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REDUCING THE CARBON FOOTPRINT OF CONSTRUCTION STEEL - LIFECYCLE ASSESSMENT OF AN ESTONIAN CASE STUDY

EHITUSTERASE SÜSINIKU JALAJÄLJE VÄHENDAMINE: SÜSINIKUHEITMETE ELUTSÜKLI ANALÜÜS EESTIS- JUHTUMIUURING

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2. To calculate the carbon footprint of construction steel based on a real Estonian construction project
3. To compare the results and conclusions with other similar studies
4. To explore possibilities for reducing the carbon footprint

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FOREWORD

The specific thesis subject and research question were worked out in conjunction with the thesis advisor based on the available material gathered by the author.

The thesis consists of a theoretical section and a practical calculations section. The theoretical section focuses on previous research in the given subject and the specifics of the construction steel industry. The practical section focuses on calculating the construction steel CO_2 emissions from a real project in Estonia, encompassing mining, logistics, production and assembly.

The author wishes to thank their thesis advisor, Emlyn David Qivitoq Witt for the efficient cooperation and mentorship, Exmet Servies OÜ, Weldex OÜ, Fortla OÜ and Cramo Estonia OÜ for providing all of the necessary data.

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ABSTRACT

The construction industry is one of the leading contributors to climate change, responsible for almost 40% of global carbon emissions. As Europe intensifies its focus on emission regulations, understanding the carbon impact of each phase of construction is essential. This thesis investigates the carbon emissions associated with production, coating, transportation, and assembly of structural steel within an Estonian construction context, analysing data from a real project completed in Estonia. The study identifies the production and initial refining stages as the most emissions-intensive, with the potential for substantial reductions through optimisation at each life cycle phase, particularly by shifting to a more sustainable steel refinement technology known as Electric Arc Furnace (EAF) steel production and optimising logistics. Comparative analysis with other load bearing materials such as concrete and cross-laminated timber (CLT) provides further insight into the viability and sustainability of steel in modern construction, emphasising the necessity of a regionally tailored approach to decarbonising construction in Estonia.

1. THEORETICAL BACKGROUND

1.1 CO2 emissions Background

The RIBA plan of work suggests that the first stage of each construction project is "preparation and briefing" if it is previously that a new building is in fact required. (RIBA 2020) In the next phases of "Concept design", "spatial coordination" and "Technical design", structural engineers alongside architects and clients make decisions on various topics from the overall design of the building to niche connections between different materials. The main objective is to find the best solution for the client, whether it be construction time, best value for money or overall cost. And an aspect that is being focused on more and more are CO_2 emissions. [1], [2]

1.1.1 Construction emissions

28% of global CO_2 emissions come from operating buildings, with an additional 11% from the design and construction phase. In total 39% of global emissions are caused by buildings and construction. Construction emissions increased by 2% between 2017 and 2018. With the totals expected to increase each year, there is an ever-growing need to find the best possible construction solutions in regard to the environment. [3]

In 2020, global CO2 emissions associated with buildings and construction accounted for 36% of global energy demand and 37% of global energy related CO_2 emissions.[4]

The demand for electricity is one of the largest contributors to global CO_2 emissions, a trend that continues to escalate as industrialisation and urbanisation increase. According to the International Energy Agency, electricity and heat production accounted for a significant portion of global CO_2 emissions in recent years, largely driven by the reliance on fossil fuels like coal and natural gas. In 2021, heat generation contributed 46% to the growth in CO_2 emissions globally, with coal being the largest single source of electricity generation, which is also the most carbon-intensive fuel. In 2021, Coal accounted for approximately 40% of the global CO_2 emissions. [5]

This reliance on fossil fuel-driven electricity also directly impacts the construction industry, which is a major consumer of energy and a significant source of greenhouse gas emissions. The construction industry is one of the largest consumers of energy globally, with significant energy demand for the production and transport of construction materials, site operations, and the maintenance of built infrastructure. This reliance on fossil fuel-driven electricity intensifies the industry's greenhouse gas (GHG) emissions, as much of the energy required for activities such as concrete and steel production comes from high-carbon sources like coal and natural gas. In turn, these emissions contribute heavily to climate change, making the construction sector a focal point for emission reduction efforts. Efforts to reduce this footprint include transitioning to renewable energy sources, improving energy efficiency in buildings, and incorporating low-carbon materials.[4]

The construction industry's contribution to CO_2 emissions is not solely a result of operational energy consumption in buildings but also from the energy required to produce construction materials, particularly those used in load-bearing structures. The production of traditional materials such as reinforced concrete and steel is highly energy-intensive and thus leads to significant CO_2 emissions.[6]

1.1.2 Emissions relating to specific materials

Reinforced concrete, a commonly used material for load-bearing structures in construction, has been shown to contribute significantly to greenhouse gas emissions. The process of producing cement, the key ingredient in concrete, is responsible for about 8% of global CO_2 emissions. This is because cement production requires extremely high temperatures, typically achieved through the combustion of coal or other fossil fuels, to transform limestone into clinker. The steel reinforcement used in concrete structures further compounds the emissions impact due to the energy-intensive nature of steel production.[6]

Cross-Laminated Timber (CLT) has emerged as an environmentally sustainable alternative to load-bearing construction steel frames, contributing significantly to lowering greenhouse gas emissions. A single-case study by Chen et al. (2020), conducted at the U.S. Forest Products Laboratory, offers a detailed life cycle assessment (LCA) comparing CLT and traditional steel frames in high-rise construction. The study demonstrated that CLT not only reduces embodied carbon emissions but also functions as a carbon sink, sequestering atmospheric $CO2$ during the tree growth phase, which offsets some of the carbon emissions associated with construction. In contrast, load-bearing steel frames contribute heavily to emissions due to the energy-intensive processes involved in steel production, which primarily relies on fossil fuels. The study found that replacing steel frames with CLT in a high-rise building design reduced the building's global warming potential (GWP) by approximately 14%.[7]

Moreover, the study emphasised the role of transportation and material sourcing in determining the environmental impact of CLT. By using locally sourced timber and lighter wood species, the project minimised transportation emissions and further enhanced the sustainability profile of CLT over steel. These findings underscore the significant potential for CLT to help decarbonise the construction industry, especially in regions where sustainable forestry practices can support the widespread adoption of wood-based materials.[7]

1.1.3 Situation in Europe

In Europe, the construction industry's focus on reducing CO_2 emissions has prompted in-depth analyses of construction materials like steel, which contributes significantly to the carbon footprint of buildings. A notable study that exemplifies this is the *Method for calculating the carbon footprint of a building* case study conducted by the European Commission, which assessed the lifecycle CO_2 emissions associated with structural steel in a high-rise office building in Sweden. One of the major insights from this study was the geographical variance in steel's carbon footprint across Europe. Countries with more renewable energy sources, like Sweden and Norway, exhibited lower emissions for steel produced through the Electric Arc Furnace (EAF) route, as their electricity grids are largely powered by hydropower.[8] However, in countries still dependent on fossil fuels for electricity, like Poland and Germany, EAF production exhibited higher emissions, albeit still lower than the Basic Oxygen Furnace and Blast Furnace (BF-BOF) method.[2]

In Sweden, initiatives like H2 Green Steel [9] have led to plans for steel production using green hydrogen, which is generated from electrolysis powered by hydropower. This shift significantly reduces emissions compared to traditional fossil fuel methods, with green hydrogen emitting only water vapor instead of CO_2 during steel production.[10] Similarly, Norway’s Statkraft, a major hydropower provider, plays a critical role in supplying renewable electricity for these low emission processes. Statkraft has entered into an agreement to supply 2 TWh per year of renewable electricity to H2 Green Steel's operations in Sweden, from 2026 to 2032. The electricity, sourced from Statkraft's hydropower plants in Northern Sweden, will power an 800 MW electrolyser producing green hydrogen for steel production, significantly reducing emissions compared to other methods.[11] Estonia's electricity grid is primarily powered by fossil fuels, notably oil shale, which is a carbon-intensive energy source. As highlighted in research done by Energy review of IEA countries, in 2023, over 60% of electricity production came from oil shale, listed as coal in the research. In total, Estonia emitted 9.918 Mt of CO_2 in 2023, ranked as 32nd In Europe in terms of emissions. [12]

Higher emissions from overall energy generation also result in higher emissions for steel element production, even when using environmentally friendly machinery. Consequently, Estonia’s carbon intensity for producing steel elements remains higher compared to countries with greener energy grids, making decarbonisation efforts more difficult in the short term. To mitigate these challenges, Estonia has been exploring renewable energy options, including wind and solar power, which could lower emissions from steel production over time. A report conducted by the Stockholm Environment Institute researched the Estonian energy sector and concluded that major policy changes are required to achieve low-carbon electricity production in Estonia. Yet comprehensive calculations for the impact of construction steel in Estonia are absent, and a full understanding of steel emissions is required in order to continue using it as viable alternative. [13]

1.1.4 The importance of construction steel

One of the key advantages of structural steel is its versatility. It can be fabricated into a wide variety of shapes and sizes, which can be customised for different structural needs. This adaptability arises from steel’s malleability and ductility, which allow it to be formed into beams, columns, plates, rods, and even intricate shapes like angles and channels. I-beams and H-beams are commonly used in the framing of large structures due to their high load-bearing capacity, making them ideal for skyscrapers and bridges. Tubes and pipes, on the other hand, offer excellent strength-to-weight ratios and are commonly used in transportation infrastructure and architectural frameworks. Furthermore, steel can undergo processes like welding, riveting, and bolting, making it easy to assemble on-site, even in complex structures. This ability to fabricate steel into different forms and combine it with other materials has made it an indispensable component in construction, offering both flexibility in design and reliability in performance. Whether it's used in structural frames, reinforcing bars in concrete, or even aesthetic elements in modern architecture, steel’s capacity to be shaped into a vast array of forms underpins its role as the backbone of modern infrastructure. [14] [15]

Structural steel plays a pivotal role in modern construction, enabling architects and engineers to create groundbreaking architectural designs that combine both form and function. Its exceptional strength, combined with inherent flexibility, allows for innovative structural designs that not only push the limits of aesthetics but also ensure long-lasting durability. Steel’s versatility is showcased in the construction of a wide variety of structures, from towering skyscrapers to expansive bridges. In skyscrapers, the high strength-to-weight ratio of steel allows for the development of tall, slender buildings that maximise space while ensuring stability and safety under substantial loads. Similarly, in bridge construction, steel is invaluable for its ability to support heavy loads while resisting dynamic forces such as traffic, wind, and seismic activity. The material's ability to span long distances without excessive material use is critical in large-scale infrastructure projects.[16]

1.2 Research question and objectives

This research aims to calculate the CO_2 emissions generated by an already existing steel-framed building in Estonia by analysing the data from the steel element production phase, assembly phase and logistics. The assessment complies with current regulations and standards, specifically standards *EVS-EN 15804:2012+A2:2019* and *EVS-EN 15978:2011*, which lay the framework for CO_2 calculations and life-cycle analysis. The results are analysed and compared to relevant research from other EU member states. Another crucial objective is for this thesis to provide base information for calculating CO_2 emissions of future construction projects in Estonia, which is required for the upcoming regulations introduced by the EU.[17]

1.3 Introduction to Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a methodology used to quantify the environmental impacts of products and processes throughout their entire life cycle, from raw material extraction to final disposal. Within the construction industry, the *EVS-EN 15804:2012+A2:2019* [18] standard provides a framework for assessing and reporting these impacts, particularly in the context of building materials such as construction steel. The standard divides the assessment into modular stages—product stage (A1-A3), construction process stage (A4-A5), use stage (B1-B7), and end-of-life stage (C1-C4), ensuring that all relevant environmental impacts are accounted for consistently across materials and products. This standardised approach is essential for generating Environmental Product Declarations (EPDs) and understanding the emissions of certain materials - particularly construction steel, as explored in the context of this thesis.

