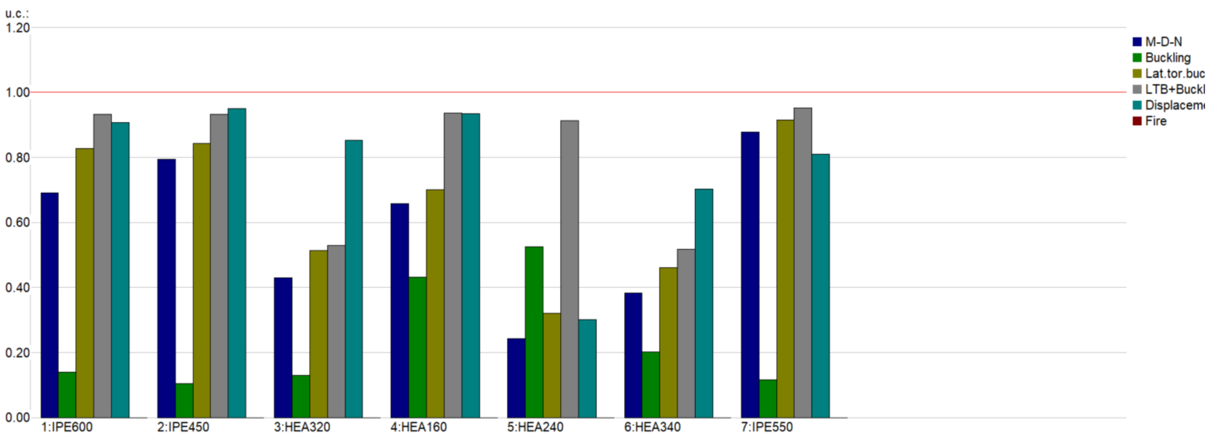

Figure 64: Unity check in Technosoft Raamwerken V6 for all 7 profiles used in the optimised design.

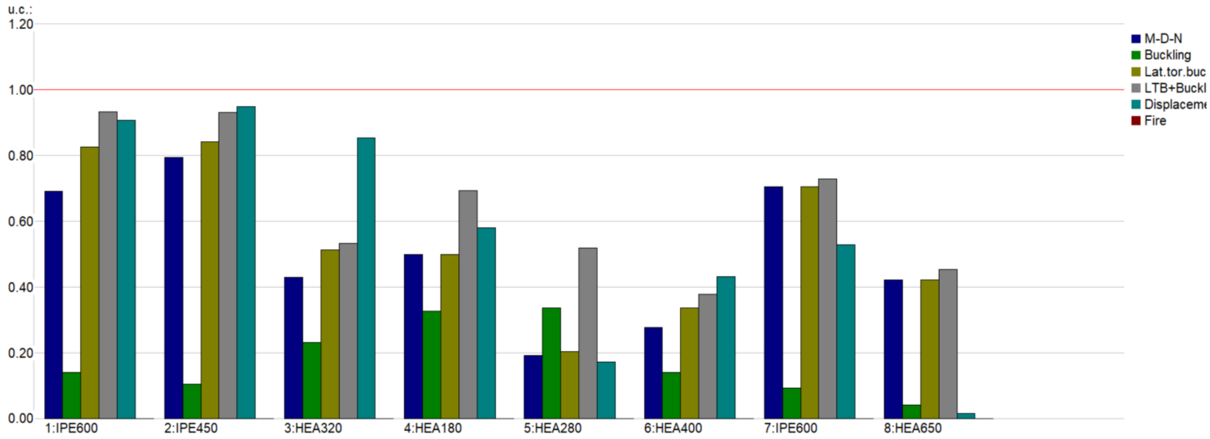

Figure 65: Unity check in Technosoft Raamwerken V6 for all 8 profiles used in the original design.

Appendix B Life Cycle Assessment

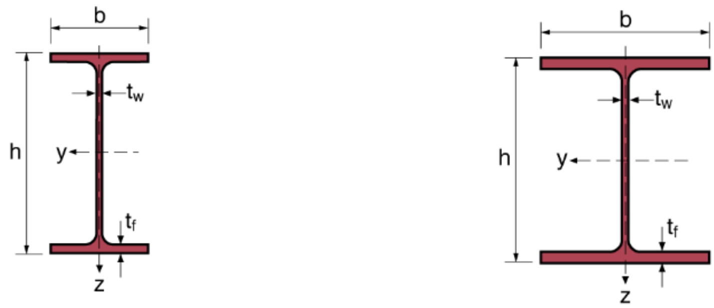

Figure 66: (a) IPE profile parameters; (b) HEA profile parameters. (Source: Profiel Vinden, n.d.)

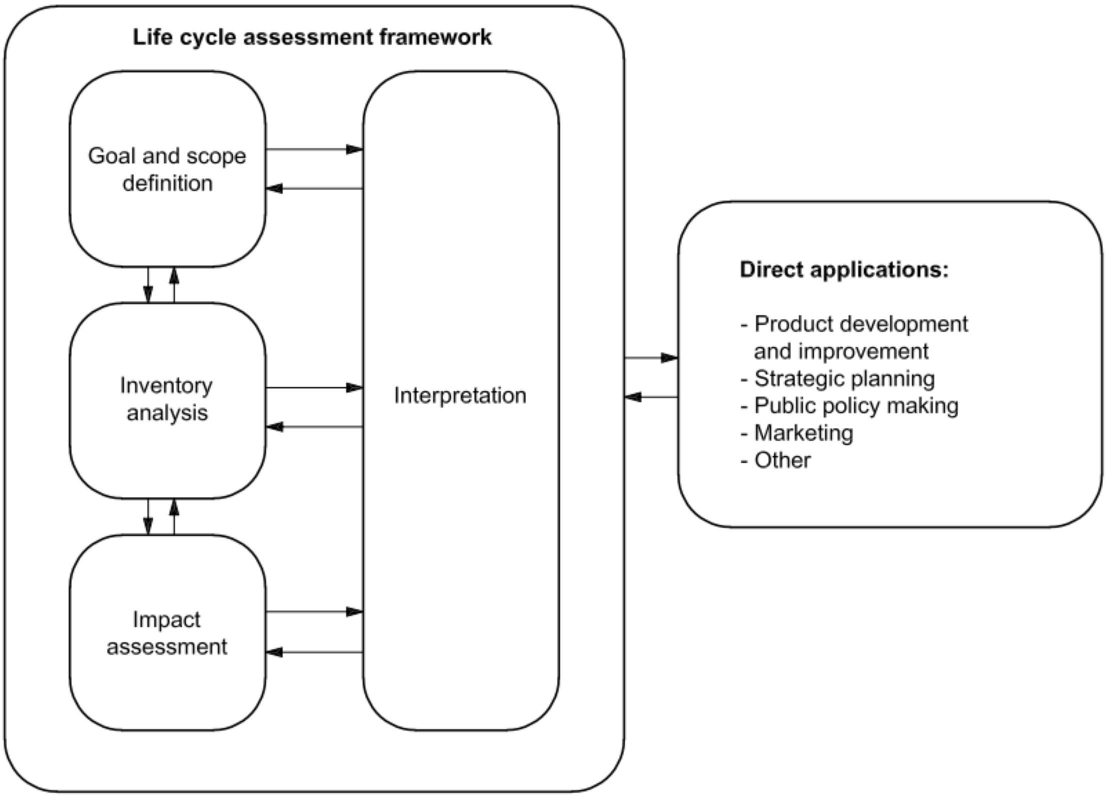

Figure 67: Life cycle assessment structure. (Source: ISO 14040, 2006a)

The next four tables show the impact assessment for the set of 11 categories outlined in NEN EN 15804 + A1 (2013) based on the 3 EPDs considered for the 4 scenarios, namely (i) Original Design with new steel elements – EPD1, (ii) Optimised design with new steel elements – EPD1, (iii) Optimised design with 80% reused steel in the end-of-life stage – EPD3 and (iv) Optimised design with 90% reused steel elements – EPD2.

Table 14: Impact assessment of the original design with new steel elements – EPD1.