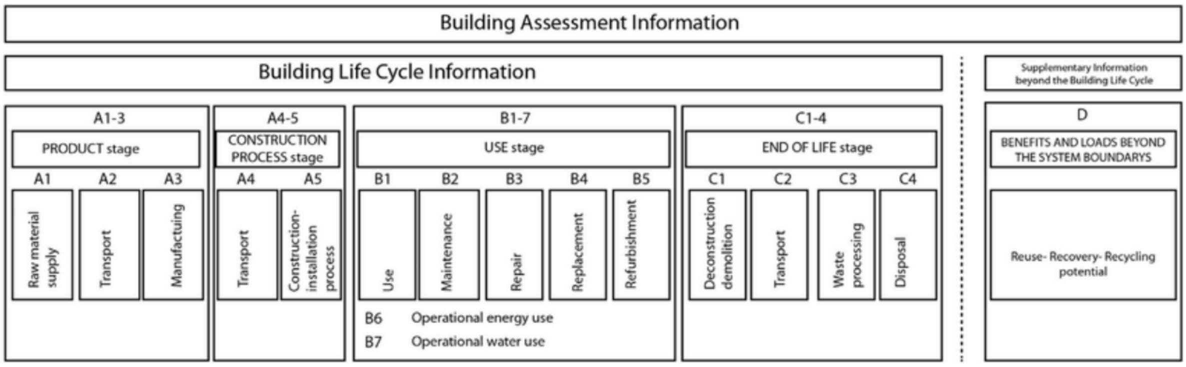

Figure 1.1 LCA phases according to *EVS-EN 15804:2012+A2:2019* [18]

Construction steel elements, widely used in modern construction, are particularly significant in LCA due to its high carbon footprint, especially when produced through energy-intensive processes such as the Blast Furnace-Basic Oxygen Furnace (BF-BOF) route. Research from Estonia Method for calculating the carbon footprint of a building[8], aligns with *EVS-EN 15804:2012+A2:2019*, thereby offering a framework for calculating the carbon footprint of construction materials, including that of massive steel elements. The method emphasises the importance of accurately assessing steel's Global Warming Potential (GWP) by incorporating emissions from all life cycle stages, including production, assembly, transportation, and end-of-life recycling, which is essential for reducing the overall environmental impact of buildings.[18]

By incorporating LCA principles and the *EVS-EN 15804:2012+A2:2019* standard into national methodologies like the *Method for calculating the carbon footprint of a building* [8], Estonia is taking significant steps toward improving the environmental sustainability of its construction industry. This approach not only facilitates compliance with EU-wide sustainability goals but also promotes the use of greener technologies in steel production and recycling initiatives, which can dramatically reduce emissions while maintaining the structural integrity of modern construction projects and methods.[19]

1.4 Why this research is important for Estonia

The construction industry is one of the largest contributors to global greenhouse gas (GHG) emissions, responsible for approximately 40% of global energy consumption and nearly one-third of all CO_2 emissions.[20] Within this sector, construction steel plays a critical role as a foundational material in buildings, infrastructure, and industrial projects. As the world increasingly moves towards sustainable development and decarbonisation, understanding and mitigating the carbon footprint of construction steel is of paramount importance. In Estonia, where the construction industry is a key driver of economic growth, the broad construction sector contributed significantly to the economy, accounting for 17.7% of the country's gross value added (GVA) in 2018 and accounted for a substantial portion of employment, with 90,122 persons employed in 2020, representing a 26.4% increase compared to 2010.[19] Research into the carbon footprint of construction steel can significantly inform national strategies aimed at reducing the environmental impacts of building activities. This research is essential in advancing Estonia's efforts to meet climate neutrality goals by 2050, while maintaining competitiveness in a region that is progressively adopting stricter environmental regulations.

Estonia, like many European Union (EU) member states, is committed to achieving climate neutrality by 2050, in line with the EU Green Deal and its binding targets under the Paris Agreement. Estonia's national climate policy, as outlined in the "Eesti 2035" strategy and the National Energy and Climate Plan [21], emphasises the need for substantial reductions in GHG emissions across all sectors, with a special focus on construction. The Estonian government has also introduced various sustainability frameworks and regulations, such as mandatory energy performance certifications for buildings and an increasing focus on Life Cycle Assessments (LCA) as part of building permit applications. [8] Research on the carbon footprint of construction steel is highly relevant in this context, as it provides the necessary data to inform policy development, compliance with EU regulations, and the adoption of best practices in the industry.

Understanding the carbon footprint of steel in the Estonian context allows for targeted interventions in three key areas:

1. Material Selection and Sustainable Sourcing: Research into the carbon footprint of steel provides valuable insights into sourcing materials from low-carbon producers or using recycled construction steel. Estonia imports a significant amount of its construction materials, including steel, from other EU countries and beyond. Mapping the carbon footprint of these imports and comparing various suppliers can inform decision-making at the project level, encouraging the selection of lower-carbon steel options.

2. Lifecycle Assessments (LCA) and Policy Compliance: Estonia is increasingly aligning its building regulations with international LCA standards, such as *EVS-EN 15804:2012+A2:2019*, which provide guidelines for calculating the environmental performance of construction products across their life cycle.

3. Innovations in Low-Carbon Construction: Research findings can stimulate innovations in the use of construction steel. For example, new methods for reducing emissions during steel element production, such as using green energy and focusing on newer technologies that are able to produce with lower emissions. [8]

2. LITERATURE REVIEW

2.1 Previous research in steel life cycle analysis

Steel is a widely used material in construction due to its strength, durability, and recyclability. Life Cycle Assessment (LCA) is a critical tool for quantifying the environmental impacts of materials such as steel, from extraction and production to usage, maintenance, and end-of-life. LCA helps stakeholders in the construction industry to make informed decisions about the environmental footprint of steel structures. The life cycle of steel includes several stages, each contributing to its overall environmental impact. These stages include raw material extraction, steel production (e.g., electric arc furnace or basic oxygen furnace processes), transportation, construction, usage, and demolition or recycling. Proper LCA of steel must account for each of these stages to give a comprehensive environmental profile. This approach ensures that the benefits of steel's high recyclability are appropriately considered, offsetting the high energy use during its production phase Estonia's alignment with EU sustainability regulations further emphasises the need for rigorous LCA assessments, especially as the country imports much of its construction steel.[22][23]

The life cycle of steel begins with raw material extraction, which primarily involves mining iron ore and producing coal for blast furnace operations. This stage has a high environmental impact due to the energy-intensive nature of mining and the associated emissions of CO_2. These pollutants significantly contribute to global warming potential, acidification, and resource depletion. Furthermore, substantial land and water use is involved in extracting raw materials for steel production, making this stage critical for LCA assessments. [24]

Estonia typically imports steel from a range of European and nearby countries. Key suppliers include Finland, Sweden, Poland, Italy and Germany, as these countries have strong steel production sectors and well-established trade relations with Estonia.[25] Estonia also sources steel from other European Union countries due to the ease of trade within the EU, as well as some imports from Russia and Ukraine, which have historically been significant steel producers. However, recent geopolitical tensions have impacted trade from these regions. [26] As Estonia imports steel from various countries, optimising the logistics of steel transportation could substantially reduce its carbon footprint. Exploring regional suppliers or switching to more energy-efficient modes of transport like rail could help Estonia minimise these emissions. The long distances steel often travels, particularly via sea and road transport, add to the embodied carbon of the material. Rail transport emits approximately 26.5grams of CO_2 equivalent per tonne-kilometre [27], sea transport emits about 3-10 grams of CO_2 per tonne-kilometre, while road transport can generate up to 120 grams per tonne-kilometre.[23]

2.2 Previous research in steel production

The steel production is a significant contributor to global CO_2 emissions, with steelmaking responsible for approximately 2.5Gt of worldwide anthropogenic CO_2 emissions in 2019. This is largely attributed to the energy-intensive processes involved in the extraction and conversion of raw materials, particularly iron ore. Among the various steel production methods, the Blast Furnace-Basic Oxygen Furnace (BF-BOF) route is the dominant approach, accounting for around 70% of global steel production. This method, though highly efficient in terms of steel yield, is also notably emission-intensive, with CO_2 emissions ranging from 1.8 to 2.2 tonnes of CO_2 per tonne of crude steel produced.[28]

Similarly, research conducted by the University of Bath, found that Steel is one of the most emission-intensive materials used in construction, primarily due to the high energy demands of its production process. [29]

2.2.1 Blast furnace (BF) and Basic Oxygen Furnace (BOF)

In the BF-BOF route, iron ore is reduced to iron using carbon, typically in the form of coke. The coke, derived from coal, serves a dual purpose: it acts as both a fuel source to generate high temperatures and as a chemical reducing agent. The International Energy Agency emphasises that the BF-BOF process's carbon footprint is intrinsically linked to the combustion of fossil fuels, making it one of the most significant contributors to industrial CO_2 emissions [28].