Impact cat./ Life cycle module	A1-A3	A4	A5	C1	C2	C3	C4	D
ADPE	1,14E+00	9,80E-03	2,46E-03	2,46E-03	3,61E-04	8,75E-03	9,78E-07	-6,65E-01
ADPF	1,42E+02	2,83E+00	6,36E+00	6,36E+00	9,36E-01	3,29E+00	1,17E-02	-2,73E+01
GWP	2,14E+04	3,84E+02	9,11E+02	9,11E+02	1,27E+02	5,03E+02	8,58E-01	-4,18E+03
ODP	1,51E-03	6,80E-05	1,13E-04	1,13E-04	2,33E-05	5,94E-05	2,85E-07	-2,24E-04
POCP	1,65E+01	2,31E-01	6,25E-01	6,25E-01	7,49E-02	3,94E-01	9,10E-04	-3,29E+00
AP	7,51E+01	1,69E+00	4,80E+00	4,80E+00	5,50E-01	4,34E+00	6,34E-03	-1,42E+01
EP	1,40E+01	3,31E-01	1,07E+00	1,07E+00	1,10E-01	9,31E-01	1,19E-03	-2,73E+00
HTP	8,12E+03	1,61E+02	2,52E+02	2,52E+02	5,08E+01	4,80E+02	3,50E-01	-1,37E+03
FAETP	1,95E+02	4,72E+00	4,01E+00	4,01E+00	1,49E+00	6,71E+00	8,69E-03	-2,83E+01
MAETP	5,54E+05	1,70E+04	1,47E+04	1,47E+04	5,37E+03	4,03E+04	2,98E+01	-8,29E+04
TETP	5,18E+02	5,71E-01	2,24E+00	2,24E+00	1,80E-01	1,56E+00	1,04E-03	-5,33E+01

Table 15: Impact assessment of the optimised design with new steel elements – EPD1.

Impact cat./ Life cycle module	A1-A3	A4	A5	C1	C2	C3	C4	D
ADPE	9,64E-01	8,29E-03	2,08E-03	2,08E-03	3,05E-04	7,40E-03	8,27E-07	-5,62E-01
ADPF	1,20E+02	2,39E+00	5,38E+00	5,38E+00	7,91E-01	2,78E+00	9,87E-03	-2,31E+01
GWP	1,81E+04	3,25E+02	7,70E+02	7,70E+02	1,07E+02	4,25E+02	7,25E-01	-3,54E+03
ODP	1,28E-03	5,75E-05	9,51E-05	9,51E-05	1,97E-05	5,02E-05	2,41E-07	-1,89E-04
POCP	1,39E+01	1,95E-01	5,28E-01	5,28E-01	6,33E-02	3,33E-01	7,69E-04	-2,78E+00
AP	6,35E+01	1,43E+00	4,05E+00	4,05E+00	4,65E-01	3,67E+00	5,36E-03	-1,20E+01
EP	1,19E+01	2,79E-01	9,04E-01	9,04E-01	9,27E-02	7,87E-01	1,01E-03	-2,31E+00
HTP	6,86E+03	1,36E+02	2,13E+02	2,13E+02	4,30E+01	4,05E+02	2,96E-01	-1,16E+03
FAETP	1,65E+02	3,99E+00	3,39E+00	3,39E+00	1,26E+00	5,67E+00	7,35E-03	-2,39E+01
MAETP	4,68E+05	1,43E+04	1,24E+04	1,24E+04	4,54E+03	3,41E+04	2,52E+01	-7,01E+04
TETP	4,38E+02	4,83E-01	1,89E+00	1,89E+00	1,52E-01	1,32E+00	8,75E-04	-4,51E+01

Table 16: Impact assessment of the optimised design with 80% reused steel in the end-of-life stage – EPD3.

Impact cat./ Life cycle module	A1-A3	A4	A5	C1	C2	C3	C4	D

ADPE	9,64E-01	8,29E-03	2,08E-03	2,08E-03	3,04E-04	7,45E-03	1,97E-07	-7,25E-01
ADPF	1,20E+02	2,39E+00	5,38E+00	5,38E+00	7,87E-01	2,79E+00	2,34E-03	-8,22E+01
GWP	1,81E+04	3,25E+02	7,70E+02	7,70E+02	1,07E+02	4,28E+02	1,73E-01	-1,23E+04
ODP	1,28E-03	5,75E-05	9,51E-05	9,51E-05	1,97E-05	5,06E-05	5,72E-08	-8,48E-04
POCP	1,39E+01	1,95E-01	5,28E-01	5,28E-01	6,28E-02	3,34E-01	1,83E-04	-1,00E+01
AP	6,35E+01	1,43E+00	4,05E+00	4,05E+00	4,62E-01	3,68E+00	1,28E-03	-4,34E+01
EP	1,19E+01	2,79E-01	9,04E-01	9,04E-01	9,21E-02	7,91E-01	2,41E-04	-8,17E+00
HTP	6,86E+03	1,36E+02	2,13E+02	2,13E+02	4,26E+01	4,09E+02	7,04E-02	-4,67E+03
FAETP	1,65E+02	3,99E+00	3,39E+00	3,39E+00	1,25E+00	5,72E+00	1,74E-03	-1,11E+02
MAETP	4,68E+05	1,43E+04	1,24E+04	1,24E+04	4,51E+03	3,44E+04	6,02E+00	-3,13E+05
TETP	4,38E+02	4,83E-01	1,89E+00	1,89E+00	1,51E-01	1,33E+00	2,08E-04	-3,02E+02

Table 17: Impact assessment of the optimised design with 90% reused steel elements – EPD2.

Impact cat./ Life cycle module	A1-A3	A4	A5	C1	C2	C3	C4	D
ADPE	2,37E-01	8,29E-03	2,08E-03	2,08E-03	3,05E-04	7,40E-03	8,27E-07	-5,35E-02
ADPF	1,99E+01	2,39E+00	5,38E+00	5,38E+00	7,91E-01	2,78E+00	9,87E-03	-1,92E+00
GWP	3,20E+03	3,25E+02	7,70E+02	7,70E+02	1,07E+02	4,25E+02	7,25E-01	-2,76E+02
ODP	2,25E-04	5,75E-05	9,51E-05	9,51E-05	1,97E-05	5,02E-05	2,41E-07	-2,34E-05
POCP	3,63E+00	1,95E-01	5,28E-01	5,28E-01	6,33E-02	3,33E-01	7,69E-04	-4,23E-01
AP	1,08E+01	1,43E+00	4,05E+00	4,05E+00	4,65E-01	3,67E+00	5,36E-03	-1,18E+00
EP	1,92E+00	2,79E-01	9,04E-01	9,04E-01	9,27E-02	7,87E-01	1,01E-03	-2,36E-01
HTP	1,16E+03	1,36E+02	2,13E+02	2,13E+02	4,30E+01	4,05E+02	2,96E-01	-1,42E+02
FAETP	2,96E+01	3,99E+00	3,39E+00	3,39E+00	1,26E+00	5,67E+00	7,35E-03	-2,26E+00
MAETP	7,87E+04	1,43E+04	1,24E+04	1,24E+04	4,54E+03	3,41E+04	2,52E+01	-7,51E+03
TETP	4,86E+01	4,83E-01	1,89E+00	1,89E+00	1,52E-01	1,32E+00	8,75E-04	-4,17E+00

Table 18, Table 19, Table 20 and Table 21 show the shadow price of each of the life cycle modules of the two designs per EPD.

Table 18: Shadow costs per life cycle module of the original design with new steel elements – EPD1.

Impact cat./ Life cycle module	A1-A3	A4	A5	C1	C2	C3	C4	D
ADPE	1,83E-01	1,57E-03	3,94E-04	3,94E-04	5,78E-05	1,40E-03	1,57E-07	-1,06E-01
ADPF	2,27E+01	4,52E-01	1,02E+00	1,02E+00	1,50E-01	5,26E-01	1,87E-03	-4,37E+00