To address the high CO_2 emissions from the BF-BOF process, research has focused on technological innovations that could significantly reduce or even eliminate emissions. One such approach is the Hydrogen Direct Reduction (H-DR) process, which replaces carbon as the reducing agent in steelmaking with hydrogen. A study from Lund University highlights the promise of this technology, noting that H-DR could reduce CO_2 emissions by up to 95% compared to conventional BF-BOF processes, provided that the hydrogen used is generated from renewable energy sources. In this process, hydrogen reacts with iron ore to produce iron and water vapor, eliminating the CO_2 emissions associated with carbon-based reduction.[30]

The main obstacle to the widespread adoption of H-DR is the cost and availability of green hydrogen. Currently, hydrogen production is primarily based on natural gas (via steam methane reforming), which still produces CO_2 emissions. For H-DR to be a viable low-emission technology, significant advancements in the production of green hydrogen through electrolysis using renewable energy sources are required. Furthermore, the transition to H-DR would necessitate substantial investments in new infrastructure and retrofitting existing steel plants, which could take decades to implement on a global scale. [30]

An alternative approach is Carbon Capture and Storage (CCS), which aims to capture up to 90% of the CO_2 produced during steelmaking and store it underground. Jean-Pierre Birat discusses in his research the potential of CCS in mitigating the environmental impact of steel production, noting that its successful implementation could dramatically lower emissions in steel plants. However, CCS faces significant challenges, including high implementation costs and the need for a supportive infrastructure network for carbon transportation and storage. [31]

2.2.2 Electric Arc Furnace (EAF)

Electric Arc Furnace (EAF) technology has revolutionized steel production by offering a more flexible and environmentally friendly alternative to the Blast Furnace method. Unlike blast furnaces which rely on a combination of iron ore and coke, EAFs primarily use scrap steel as their feedstock, significantly reducing the need for raw materials and the associated environmental impact. This process involves melting scrap steel using high-power electric arcs, allowing for rapid heating and efficient recycling of steel materials. EAFs contribute to sustainability efforts by facilitating the recycling of steel, conserving natural resources and reducing energy consumption. The ability to produce steel from 100% scrap material underscores the role of EAFs in promoting a circular economy within the steel industry. [32]

In contrast to the BF-BOF route, the Electric Arc Furnace (EAF) method presents a more sustainable option, particularly in terms of CO_2 emissions. The EAF process primarily uses scrap steel as its main feedstock, which drastically reduces the need for energy-intensive iron ore reduction. The CO_2 emissions associated with EAF production are considerably lower, ranging between 0.4 and 0.8 tonnes of CO_2 per tonne of steel, depending on the energy mix used to power the furnaces (World Steel Association, 2020). If the electricity used in the EAF process is generated from renewable sources, these emissions can be further reduced, making EAF a more environmentally friendly option. However, the use of the EAF route is constrained by the availability of scrap steel. While EAF currently accounts for around 30% of global steel production, its scalability is limited by the supply of recyclable steel. Moreover, the environmental benefits of EAF are highly dependent on the carbon intensity of the electricity grid. In regions where coal or other fossil fuels dominate the electricity generation mix, the CO_2 savings of EAF can be diminished. [33]

2.2.3 BOF and EAF comparison

The company ArcelorMittal is a European steel manufacturer that uses the BOF method. According to their EPD, the global warming potential for producing one metric ton of steel generates 818 kg of CO_2. This figure captures emissions from the extraction and processing of raw materials, the transportation of these inputs to manufacturing sites, and the steelmaking procedure. [34]

The same company also manufactures steel using the EAF method, for which they have conducted another EPD that tells an entirely different story. This EPD, following the standards of *EVS-EN 15804:2012+A2:2019*, covers the lifecycle phases A1-A3. According to the document, the Global Warming Potential (GWP) across these phases totals 370 kg CO_2 equivalent per metric ton, or 0.37 kg of CO_2 per kg produced. The EPD also confirms that the plant uses 100% renewable energy. [35]

The CO_2 emission difference between the two EPD-s is 0.448 kg, making the BOF method more that than twice as harmful to the environment when compared to the EAF method. The BOF method relies on iron ore and coal, making it energy-intensive and carbon-heavy. While EAF uses recycled scrap steel and 100% renewable energy, highlighting a more sustainable approach. As more focus is going towards making manufacturing processes more environmentally friendly, the ArcelorMittal's EAF EPD showcases how the steel industry can adapt to sustainability trends by combining the use of recycled materials, efficient production technologies, and renewable energy sources. This approach aligns with global efforts to mitigate climate change by reducing CO_2 emissions in the construction sector. [34][35]

2.3 Previous research in steel logistics

As steel is a highly versatile and commonly used material in modern construction, its lifecycle emissions—especially during the transportation phase—are significant contributors to the environmental impact of building projects. From raw material extraction to delivery at construction sites, various stages of steel transportation produce CO_2 primarily due to the fuel consumption of the vehicles involved. Emissions are typically calculated based on the fuel used, the mode of transportation, and the distance travelled.[36]

As outlined in the *Method for calculating the carbon footprint of a building*, transportation emissions are calculated using a "well-to-wheel" approach, which includes the extraction, production, and consumption of fuel during transportation. The heaviest contributors to transportation emissions are heavy building materials like concrete and steel, which tend to reach full vehicle load capacities, maximising the transportation-related emissions per distance travelled. The emissions are further influenced by whether the materials are locally sourced or imported, with longer distances resulting in significantly higher emissions. [8]

The steel industry's emissions are often attributed to stages A1-A3 of the LCA, according to the *EVS-EN 15804:2012+A2:2019* standard which includes raw material extraction, processing, and manufacturing. These stages are heavily reliant on fossil fuels, especially in blast furnace processes used for producing primary steel from iron ore. According to global studies, producing one ton of steel can emit approximately 1.8 tons of CO_2, largely depending on the method of production (basic oxygen furnace vs. electric arc furnace).[8], [18]

For example, transporting 1 tonne of steel over 500 kilometres by a 40-tonne semi-trailer would result in approximately 0.05 tonnes of CO_2 emissions. In this case the calculation is as follows:

$$CO_2(kg) = load\ in\ tonnes * distance\ in\ km * emission\ factor(0.1kg\ CO_2/tonne - km) \quad (2.1)$$

$$CO_2(kg) = 1\ tonne * 500\ km * 0.1kg\ CO_2/tonne - km = 50kg\ CO_2 = 0.05\ tonnes\ CO_2$$

When applying the same calculation method for ship transport, the conclusion is 0.0075 tonnes of CO_2 and 0.015 tonnes of CO_2 for trains per tonne of material transported.

When comparing the emissions from steel production to the emissions from transportation and logistics, it becomes clear that while transportation is an important contributor, the majority of the carbon emissions related to steel stem from the production phase. In many cases, the transportation of steel accounts for only a fraction of the overall emissions of the material.[23]

2.4 Previous research in steel assembly

Although a great deal of attention has been given to CO_2 emissions during steel production, the assembly phase itself also significantly contributes to a project's carbon footprint. Recent studies have begun to delve deeper into this issue, showing that the use of diesel-powered machinery, transportation of prefabricated steel components, and on-site assembly methods such as welding and bolting are key sources of emissions.[37]

Assembly emissions are generated through a combination of transportation of materials to the construction site, the operation of heavy machinery, and the energy consumed during the erection and installation of steel structures. These emissions, though often overshadowed by those from steel production, are significant, particularly in large-scale construction projects where the volume of steel is substantial, and construction logistics are complex. Heavy machinery such as cranes and transport trucks, which are essential for lifting and positioning steel beams, are often powered by fossil fuels. This creates substantial CO_2 emissions, especially on projects that require long operation times and significant amounts of steel. Research conducted by Mid Sweden University found that construction equipment could account for 20% of a building's total CO_2 emissions, especially when diesel-powered machinery is used continuously over long periods. Although the study focused on wood as a primary material, many of its insights can be applied to other materials like structural steel, especially regarding the use of fossil fuels and CO_2 emissions during the construction phase. [37]

The research showed that on-site construction and transportation contribute significantly to the overall CO_2 emissions. Construction machinery such as cranes, transport trucks, and other heavy equipment are often powered by diesel or other fossil fuels. These machines account for a large proportion of energy consumption during the assembly phase, particularly when used continuously for long periods. The study estimated that construction machinery alone could contribute up to 20% of the building's total CO_2 emissions. [37]

The techniques used during the assembly process are a major determinant of the level of CO_2 emissions produced. Welded steel connections, which are commonly used in large-scale construction projects, typically generate more emissions than bolted connections due to the electricity required for welding. Research conducted on a dormitory building at the Tongzhou Campus calculated carbon emissions for various project phases. During assembly, flange joints emitted 55.52 kg of CO_2 per ton, while welded joints emitted 120.02 kg of CO_2 per ton—116.2% more due to additional welding materials and energy use.[38]

2.5 Advancements in the sector

The production of construction steel has seen remarkable advancements over the past few decades, particularly in terms of reducing CO_2 emissions. These improvements are largely attributable to innovations in machinery, production methods, and logistical practices. Traditionally, steel production relied heavily on blast furnaces, which are energy-intensive and emit substantial amounts of CO_2 due to the combustion of coke made from coal. However, the advent of electric arc furnaces (EAF) has revolutionised the industry by enabling the use of recycled scrap steel as a primary input, significantly reducing both energy consumption and carbon emissions. EAFs can reduce CO_2 emissions by as much as 75% compared to traditional blast furnace methods, making them a cornerstone of modern steel production.[32]

2.5.1 Other methods for emission reduction

In addition to advancements in machinery, other production modifications have further contributed to lower CO_2 emissions. For example, the introduction of direct reduced iron (DRI) technology allows steel to be produced using natural gas rather than coke, which results in a much lower carbon footprint. DRI production is particularly effective when combined with EAF technology, creating a hybrid system that maximises efficiency and minimises emissions. the carbon footprint in the DRI + EAF route can be roughly 50% to 70% lower than the traditional blast furnace route, depending on the specifics of the technology and the energy mix used in electricity generation. The exact reduction in CO_2 emissions can vary based on the efficiency of the process, the quality of the input materials, and the source of electricity used in the EAF. For example, using oil shale generates more CO_2 than natural gas. This method also supports the industry's shift towards utilising hydrogen as a reducing agent, a development that holds the potential to drastically cut emissions in the future.[28]

Logistics has also played a crucial role in reducing the environmental impact of steel production. Improvements in transportation networks, such as the optimisation of supply chains and the increased use of rail and sea transport over trucking, have reduced the carbon footprint associated with moving raw materials and finished steel. The expansion of rail networks during the Industrial Revolution in the 19th century made it possible to efficiently transport large quantities of raw materials to steel mills and distribute finished products to markets. Today, rail transport continues to play a crucial role in the steel industry, offering an efficient means of moving bulk goods over long distances with a lower carbon footprint compared to road transport. Throughout the 20th century, both rail and ship transportation were increasingly optimised for steel production logistics. The development of intermodal transportation systems, where goods are transferred seamlessly between ships, trains, and trucks, further improved efficiency. In recent decades, the focus has shifted towards sustainability, with logistics companies and steel producers working to optimise transportation routes, adopt more energy-efficient engines, and invest in greener technologies to reduce CO2 emissions. Rail and ship transportation, due to their lower emissions compared to road transport, have become increasingly favoured in efforts to reduce the overall carbon footprint of the steel supply chain. [32]

Furthermore, the integration of circular economy principles, such as recycling steel and repurposing by-products from the steelmaking process, has lessened the demand for virgin raw materials, thereby decreasing the overall energy consumption and emissions associated with steel production. These advancements reflect a broader industry trend towards sustainability, driven by both technological innovation and a growing global commitment to reducing greenhouse gas emissions.[39]

2.6 Relevant research in Estonia

The *Method for calculating the carbon footprint of a building* provides a detailed methodology for calculating the carbon footprint of buildings, focusing on assessing the life cycle of materials used in construction. The document, published by Estonia's Ministry of Climate, outlines how to systematically calculate CO_2 emissions across various phases of a building’s life cycle, from material extraction to end-of-life disposal. In the context of construction steel, a material that significantly contributes to the environmental impact of buildings, this document plays a pivotal role in standardising carbon accounting. This analysis delves into the specific provisions regarding construction steel, examining the methodology for CO_2 calculations, and evaluates its alignment with broader European standards like *EVS-EN 15804:2012+A2:2019*.[8], [18]

Steel is a fundamental material in modern construction, used in structural components like beams, columns, and reinforcements. The document emphasises that a comprehensive carbon footprint calculation for construction steel must follow the lifecycle stages, as outlined in *EVS-EN 15804:2012+A2:2019*, and breaks down the environmental impact into:

Product Stage (A1–A3):

This includes raw material extraction (iron ore mining), transportation, and steel manufacturing. The document specifies that emissions during this phase are primarily attributed to the energy-intensive nature of steelmaking, particularly the Blast Furnace-Basic Oxygen Furnace (BF-BOF) route, which emits approximately 1.8–2.2 tonnes of CO_2 per tonne of steel produced.[18]

The Electric Arc Furnace (EAF) method, which uses recycled steel and is significantly less carbon-intensive (approximately 0.3–1 tonne of CO_2 per tonne), is also mentioned as a less impactful alternative.[18]

Construction Process Stage (A4–A5):

This phase covers transportation of steel to the construction site and installation. Transportation emissions are calculated based on factors such as distance travelled, and the type of vehicle used. The emissions in this phase, although relatively small compared to the product stage, can be reduced by optimising transportation logistics.[18]

Use Stage (B1–B7):

In the context of steel, the use phase generally involves maintenance and repair, which has a negligible carbon footprint compared to other phases. However, in the case of high-strength steel used in buildings, longevity reduces the need for replacement and repair, thus indirectly lowering the overall environmental impact.[18]

End-of-Life Stage (C1–C4):

This stage addresses the deconstruction and recycling of steel. Given steel's high recyclability (up to 90%), the document encourages recycling, which can offset a significant portion of emissions. Recycling steel at the end of a building's life can lead to substantial CO_2 savings, aligning with the principles of the Circular Economy.[18]

Beyond Building Life (D):

This phase considers the benefits of recycling and reusing materials, as the carbon credits from recycled steel can be applied to future constructions, creating a more sustainable steel supply chain.[18]

Figure 2.1 Processes included in an LCA[40]

By aligning with the principles of *EVS-EN 15804:2012+A2:2019* and promoting a lifecycle approach, the document ensures that the carbon emissions of construction steel are accurately accounted for, from production to recycling. This approach is essential for reducing the carbon footprint of buildings and achieving the sustainability goals set out in European environmental policy. Structural engineers, architects, and policymakers should work together to implement the recommendations from this document, particularly by promoting recycled steel, green steel technologies, and more sustainable supply chains.

2.7 Implications of existing research

The analysis of CO_2 emissions from steel production, logistics, and assembly underscores the critical role of the steel industry in global emissions, contributing approximately 2.5 gigatons of CO_2 emission in 2019, accounting for 7-9% of global anthropogenic CO_2 emissions. However, when it comes to Estonia, the research landscape for steel-related CO_2 emissions is relatively underdeveloped. While global data points to the significant environmental impact of steel production, Estonia's national studies on this topic remain limited. The country lacks comprehensive research that examines the specific emissions associated with construction steel, its supply chain, and assembly processes.

This gap in research is particularly concerning given Estonia's alignment with European Union sustainability goals, which call for the rigorous assessment of building materials' carbon footprints. Although the Estonian document "Method for calculating the carbon footprint of a building" provides a framework for calculating the carbon footprint of buildings, the formulas do not go into the specialties of steel-specific factors in many aspects. This deficiency highlights the need for more localised research that considers Estonia's reliance on imported steel, the carbon intensity of transportation, and the energy mix used in steel production and construction.

Without detailed, Estonia-specific studies on construction steel's CO_2 emissions, it becomes difficult for the country to fully align with EU environmental policies or make informed decisions about reducing the carbon footprint of its construction sector. Moving forward, Estonia would benefit from conducting dedicated research into the environmental impacts of steel production and usage, including the adoption of low-emission technologies, hydrogen-based steelmaking, and improved logistics practices. These efforts will be crucial to ensure that Estonia meets its climate targets while promoting a more sustainable construction industry.

3. METHODOLOGY

3.1 Research approach

In this study of construction steel emissions in Estonia, I adopt a bottom-up approach, using a real construction project as a case study. This method allows me to calculate emissions based on the specific processes and equipment involved, rather than relying on generalised data. By focusing on the actual methods and machines employed on-site, I can offer a detailed Life Cycle Assessment (LCA) that captures the nuances of local construction practices.

My primary data collection focuses on two stages: steel production and transportation, and on-site construction activities, and machinery use during the assembly process. This involves tracking the types of machinery used (e.g., cranes, welding equipment, trucks) and the corresponding energy consumption and fuel types (diesel, electricity, etc.). Additionally, I account for the emission factors related to each type of equipment, sourced from different databases and region-specific energy data for Estonia.

The steel element production phase will be particularly crucial, as machinery for cutting and welding massive steel objects is a significant contributor to a project’s overall carbon footprint. For example, I will calculate emissions from all of the machines used in the production phase, as well as welding done by the workers. by quantifying the amount of electricity consumed by each machine during these processes. This approach to data collection ensures that the LCA reflects real-world conditions, making the results highly relevant for both practitioners and policy makers.

3.2 LCA Calculations and calculation phases

The calculation methodology for construction steel CO_2 emissions is grounded in the *EVS-EN 15804:2012+A2:2019* standard, which provides a comprehensive framework for Life Cycle Assessment (LCA) for construction. This framework ensures a systematic approach to quantifying environmental impacts, particularly global warming potential (GWP), which encompasses CO_2 emissions. As the basis for this thesis is a recently finalised construction project in Estonia, the calculations will be focused on the product (A1-A3) and construction (A4-A5) stages, relying on the data gathered from the production and construction processes, as well as data collected by the steel element production company, Exmet Services OÜ.[18], [41] The Product Stage (A1-A3) encompasses the environmental impacts associated with raw material extraction, transportation to production facilities, and the manufacturing of construction steel. These phases are often the most emission-intensive due to the high energy demands of steel production.

A1 involves the extraction of iron ore and the production of key raw materials, such as coal, used in the BF-BOF and EAF methods. *Method for calculating the carbon footprint of a building* emphasises the need to use region-specific data for emission factors is crucial to ensure that the carbon intensity of raw material extraction reflects the local context. the database referred to in this thesis for such data is EcoInvent, which is used in phases A1 and A2, through Exmet EPD. Information from this database ensures that for instance, if the steel is imported into Estonia, the methodology takes into account the specific emission factors from the country of origin to reflect the true environmental impact. Furthermore, emissions from ancillary materials used in steel production (such as limestone in iron reduction) are also included in this phase.[8], [42]

As this research focuses on a steel project produced by Exmet services OÜ, phase A1 is based on data collected by Exmet.[41], [43]

Phase A2 involves the transportation of raw materials from phase A1 production facilities to Exmet Services facilities. The CO_2 emissions in this stage are calculated based on the distance travelled, the mode of transportation (e.g., road, rail, or sea), and the fuel efficiency of the transport vehicles. In the case of steel, transportation emissions vary widely depending on the geographic source of raw materials. For example, transportation from a local European source would have a significantly lower carbon footprint than importing ore from distant regions such as Australia. However, in the case of this project, all of the steel is sourced from European countries. In this phase the calculation follows the formula 3.1.

$$\begin{aligned}&\mathrm{CO_2(kg)} = \text{imported steel (kg)} * \text{Distance travelled(km)} * \text{fuel consumption } (\mathrm{l/(kg * km)}) * \\ &\mathrm{CO_2} \text{ emitted per l of fuel consumed (kg/l)}\end{aligned} \tag{3.1}$$

The imported kilogrammes are calculated based on the imported % documented in the Exmet EPD, Additionally, the distances travelled from different countries and fuel consumption per kg-km are also documented in the Exmet services EPD.[43]

The A3 phase covers the manufacturing of steel, including the various processes involved in converting raw materials into construction steel products. According to the *EVS-EN 15804:2012+A2:2019* standard, the manufacturing stage must account for direct process emissions (e.g., CO_2 from coke combustion) and indirect emissions associated with energy use (electricity and heat). The methodology emphasises the importance of considering the energy mix used in steel production, as the carbon intensity of electricity varies significantly across different regions. In countries with a high share of renewable energy in the grid, the emissions from the EAF process can be as low as 0.3 tonnes of CO_2 per tonne of steel, while in regions dependent on coal, the emissions are higher.[18], [41], [43]

This thesis calculates phase A3 in three different stages. Firstly, the production phase, in which 6 different machines are used, and CO_2 levels are calculated for each machine separately. Secondly is the transportation of produced steel elements to the coating facility. Thirdly is the coating process.

The calculation goes as follows:

Production phase:

$$\mathrm{CO_2(kg)} = \text{total machine operation time(h)} * \text{electricity consumption of machine (kW/h)} * \text{CO2 emitted (kg/kW)} \quad (3.2)$$

Total machine operation times were documented during the real production phase of the selected project. Data for the electricity consumption of each machine is gathered by Exmet Services and emissions per kW used are calculated based on the real energy mix used using equation 3.3. As the "other" is not specified, it is considered energy imported from Finland in the calculation.

$$\mathrm{CO_2(kg)} = (\text{Shale oil kg } \mathrm{CO_2}/\mathrm{kW} * 62\%) + (\text{Imported kg } \mathrm{CO_2}/\mathrm{kW} * 18\%) + (\text{wood chips kg } \mathrm{CO_2}/\mathrm{kW} * 8\%) + (\text{wind kg } \mathrm{CO_2}/\mathrm{kW} * 5\%) + (\text{other kg } \mathrm{CO_2}/\mathrm{kW} * 2\%) + (\text{coal gas kg } \mathrm{CO_2}/\mathrm{kW} * 5\%) \quad (3.3)$$

The percentages used in the equation are real values present in Exmet's energy mix.

Transportation phase:

$$\mathrm{CO_2(kg)} = \text{total distance travelled (km)} * \text{fuel consumption (l/km)} * \text{CO2 emitted (kg/l)} \quad (3.4)$$

Fuel consumption takes into account the mass of the load with the formula 3.5.

$$\text{Fuel consumption(l/km)} = (\text{base fuel consumption (l/100km)} * (1 + \text{fuel consumption increase per load}))/100 \quad (3.5)$$

$$\text{fuel consumption increase per load} = \text{fuel consumption increase per 100kg of load } (0.5) * \text{load factor}$$
[44] (3.6)

Load factor (full load represented as number of 100kgs, example: 11000kg=110)

Coating phase:

$$CO_2(\text{kg}) = \text{quantity of paint used (l)} * \text{CO2 emitted (kg/l)} \quad (3.7)$$

Values used in this formula are based on the EPD findings from the companies.[45], [46]

The Construction Process Stage (A4-A5) includes the transportation of steel products to the construction site and their installation. Although these stages generally account for a smaller portion of the overall carbon footprint compared to the production stages, they are still significant and must be carefully assessed.

The transportation of construction steel from the coating facility to the construction site is captured in A4. Similar to the transportation of raw materials (A2), this phase calculates emissions based on the distance travelled, vehicle type, and fuel consumption. In the case of this construction project, all of the transportation to the construction site was done by trucks.

The formula is the same as A3 transportation phase formula 3.4.

$$CO_2(\text{kg}) = \text{total distance travelled (km)} * \text{fuel consumption (l/km)} * \text{CO2 emitted (kg/l)} \quad (3.4)$$

Fuel consumption is calculated with formula 3.5. The mass of the load on the way to the construction site is 8500kg and from the construction site 0kg. Fuel consumption calculations are based on these load masses.