GWP	1,07E+03	1,92E+01	4,56E+01	4,56E+01	6,34E+00	2,51E+01	4,29E-02	-2,09E+02
ODP	4,53E-02	2,04E-03	3,38E-03	3,38E-03	6,99E-04	1,78E-03	8,54E-06	-6,71E-03
POCP	3,30E+01	4,62E-01	1,25E+00	1,25E+00	1,50E-01	7,87E-01	1,82E-03	-6,57E+00
AP	3,00E+02	6,75E+00	1,92E+01	1,92E+01	2,20E+00	1,74E+01	2,54E-02	-5,67E+01
EP	1,26E+02	2,98E+00	9,63E+00	9,63E+00	9,87E-01	8,38E+00	1,07E-02	-2,46E+01
HTP	7,31E+02	1,45E+01	2,27E+01	2,27E+01	4,57E+00	4,32E+01	3,15E-02	-1,24E+02
FAETP	5,85E+00	1,42E-01	1,20E-01	1,20E-01	4,47E-02	2,01E-01	2,61E-04	-8,48E-01
MAETP	5,54E+01	1,70E+00	1,47E+00	1,47E+00	5,37E-01	4,03E+00	2,98E-03	-8,29E+00
TETP	3,11E+01	3,43E-02	1,34E-01	1,34E-01	1,08E-02	9,39E-02	6,21E-05	-3,20E+00
Total [€]	**2,38E+03**	**4,63E+01**	**1,01E+02**	**1,01E+02**	**1,50E+01**	**9,97E+01**	**1,17E-01**	**-4,38E+02**

Table 19: Shadow costs per life cycle module of the optimised design with new steel elements – EPD1.

Impact cat./ Life cycle module	A1-A3	A4	A5	C1	C2	C3	C4	D
ADPE	1,54E-01	1,33E-03	3,33E-04	3,33E-04	4,88E-05	1,18E-03	1,32E-07	-8,99E-02
ADPF	1,91E+01	3,82E-01	8,61E-01	8,61E-01	1,27E-01	4,44E-01	1,58E-03	-3,70E+00
GWP	9,04E+02	1,62E+01	3,85E+01	3,85E+01	5,36E+00	2,12E+01	3,63E-02	-1,77E+02
ODP	3,83E-02	1,72E-03	2,85E-03	2,85E-03	5,91E-04	1,51E-03	7,22E-06	-5,67E-03
POCP	2,79E+01	3,91E-01	1,06E+00	1,06E+00	1,27E-01	6,65E-01	1,54E-03	-5,56E+00
AP	2,54E+02	5,70E+00	1,62E+01	1,62E+01	1,86E+00	1,47E+01	2,14E-02	-4,79E+01
EP	1,07E+02	2,51E+00	8,14E+00	8,14E+00	8,34E-01	7,08E+00	9,07E-03	-2,08E+01
HTP	6,18E+02	1,23E+01	1,92E+01	1,92E+01	3,87E+00	3,65E+01	2,66E-02	-1,05E+02
FAETP	4,94E+00	1,20E-01	1,02E-01	1,02E-01	3,77E-02	1,70E-01	2,20E-04	-7,17E-01
MAETP	4,68E+01	1,43E+00	1,24E+00	1,24E+00	4,54E-01	3,41E+00	2,52E-03	-7,01E+00
TETP	2,63E+01	2,90E-02	1,13E-01	1,13E-01	9,12E-03	7,94E-02	5,25E-05	-2,70E+00
Total [€]	**2,01E+03**	**3,91E+01**	**8,54E+01**	**8,54E+01**	**1,27E+01**	**8,42E+01**	**9,93E-02**	**-3,70E+02**

Table 20: Shadow costs per life cycle module of the optimised design with 80% reused steel in the end-of-life stage – EPD3.