The A5 phase covers the emissions generated during the installation of steel structures at the construction site. This includes the use of construction machinery such as cranes, generators, and welding equipment, all of which consume energy or fuel and produce CO_2 emissions. The calculation formula is 3.8.

Diesel fuel machinery:

$$CO_2(\text{kg}) = \text{total machine operation time (h)} * \text{fuel consumption (l/h)} * \text{CO2 emitted (kg/l)} \quad (3.8)$$

Electricity consuming machinery:

$$CO_2(\text{kg}) = \text{total machine operation time (h)} * \text{electricity consumption (kW/h)} * \text{CO2 emitted (kg/kW)} \quad (3.9)$$

All of the information for the calculations are gathered from 2 sources. Firstly, the LCA and EPD documents conducted by the construction steel producer Exmet Services OÜ, which produced all of the elements for the project in the centre of this thesis. Secondly, all of the direct data gathered by the writer of this thesis during the steel production, assembly and the related logistics.[41], [43]

4. CASE STUDY PROJECT

4.1 Project introduction

This thesis is based on a 10000m2 warehouse and office building near Tallinn which started construction in 2023 and by now is successfully completed. This specific project was selected due to the fact that the load bearing structure is comprised of concrete columns joined by a steel framework. This is a standard load-bearing solution used all around Estonia and the rest of the world. Additionally, the author of this thesis was the project manager for construction steel for this project. The author coordinated and managed all of the production processes, logistics, deadlines and on-site operations. Owing to this role, the author gained the knowledge to fully analyse the project's carbon footprint, from production to assembly.

The building is 105m long, 42m wide, and 12m tall from the ground floor. From the total space, an area of 55m x 6m is designated for offices and all the rest is a warehouse. On the longer sides of the building, there are 15 reinforced concrete columns spaced 6 meters apart, and in the centre of the building, there are 5 columns spaced 15 meters apart. All the columns are connected at the roof level with steel trusses to ensure the building's rigidity and stability. The total steel mass of this project is 93 tonnes, which includes trusses, diagonal joints, roof joints, smoke hatches, window frames, door frames and canopy elements. This type of steel and concrete combination is commonly used for warehouses. All of the overall production information is presented as such:

Table 4.1 Case study project steel element specification

Category	**amount(pcs)**	**total mass(kg)**
assembly detail	332	736
Truss	47	52333
Assembly plate	195	401
Frame	163	19664
Beam	220	19855
Total:	957	92989

Producing the steel elements took 1720 hours in total, which includes all of the welding and machine hours. The welding for this project was done by 8 different welders and 5 different machines were used in the cutting and drilling stages. Logistics processes to the coating facility were 30 hours and the coating process itself approximately 250 hours. LCA phase A3 is comprised of these 3 processes, which in total account for 2000 hours.

Transporting the coated details to the construction site in phase A4 took 90 hours in total, this accounts for 22 trips and all of the loading times. Lastly, the actual assembly phase A5 included 3 machines and 6 workers, including the crane operator. The first machine used was a telehandler Manitou MT1840 EASY ST5 (Manitou), used for 126 hours on the construction site. This machine was used to transport steel elements on the site, lift elements in place and lift workers to different heights. Secondly, the chosen crane was a Liebherr LTM 1055-3.2 (Liebherr). This was used in the initial unloading phase and lifting trusses, utilised in total for 50 hours, this included the machine itself as well as the operator. Lastly, a boom lift Genie Z33/18 (Genie) was used for 440 hours. This was the main tool used to reach necessary heights. On site welding took 112 hours with the arc welding method.[47], [48], [49], [50]

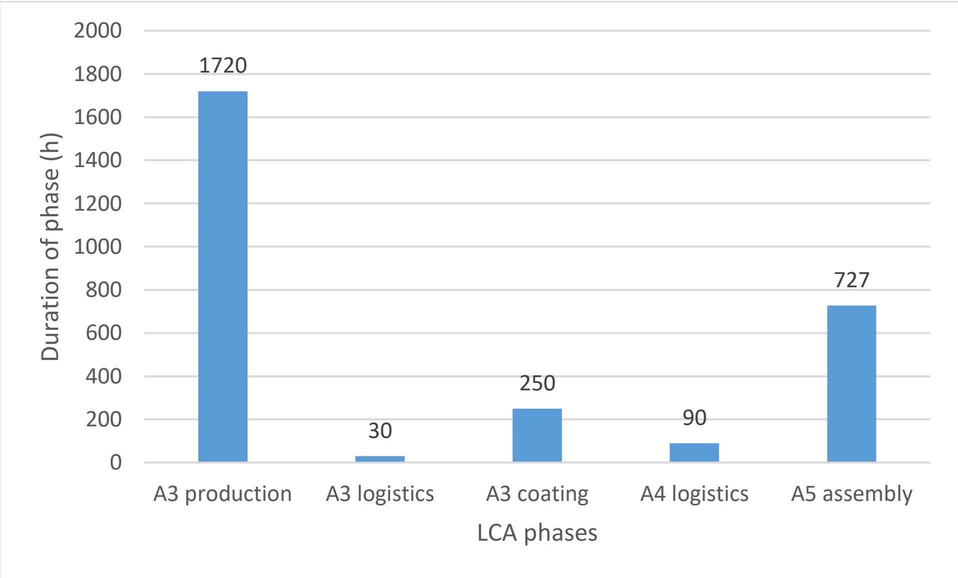

Figure 4.1 Case study project LCA phase durations

4.2 Production information

When analysing steel element production, it is reasonable to divide the process into 2 main subsections- production of plates and profiles, and welding. The plates and the profiles are produced at the same time, using specific machinery, after which they are welded together by operators. In the case of the selected project for this thesis, the plates were produced by 3 different machines, the profiles produced by a combination of 2 machines (one for cutting and one for drilling), and welding was done by 6 different operators. Dividing the production into these categories, allows for the production data to be presented in an understandable and easily developable format. All of the information about production times, machine models and electricity consumption are presented in the table:

Table 4.2 Case study project production information

Machine	Fuel type	Time (h)	Electricity consumption(kW/h)
Bystar Fiber 12 kW	electricity	0.85	55
Microstep II	electricity	2.57	50
Microstep I	electricity	26.05	50
KDP1036	electricity	45.42	74
KBS1051	electricity	45.42	73
Arc welding	electricity	1600	9.2

Table 4.3 Case study project transportation to coating facility information

Transport type	Total distance travelled (km)	Fuel consumption (l/km)
truck	816	0.474

Table 4.4 Case study project coating process information

Paint type	Area painted (m^2)	Paint used (l)	CO_2 emitted (kg/l)
Teknol 3890	559.7	270	2.31
Firetex FX5000	1701	330	2.8

4.3 On-site information

The on-site information includes all processes and machinery involved in the steel assembly phase of the project. This encompasses cranes, welding equipment, forklifts, lifts, and trucks for transporting steel elements. Throughout the assembly, both man-hours and machine-hours are carefully recorded. Additionally, due to the precise scheduling required for steel deliveries, logistics are also thoroughly documented. This comprehensive data collection ensures accurate calculations of CO_2 emissions.

Table 4.5 Case study project assembly process information

Machine	Fuel type	Time (h)	Fuel consumption (l/h) or (kW/h)
MANITOU MT1840 EASY ST5	Diesel	125.5	10
Liebherr LTM 1055-3	Diesel	50	60
arc welding	electricity	112	4
Genie Z33/18	electricity	439.5	8.73

Table 4.6 Case study project construction site logistics information

Construction site transport		
Transport type	**Total distance travelled (km)**	**Fuel consumption (l/km)**
Truck to site	1232	43
Truck from site	1232	30

Transport to and from the site are calculated separately, due to the different load masses. The mass of the load being transported has an effect on the fuel consumption as highlighted in the fuel consumption 3.5.

4.4 Exmet CO_2 findings

The life cycle assessment conducted by Exmet Services OÜ provides an environmental impact analysis for their production. This study adheres to the standards *EVS-EN ISO 14044:2006*[51], *ISO 14025:2006*[52], and *EVS-EN 15804:2012+A2:2019*[53], focusing on the product's environmental performance over its life cycle. The LCA methodology applies the SimaPro 9.4.0.2 software for calculating environmental impacts according to key metrics, including:

- Global Warming Potential (GWP)
- Acidification Potential (AP)
- Eutrophication Potential (EP)
- Abiotic Depletion (ADP)
- Ozone Depletion Potential (ODP)

The primary goal of the study was to produce an Environmental Product Declaration (EPD) for welded and surface-treated steel products. The EPD aimed to quantify the environmental impacts of steel structure. By focusing on both upstream and downstream processes, the study allowed Exmet to identify environmental hotspots and optimise their production methods. The declared unit for the study is 1 kg of steel product, ensuring consistency in the results, and the report follows a "Cradle to completion"(*EVS-EN 15804:2012+A2:2019*) system, meaning it includes stages A1 (raw materials) through A5 (assembly and installation) and C1 (deconstruction) through D (recycling and disposal).[18], [41], [43]

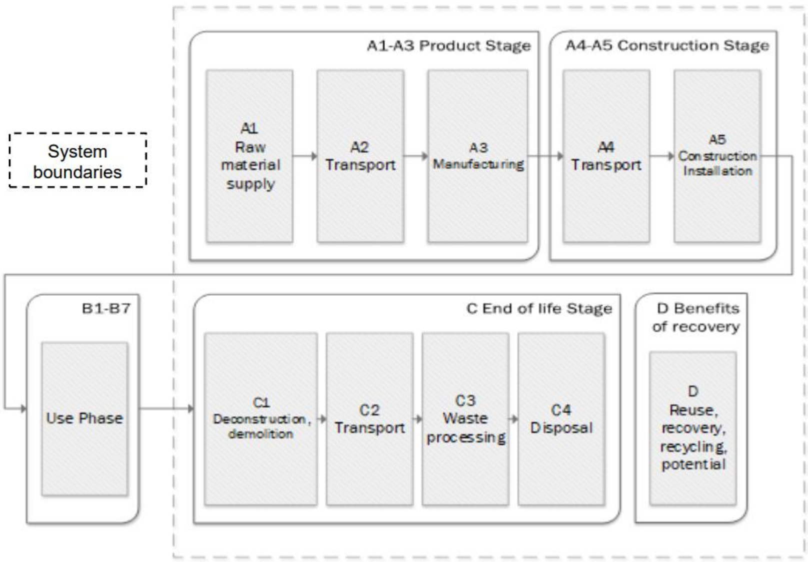

Figure 4.2 LCA phase order according to Exmet Services OÜ LCA[41]

4.4.1 Cradle-to-Gate Emissions modules A1-A5

1. Cradle-to-Gate Emissions (Modules A1-A3):

The majority of environmental impacts stem from the raw material extraction and steel production stages. The steel used in Exmet's products contains approximately 8%

recycled content, with the remainder produced through energy-intensive processes, primarily in basic oxygen furnaces. [41], [43]

Global Warming Potential (GWP) for raw material extraction is the most significant contributor, with over 76% of total emissions linked to steel production.[41], [43]

Other notable impacts include acidification and resource depletion due to energy consumption during manufacturing.