Impact cat./ Life cycle module	A1-A3	A4	A5	C1	C2	C3	C4	D
ADPE	1,54E-01	1,33E-03	3,33E-04	3,33E-04	4,86E-05	1,19E-03	3,15E-08	-1,16E-01
ADPF	1,91E+01	3,82E-01	8,61E-01	8,61E-01	1,26E-01	4,47E-01	3,75E-04	-1,32E+01
GWP	9,04E+02	1,62E+01	3,85E+01	3,85E+01	5,33E+00	2,14E+01	8,64E-03	-6,15E+02
ODP	3,83E-02	1,72E-03	2,85E-03	2,85E-03	5,91E-04	1,52E-03	1,72E-06	-2,54E-02
POCP	2,79E+01	3,91E-01	1,06E+00	1,06E+00	1,26E-01	6,69E-01	3,65E-04	-2,00E+01
AP	2,54E+02	5,70E+00	1,62E+01	1,62E+01	1,85E+00	1,47E+01	5,10E-03	-1,74E+02
EP	1,07E+02	2,51E+00	8,14E+00	8,14E+00	8,29E-01	7,12E+00	2,17E-03	-7,36E+01
HTP	6,18E+02	1,23E+01	1,92E+01	1,92E+01	3,84E+00	3,68E+01	6,34E-03	-4,20E+02
FAETP	4,94E+00	1,20E-01	1,02E-01	1,02E-01	3,75E-02	1,72E-01	5,23E-05	-3,33E+00
MAETP	4,68E+01	1,43E+00	1,24E+00	1,24E+00	4,51E-01	3,44E+00	6,02E-04	-3,13E+01
TETP	2,63E+01	2,90E-02	1,13E-01	1,13E-01	9,06E-03	7,99E-02	1,25E-05	-1,81E+01
Total [€]	**2,01E+03**	**3,91E+01**	**8,54E+01**	**8,54E+01**	**1,26E+01**	**8,48E+01**	**2,37E-02**	**-1,37E+03**

Table 21: Shadow costs per life cycle module of the optimised design with 90% reused steel elements – EPD2.

Impact cat./ Life cycle module	A1-A3	A4	A5	C1	C2	C3	C4	D
ADPE	3,80E-02	1,33E-03	3,33E-04	3,33E-04	4,88E-05	1,18E-03	1,32E-07	-8,55E-03
ADPF	3,18E+00	3,82E-01	8,61E-01	8,61E-01	1,27E-01	4,44E-01	1,58E-03	-3,08E-01
GWP	1,60E+02	1,62E+01	3,85E+01	3,85E+01	5,36E+00	2,12E+01	3,63E-02	-1,38E+01
ODP	6,74E-03	1,72E-03	2,85E-03	2,85E-03	5,91E-04	1,51E-03	7,22E-06	-7,03E-04
POCP	7,27E+00	3,91E-01	1,06E+00	1,06E+00	1,27E-01	6,65E-01	1,54E-03	-8,46E-01
AP	4,32E+01	5,70E+00	1,62E+01	1,62E+01	1,86E+00	1,47E+01	2,14E-02	-4,74E+00
EP	1,73E+01	2,51E+00	8,14E+00	8,14E+00	8,34E-01	7,08E+00	9,07E-03	-2,12E+00
HTP	1,04E+02	1,23E+01	1,92E+01	1,92E+01	3,87E+00	3,65E+01	2,66E-02	-1,28E+01
FAETP	8,87E-01	1,20E-01	1,02E-01	1,02E-01	3,77E-02	1,70E-01	2,20E-04	-6,78E-02
MAETP	7,87E+00	1,43E+00	1,24E+00	1,24E+00	4,54E-01	3,41E+00	2,52E-03	-7,51E-01
TETP	2,92E+00	2,90E-02	1,13E-01	1,13E-01	9,12E-03	7,94E-02	5,25E-05	-2,50E-01
Total [€]	**3,47E+02**	**3,91E+01**	**8,54E+01**	**8,54E+01**	**1,27E+01**	**8,42E+01**	**9,93E-02**	**-3,57E+01**

Appendix C Life Cycle Cost Analysis

Table 22: Life cycle costs for the different processes considered in EPD1 for the original design. Unit is in €.