2. Raw material transportation (Module A2):

Steel is transported from multiple countries, including Poland, Italy, and Denmark. Road transport using EURO6 lorries is the primary mode of delivery, contributing to about 9% of the product's total GWP. This highlights the role of logistics optimisation in reducing the overall carbon footprint.[41], [43]

Material	Country of supply	Type of transport	kg/DU	Road transport	
				km	kgkm
Steel	Poland	Lorry, 16-32t, EURO6, RER	0,55962	970	542,84
	Italy	Lorry, 16-32t, EURO6, RER	0,21524	2485	534,87
	Denmark	Lorry, 16-32t, EURO6, RER	0,16143	1270	205,02
	Turkey	Lorry, 16-32t, EURO6, RoW	0,02152	3500	75,33
	Czech Republic	Lorry, 16-32t, EURO6, RER	0,11838	1560	184,68
Welding wire	Italy	Lorry, 16-32t, EURO6, RER	0,00990	2485	24,60
Abrasive	Estonia	Lorry, 3.5-7.5t, EURO6, RER	0,00370	50	0,19
Wood		Lorry, 3.5-7.5t, EURO6, RER	0,00559	50	0,28
Metal strips		Lorry, 3.5-7.5t, EURO6, RER	0,00101	50	0,05
Gases		Lorry, 3.5-7.5t, EURO6, RER	0,00029	50	0,01

Figure 4.3 Transportation of Raw materials to Exmet production plant [41]

3. Manufacturing (Module A3):

Exmet's production processes, including shot-blasting, cutting, and welding, contribute approximately 6.5% to the total GWP. The surface coating process, performed at an outsourced facility, adds to the environmental impact, particularly in terms of energy use and emissions from metal coating procedures.[41], [43]

4. Transport of the Product to the Construction Site (Module A4)

Module A4 in the Life Cycle Assessment (LCA) framework focuses on the transportation of steel products from the production facility to the construction site. This stage plays a significant role in the total environmental footprint of steel products, especially for international deliveries, where both road and sea transport are involved. Transport is analysed for three primary regions: Estonia (domestic market), Finland, and Sweden.[41], [43]

Type	Vehicle	Distance, km	Fuel/energy consumption, l/tkm	Value, l/t
Estonia				
Road	Lorry 16-32t, EURO6	70	0,0431	3,02
Finland				
Road	Lorry 16-32t, EURO6	119	0,0431	5,13
Sweden				
Road	Lorry 16-32t, EURO6	208	0,0431	8,97
Finland				
Water	Sea Ferry	81	0,0298	2,41
Sweden				
Water	Sea Ferry	400	0,0298	11,91

Figure 4.4 Transportation of steel elements to construction site[41]

5. Module A5 construction installation

Module A5 focuses on the emissions generated during the construction and installation phase at the building site. This includes the use of heavy machinery to assemble the steel products and manage waste from packaging materials. The environmental impact of this module stems primarily from the operation of construction equipment and the disposal of packaging waste. The operational times of machines (Lattice boom cranes, forklifts, hydraulic cranes, crawler loaders) vary depending on the size and complexity of the structure. On average, 17 to 21 minutes of machinery operation is required per tonne of steel installed. The use of these machines, primarily powered by diesel fuel, is a major source of emissions during this phase. [41], [43]

During the installation process, packaging materials such as wooden planks and metal strips are discarded. The management of this waste is handled according to regional waste treatment practices:

- Wooden planks are typically recycled, reducing their environmental impact.
- Metal strips are processed according to local waste management strategies, with portions recycled, incinerated, or sent to landfills. In Sweden and Finland, around 85% of waste steel is recycled, with the remainder being managed through incineration or landfill.

The emissions generated in Module A5 represent approximately 5% of the total GWP for the life cycle of the steel product.[41], [43]

4.4.2 End-of-Life Recycling and Recovery (Modules C1-C4, D)

Steel is widely recycled, and this LCA assumes a high recycling rate, particularly in Estonia where 100% of waste steel is recovered. In Finland and Sweden, the recycling rates are slightly lower (85.1% and 85.8%, respectively), with some steel waste being sent to incineration or landfill. Module D accounts for the positive environmental benefits of recycling, which offsets some of the impacts from earlier life cycle stages.[41], [43]

Key environmental findings:

- Global Warming Potential (GWP): The total GWP per kilogram of welded and surface-treated steel is 1.8 kg CO_2-equivalent, with raw material production being the dominant contributor.
- Transportation: Transporting steel from the manufacturing plant to construction sites in Estonia, Finland, and Sweden adds significantly to emissions
- Recycling: Recycling at the end of the product's life provides substantial environmental benefits, reducing the net GWP by around 6%.

4.4.3 Strategic Implications for Estonia

The findings from this LCA report are critical for the Estonian steel and construction sectors. Given Estonia's commitment to reducing greenhouse gas emissions by 70% by 2030 under the National Energy and Climate Plan[21], improving the environmental performance of steel products can contribute significantly to national climate goals. Key areas for strategic action include:

1. Optimising Material Sourcing: Steel sourced from countries with lower carbon-intensity production processes or higher recycled content can drastically reduce GWP.
2. Improving Logistics Efficiency: Reducing transportation distances and improving vehicle utilisation could significantly cut emissions from the transportation phase.
3. Enhancing Recycling Infrastructure: Maintaining high recycling rates and encouraging further use of secondary steel materials can help minimise the overall environmental impact of the produced steel.

5. FINDINGS

5.1 Production CO_2 calculations

A1 calculations are based on research conducted by Exmet Servies OÜ. In phase A1, the calculation for raw material supply focuses on the environmental impact of sourcing and producing steel, of which 8% of the steel is produced using the EAF method. The environmental data for steel production comes from the Ecoinvent v3.8 database. This database provides extensive information on resource use, emissions, and other key environmental metrics for steel production, ensuring accurate impact assessment across categories like Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), and Abiotic Depletion Potential (ADP) for both fossil and non-fossil resources.

The Global Warming Potential (GWP) in Phase A1 is measured as 1.8 kg of CO_2 equivalents per kilogram of steel products. This means that for every kilogram of welded and surface-treated steel produced, 1.8 kilograms of CO_2 are emitted during the raw material extraction and initial processing stages. With this information it is possible to calculate the A1 phase CO_2 emissions for the specific project of this thesis:

Table 5.1 Case study project Phase A1 emissions calculation

Steel produced (kg)	**CO_2 emitted per kg of steel (kg)**	**Total CO_2 emitted (kg)**
92989	1.8	167380

According to Exmet's data 8% of the steel is produced in this phase using the EAF method and 92% produced via the BOF process. In the context of this project, that would equate to 7439 kg having been produced through EAF and 85550 kg through BOF method. These findings fall in line with the standard BOF method emissions.

Considering that Exmet imports 92% BOF method, 1.8 kg of CO_2 emissions per kg of steel produced is a low number. This can be compared to different steel manufacturers:

The Spanish manufacturer Acerinox EUROPA, S.A.U. declares 2.78 kg of CO_2 emissions per kg of steel plates/sheets produced. [54]

The Austrian manufacturer Voestalpine declares 2.17 kg of CO_2 per kg of steel produced.[55]

The German manufacturer Salzgitter AG declares 2.28 kg of CO_2 per kg of steel produced. [56]

And the aforementioned ArcelorMittal declares 0.818 kg of CO_2 per kg of steel produced. [34]

Exmet imports steel profiles and sheets, which have different levels of emissions. From the examples given, only ArcelorMittal produced profiles and also has the lowest CO_2 emissions. The low emission number of Exmet comes from the fact that most of the imported steel are profiles, which emit less CO_2 than plates in the A1 manufacturing phase.

A2 calculations are also based on the Exmet EPD, according to which the raw steel material is transported to Exmet production facilities from different European countries of Poland, Italy, Denmark, Czech Republic and Turkey. In total, 92989 kg of steel elements were produced for the project in the centre of this thesis. For the purpose of CO2 calculations, steel import percentages were correlated with the kilogrammes of produced steel. [43]

Table 5.2 Case study project Phase A2 logistics data

Country of origin	% of Exmet steel	kg of selected project (kg)	Distance travelled (km)	Mode of transport
Poland	52	48354	970	truck
Italy	20	18598	2485	truck
Denmark	15	13948	1270	truck
Czech Republic	11	10229	1560	truck
Turkey	2	1860	3500	truck

With this data it is possible to calculate CO_2 emissions from each country by using the fuel consumption values per kg-km presented in the EPD. Calculations are completed with formula 3.1.

Table 5.3 Case study project Phase A2 logistics emissions

Country of origin	**Imported material (kg)**	**Distance travelled (km)**	**Fuel consumption (l/(kg*km))**	**CO2 emitted (kg/l)**	**CO2 emitted total (kg)**
Poland	48354	970	0.0000441	2.68	5543
Italy	18598	2485	0.0000441	2.68	5462
Denmark	13948	1270	0.0000441	2.68	2095
Czech	10229	1560	0.0000441	2.68	1887
Turkey	1860	3500	0.0000441	2.68	769
					15754

Calculations in table 5.3 are based on formula 3.1.

For phase A3, according to Exmet services, the energy mix used in the Estonian production facilities is: 62% from shale oil, 18% imported electricity from Finland, 8% wood chips, 7% wind power and 2% other sources. The energy mix is calculated with formula 3.3.

$$CO_2(kg) = (Shale\ oil\ \text{kg}\ CO_2/kW\ * 62\%) + (Imported\ \text{kg}\ CO_2/kW\ * 18\%) + (wood\ chips\ \text{kg}\ CO_2/kW\ * 8\%) + (wind\ \text{kg}\ CO_2/kW * 5\%) + (other\ \text{kg}\ CO_2/kW * 2\%) + (\text{coal gas kg}\ CO_2/kW * 5\%) = (1 * 0.62) + (0.094 * 0.2) + (0.058 * 0.08) + (0.011 * 0.07) + (0.86 * 0.05) = 0.687kg \quad (3.3)$$

As the "other" is not specified in the energy mix, it is considered as imported energy from Finland in the calculation. The emission values used in the calculation are based on information gathered from different sources.[57], [58], [59], [60], [61]

Table 5.4 Case study project phase A3 production information

Machine	Fuel type	Time (h)	Electricity consumption (kW/h)	Electricity consumed total(kw)	CO2 emitted (kg/kW)	CO2 emitted (kg)
Bystar Fiber 12 kW	electricity	0.85	55	46.75	0.687	32
Microstep II	electricity	2.57	50	128.5	0.687	88
Microstep I	electricity	26.05	50	1302.5	0.687	895
KDP1036	electricity	45.42	74	3361.08	0.687	2309
KBS1051	electricity	45.42	73	3315.66	0.687	2278
Arc welding	electricity	1600	9.2	14720	0.687	10113
						15715

Calculations in table 5.4 are based on formulas 3.2 and 3.3.

Table 5.5 Case study project phase A3 transportation to coating facility emissions

Transport type	Distance (km)	Times travelled	Total distance travelled (km)	Fuel consumption (l/km)	Total fuel consumed (l)	CO2 emitted (kg/l)	CO2 emitted total (kg)
Truck	102	8	816	0.474	386.8	2.68	**1037**

Calculations in table 5.5 are based on formulas 3.4, 3.5 and 3.6.