	Min	Average	Max	Min	Average	Max
Cost/Year	**0**	**0**	**0**	**50**	**50**	**50**
Product stage (A1-A3)	**31035**	**36031**	**41026**	**0**	**0**	**0**
Raw material	18057	20314	22572	0	0	0
Transport	490	523	556	0	0	0
Fabrication	7235	8682	10129	0	0	0
Coating (Fire protection)	4007	5009	6010	0	0	0
Testing	0	0	0	0	0	0
Reconditioning	0	0	0	0	0	0
Engineering	1247	1503	1759	0	0	0
Construction Stage (A4-A5)	**3161**	**3718**	**4274**	**0**	**0**	**0**
Transport	490	523	556	0	0	0
Construction	2671	3194	3718	0	0	0
Demolition stage (C1-C2)	**0**	**0**	**0**	**3149**	**3682**	**4215**
Demolition audit	0	0	0	812	964	1116
Deconstruction audit	0	0	0	309	367	425
Demolition	0	0	0	1231	1462	1693
Deconstruction	0	0	0	317	376	436
Transport-Recycling	0	0	0	305	326	347
Transport - Reuse	0	0	0	174	186	198
Potential Savings (D)	**0**	**0**	**0**	**-4211**	**-4211**	**-4211**
Recycling	0	0	0	-2356	-2356	-2356
Reuse	0	0	0	-1854	-1854	-1854

Table 23: Life cycle costs for the different processes considered in EPD1 for the optimised design. Unit is in €.

	Min	Average	Max	Min	Average	Max
Cost/Year	**0**	**0**	**0**	**50**	**50**	**50**
Product stage (A1-A3)	**26233**	**30455**	**34677**	**0**	**0**	**0**
Raw material	15263	17171	19079	0	0	0
Transport	414	442	470	0	0	0
Fabrication	6115	7338	8561	0	0	0
Coating (Fire protection)	3387	4234	5080	0	0	0
Testing	0	0	0	0	0	0
Reconditioning	0	0	0	0	0	0
Engineering	1054	1270	1486	0	0	0
Construction Stage (A4-A5)	**2672**	**3142**	**3613**	**0**	**0**	**0**
Transport	414	442	470	0	0	0
Construction	2258	2700	3142	0	0	0
Demolition stage (C1-C2)	**0**	**0**	**0**	**2662**	**3112**	**3563**
Demolition audit	0	0	0	686	815	944

Deconstruction audit	0	0	0	261	310	359
Demolition	0	0	0	1041	1236	1431
Deconstruction	0	0	0	268	318	368
Transport - Recycling	0	0	0	258	275	293
Transport - Reuse	0	0	0	147	157	167
Potential Savings (D)	**0**	**0**	**0**	**-3559**	**-3559**	**-3559**
Recycling	0	0	0	-1992	-1992	-1992
Reuse	0	0	0	-1567	-1567	-1567

Table 24: Life cycle costs for the different processes considered in EPD2 for the optimised design. Unit is in €.

	Min	**Average**	**Max**	**Min**	**Average**	**Max**
Cost/Year	**0**	**0**	**0**	**50**	**50**	**50**
Product stage (A1-A3)	**13339**	**15114**	**16888**	**0**	**0**	**0**
Raw material	6959	7596	8233	0	0	0
Transport	1159	1238	1317	0	0	0
Fabrication	612	734	856	0	0	0
Coating (Fire protection)	339	423	508	0	0	0
Testing	2455	2709	2964	0	0	0
Reconditioning	762	1143	1524	0	0	0
Engineering	1054	1270	1486	0	0	0
Construction Stage (A4-A5)	**3417**	**3938**	**4459**	**0**	**0**	**0**
Transport	1159	1238	1317	0	0	0
Construction	2258	2700	3142	0	0	0
Demolition stage (C1-C2)	**0**	**0**	**0**	**2662**	**3112**	**3563**
Demolition audit	0	0	0	686	815	944
Deconstruction audit	0	0	0	261	310	359
Demolition	0	0	0	1041	1236	1431
Deconstruction	0	0	0	268	318	368
Transport - Recycling	0	0	0	258	275	293
Transport - Reuse	0	0	0	147	157	167
Potential Savings (D)	**0**	**0**	**0**	**-3559**	**-3559**	**-3559**
Recycling	0	0	0	-1992	-1992	-1992
Reuse	0	0	0	-1567	-1567	-1567

Table 25: Life cycle costs for the different processes considered in EPD3 for the optimised design. Unit is in €.