Table 5.6 Case study project phase A3 coating emissions

Paint type	Area painted (m2)	Paint used (l)	CO2 emitted (kg/l)	CO2 total (kg)
Teknol 3890	559.7	270	2.31	624
Firetex FX5000	1701	330	2.8	924
				1548

Calculations in table 5.6 are based on formula 3.7

5.2 On-site CO_2 calculations

Phase A4 calculations are based on 3.4 and 3.5. The calculation results are as follows:

Table 5.7 Case study project phase A4 logistics emissions

Transport type	Distance (km)	Times travelled	Total distance travelled (km)	Fuel consumption (l/km)	Total fuel consumed (l)	CO2 emitted (kg/l)	CO2 emitted total (kg)
Truck to site	112	11	1232	0.43	529.76	2.68	1420
Truck from site	112	11	1232	0.30	369.6	2.68	991
							2411

Calculations in table 5.7 are based on formulas 3.4 and 3.5

Table 5.8 Case study project phase A5 assembly emissions

Machine	Fuel type	Time (h)	Fuel consumption (l/h)	Total fuel consumed (l)	CO2 emitted (kg/l)	CO2 emitted total (kg)
MANITOU MT1840	Diesel	126	10	1255	2.68	3363
Liebherr LTM 1055-3	Diesel	50	60	3000	2.68	8040
Machine	**Fuel type**	**Time (h)**	**Electricity consumption (kW/h)**	**Total electricity consumed**	**CO_2 emitted (kg/kW**	**CO_2 emitted total (kg)**
arc welding	electricity	112	9.2	1030.4	0.687	708
Genie Z33/18	electricity	440	8.73	3837	0.687	2636
						14747

Calculation in table 5.8 are based on formulas 3.8 and 3.9.

5.3 Emissions across all stages

With all of the calculations completed for the separate phases, they can be brought out in one table:

Table 5.9 Case study project CO2 emission totals

Phase A1: CO_2 from excavation, initial refining	167380
Phase A2: CO_2 from raw material transportation	15754
Phase A3: CO_2 from production	15715
Phase A3: CO_2 from transport	1037
Phase A3: CO_2 from coating	1548
Phase A4: CO_2 from transport	2411
Phase A5: CO_2 from assembly	14747
	218592

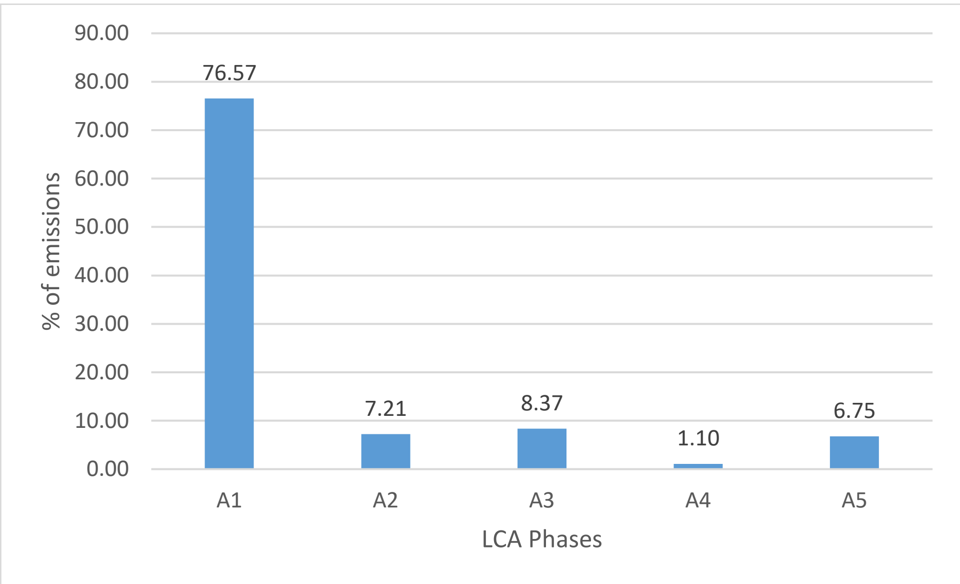

Figure 5.1 LCA phase emission percentages

5.4 Alternative methods

Originally in phase A1 92% of the steel was manufactured using BOF method and 8% using EAF method. IF relying on the data provided by Arcelor Mittal, EAF emits 0.37kg of CO_2 per kg of steel produced. If all of the steel for this project had been produced via EAF, the total emission in phase A1 would be:

$$CO_2(kg) = 0.37 * 92989 = 34406\ kg \quad (5.2)$$

This is 132974.270 kg lower than the real emission, making it 80% more efficient in terms of CO_2 emissions.

In phase A2 all of the steel was imported using trucks, which have a higher emission rate than rail or sea transport.

Table 5.10 Case study project phase A2 logistics data

Country of origin	% of Exmet steel	kg of selected project (kg)	Distance travelled (km)	Mode of transport
Poland	52	48354	970	truck
Italy	20	18598	2485	truck
Denmark	15	13948	1270	truck
Czech Republic	11	10229	1560	truck
Turkey	2	1860	3500	truck

For phase A2, calculations are done for rail and sea transportation, where in one case all of the steel is transported via sea and in the second case by rail. The distances are changed based on real harbours and rail networks.

The calculations are done with the formula 5.3.

$$CO_2(kg) = \frac{imported\ material\ (kg)}{1000} * distance\ travelled(km) * CO_2\ emitted\ per\ tonne - km(kg) \quad (5.3)$$

Table 5.11 Phase A2 theoretical ferry logistics emissions

Country of origin	Imported material (kg)	Distance travelled (km)	CO2 emitted per tonne-km (kg)	CO2 emitted total (kg)
Poland (Gdansk)	48354	600	0.01	290
Italy (Venice)	18598	8900	0.01	1655
Denmark (Grenaa)	13948	1180	0.01	165
Czech Republic	10229	1500	0.01	153
Turkey (Istanbul)	1860	9400	0.01	175
				2438

Calculations in table 5.11 are based on formula 5.3

Table 5.12 Phase A2 theoretical rail logistics emissions

Country of origin	Imported material (kg)	Distance travelled (km)	CO2 emitted per tonne-km(kg)	CO2 emitted total (kg)
Poland	48354	1200	0.0265	1538
Italy	18598	2800	0.0265	1380
Denmark	13948	1200	0.0265	444
Czech Republic	10229	1500	0.0265	407
Turkey	1860	3800	0.0265	187
				3955

Calculations in table 5.12 are based on formula 5.3

Based on these calculations we are able to create a table showing the most optimal routes for importing.

Table 5.13 Phase A2 theoretical optimal logistics

Country of origin	Imported material (kg)	Distance travelled (km)	CO2 emitted per tonne-km(kg)	CO2 emitted total (kg)
Poland(sea)	48354	600	0.01	290
Italy(rail)	18598	2800	0.0265	1380
Denmark(sea)	13948	1180	0.01	165
Czech Republic(sea)	10229	1500	0.01	153
Turkey(sea)	1860	9400	0.01	175
				2163

As the table reveals, in no situation is road transport the most efficient in terms of emissions. In every case it is more optimal to import the materials either by sea or by rail. If the most optimal transportation options had been used for this case project, the emission from phase A2 would have been 13591 kg lower, in other words 86% more efficient.

In phase A3, the energy mix is highly polluting due to the high use of oil shale. If the manufacturing relied entirely on green energy, the emissions would be noticeably lower.

This table shows emission from phase A3 production, if the energy mix had been 100% wind.

Table 5.14 Phase A3 theoretical production emissions

Machine	Fuel type	Time (h)	Electricity consumption (kW/h)	Electricity consumed total(kw)	CO2 emitted (kg/kW)	CO2 emitted(kg)
Bystar Fiber 12	electricity	0.85	55	46.75	0.011	1
Microstep II	electricity	2.57	50	128.5	0.011	1
Microstep I	electricity	26.05	50	1302.5	0.011	14
KDP1036	electricity	45.42	74	3361.08	0.011	37
KBS1051	electricity	45.42	73	3315.66	0.011	36
Arc welding	electricity	1600	9.2	14720	0.011	162
						252

Calculations in table 5.14 are based on formulas 3.2 and 3.3.

In this situation, the emissions are 15463 kg, or 98.4% less kg of CO_2 when compared to the real solution. In terms of phase A3 transport production facility to coating facility, if a combination of rail and road transport had been used the CO_2 emissions outcome would be the following:

Table 5.15 Phase A3 theoretical transportation to coating facility emissions

Transport type	Distance (km)	Times travelled	Total distance travelled (km)	Fuel consumption (l/km)	Total fuel consumed (l)	CO2 emitted (kg/l)	CO2 emitted total (kg)
Truck	20	8	160	0.474	75.84	2.68	203
Transport type	**Distance (km)**	**Times travelled**	**Total distance travelled (km)**	**Imported material (kg)**	**CO2 emitted per tonne-km (kg)**		**CO2 emitted total (kg)**
train	100	8	800	11623.625	0.0265		246
							450

The calculations in table 5.15 are based on formulas 3.4, 3.5, 3.6 and 5.1.

As the table shows, a combination of rail and road transport would have resulted in approximately 450 kg of CO_2 emitted. This result is 587 kg or 57% less CO_2 than the real transportation method used.

The A3 coating phase itself is left unchanged due to strict regulations surrounding the need for environmental and fire protection.

In phase A4 transportation from coating facility to the construction site, a combination of rail and road transportation can be considered. In that case the results are as follows:

Table 5.16 Phase A4 theoretical construction site logistics emissions

Transport type	**Distance (km)**	**Times travelled**	**Total distance travelled (km)**	**Fuel consumption (l/km)**	**Total fuel consumed (l)**	**CO2 emitted (kg/l)**	**CO2 emitted total (kg)**
Truck to site	35	11	385	0.474	182.49	2.68	489
Truck from site	35	11	385	0.3	115.5	3.68	425
Transport type	**Distance (km)**	**Times travelled**	**Total distance travelled (km)**	**Imported material (kg)**	**CO2 emitted per tonne-km (kg)**		**CO2 emitted total (kg)**
train	100	11	1100	8453.545	0.0265		246
							1161

Calculations in table 5.16 are based on formulas 3.4, 3.5, 3.6 and 5.1.

In this case the CO_2 emissions would be 1250 kg or 52% than the real transportation method used.

For the A5 assembly phase a collection of more environmentally friendly alternative machinery could be used, in which case CO_2 emissions would be drastically lower.

Table 5.17 Phase A5 theoretical on-site assembly emissions

Machine	Fuel type	Time (h)	Electricity consumption (kW/h)	Total electricity consumed (KW)	CO_2 emitted (kg/kW)	CO_2 emitted total (kg)
arc welding	electricity	112	9.2	1030.4	0.687	708
Genie Z-33/18 E	electricity	440	2.1	923	0.687	634
Manitou MT 625 E	electricity	126	6.25	788	0.687	541
Liebherr LTC 1050-	electricity	50	50	2500	0.687	1718
						3600

Calculations in table 5.17 are based on formulas 3.3 and 3.9.