	Min	**Average**	**Max**	**Min**	**Average**	**Max**
Cost/Year	**0**	**0**	**0**	**50**	**50**	**50**
Product stage (A1-A3)	**26233**	**30455**	**34677**	**0**	**0**	**0**
Raw material	15263	17171	19079	0	0	0
Transport	414	442	470	0	0	0
Fabrication	6115	7338	8561	0	0	0
Coating (Fire protection)	3387	4234	5080	0	0	0
Testing	0	0	0	0	0	0
Reconditioning	0	0	0	0	0	0

Engineering	1054	1270	1486	0	0	0
Construction Stage (A4-A5)	**2672**	**3142**	**3613**	**0**	**0**	**0**
Transport	414	442	470	0	0	0
Construction	2258	2700	3142	0	0	0
Demolition stage (C1-C2)	**0**	**0**	**0**	**3856**	**4484**	**5111**
Demolition audit	0	0	0	163	194	225
Deconstruction audit	0	0	0	1307	1552	1797
Demolition	0	0	0	248	294	341
Deconstruction	0	0	0	1339	1591	1842
Transport - Recycling	0	0	0	61	66	70
Transport - Reuse	0	0	0	737	787	837
Potential Savings (D)	**0**	**0**	**0**	**-8311**	**-8311**	**-8311**
Recycling	0	0	0	-474	-474	-474
Reuse	0	0	0	-7837	-7837	-7837

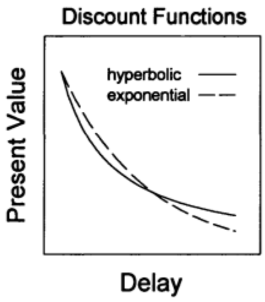

Figure 68: Difference between the exponential and hyperbolic discounting. (Source: Green & Myerson, 1996)

Table 26: Sensitivity of the LCC value to the change of the discount rate for the original design with new steel elements.

Nominal Discount rate [%]	LCC (A-C) MIN	LCC (A-C) AVG	LCC (A-C) MAX	LCC Change
0%	74481	86854	99226	12372
1%	58140	67745	77350	9605
2%	48503	56477	64451	7974
3%	42790	49797	56804	7007
4%	39385	45815	52246	6430
5%	37345	43430	49515	6085
6%	36117	41993	47870	5877
7%	35373	41124	46875	5751
8%	34921	40595	46270	5674
9%	34645	40272	45900	5627
10%	34475	40074	45673	5599

Table 27: Sensitivity of the LCC value to the change of the discount rate for the optimised design with new steel elements.

Nominal Discount rate [%]	LCC (A-C) MIN	LCC (A-C) AVG	LCC (A-C) MAX	LCC Change
0%	62956	73414	83872	10458

1%	49143	57262	65381	8119
2%	40998	47738	54478	6740
3%	36169	42091	48014	5922
4%	33291	38726	44161	5435
5%	31566	36710	41853	5143
6%	30528	35495	40463	4967
7%	29900	34761	39621	4861
8%	29517	34314	39110	4796
9%	29284	34040	38797	4757
10%	29140	33873	38605	4732

Table 28: Sensitivity of the LCC value to the change of the discount rate for the optimised design with reused steel elements.

Nominal Discount rate [%]	LCC (A-C) MIN	LCC (A-C) AVG	LCC (A-C) MAX	LCC Change
0%	50807	58868	66929	8061
1%	36994	42717	48439	5722
2%	28849	33192	37536	4343
3%	24020	27546	31072	3526
4%	21142	24180	27219	3038
5%	19418	22164	24910	2746
6%	18379	20950	23520	2571
7%	17751	20215	22679	2464
8%	17369	19768	22167	2399
9%	17135	19495	21855	2360
10%	16992	19327	21663	2336

Table 29: Sensitivity of the LCC value to the change of the discount rate for the optimised design with 80% reused steel elements at the end-of-life stage.

Nominal Discount rate [%]	LCC (A-C) MIN	LCC (A-C) AVG	LCC (A-C) MAX	LCC Change
0%	78237	90960	103683	12723
1%	58225	67691	77156	9465
2%	46425	53969	61514	7545
3%	39429	45835	52240	6406
4%	35259	40986	46713	5727
5%	32761	38081	43401	5320
6%	31256	36332	41407	5075
7%	30346	35273	40200	4927
8%	29792	34629	39466	4837
9%	29454	34236	39018	4782
10%	29246	33994	38742	4748