All of the machines are switched for more environmentally friendly alternatives in this phase. In this case, the emissions would be 11147 kg of CO_2 or 76% lower than the actual on-site situation. [49], [50], [62], [63]

If the best possible solutions in terms of CO_2 emissions had been used in every phase of this construction project, the total emissions had been the following:

Table 5.18 Theoretical CO2 emission totals

Phase A1: CO_2 from excavation, initial refining	34406
Phase A2: CO_2 from raw material transportation	2163
Phase A3: CO_2 from production	252
Phase A3: CO_2 from transport	450
Phase A3: CO_2 from coating	1548
Phase A4: CO_2 from transport	1161
Phase A5: CO_2 from assembly	3600
	43580

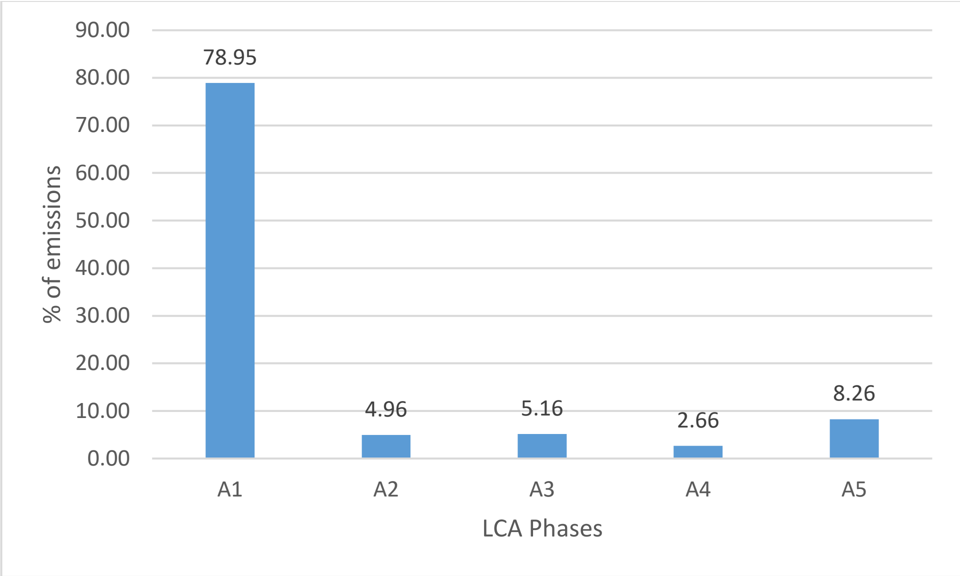

Figure 5.2 Theoretical LCA phase emission percentages

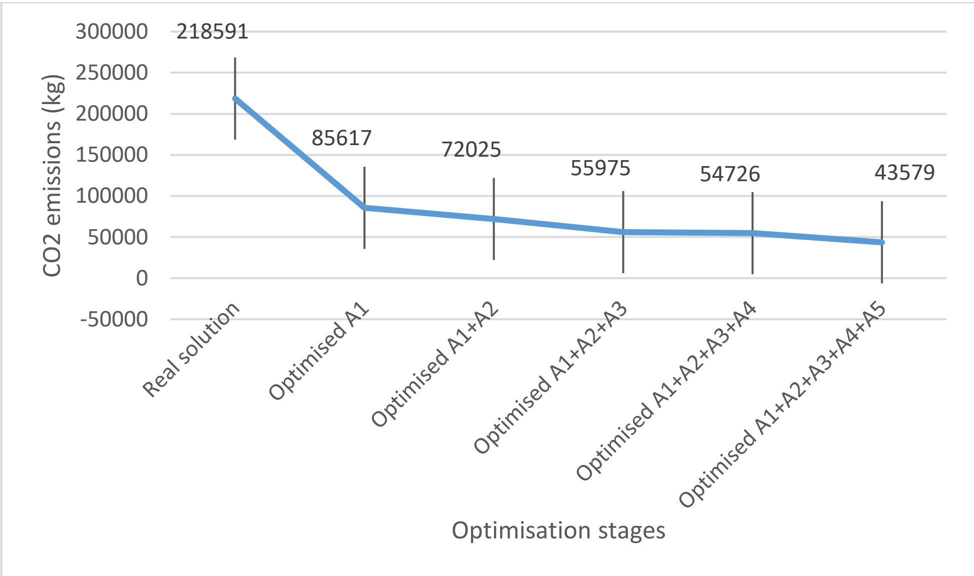

Figure 5.3 Optimisation of LCA stages A1-A5

5.5 Graphical showcase of optimising each LCA phase separately

These graphs shawcase the LCA emissions of each phase in percentages, focusing on the percentage of saved emissions in one particular phase, in relation to the rest of the phases.

5.5.1 Phase A1 potential savings

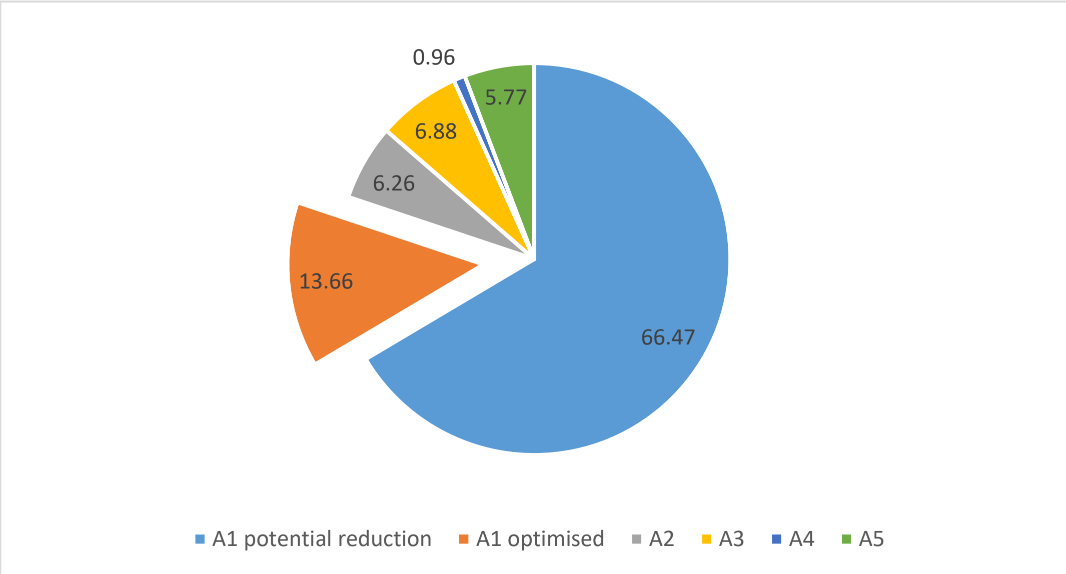

Figure 5.4 Theoretical phase A1 optimised emissions

5.5.2 Optimising phase A2

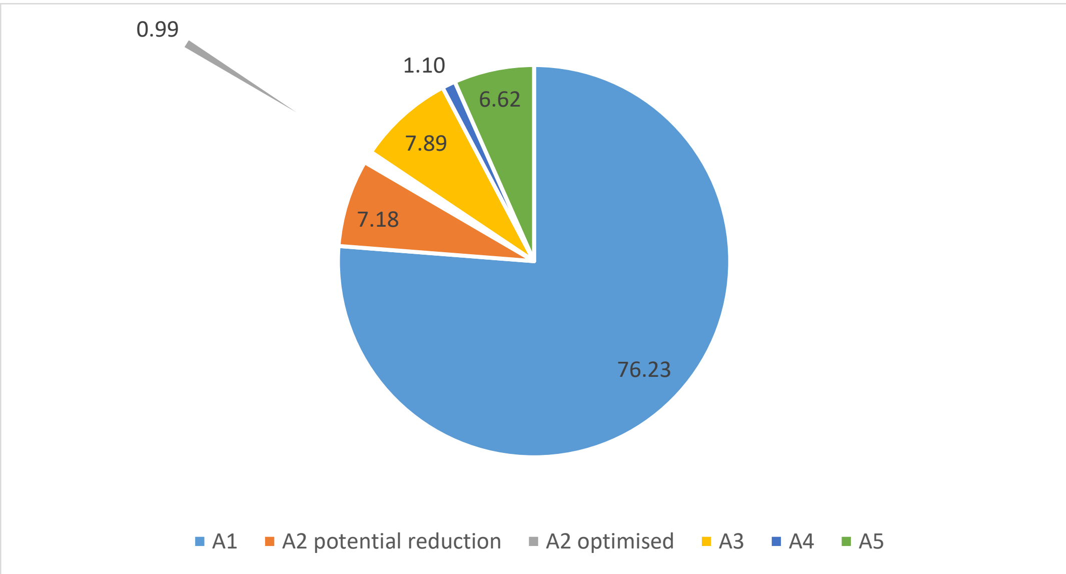

Figure 5.5 Theoretical phase A2 optimised emissions

5.5.3 Optimising phase A3

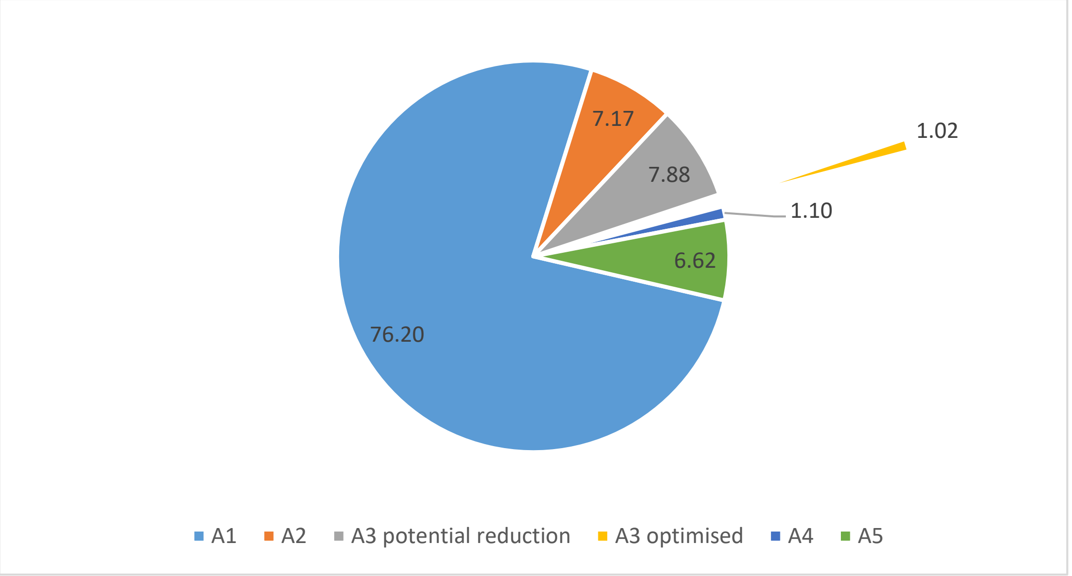

Figure 5.6 Theoretical phase A3 optimised emissions

5.5.4 Optimising phase A4

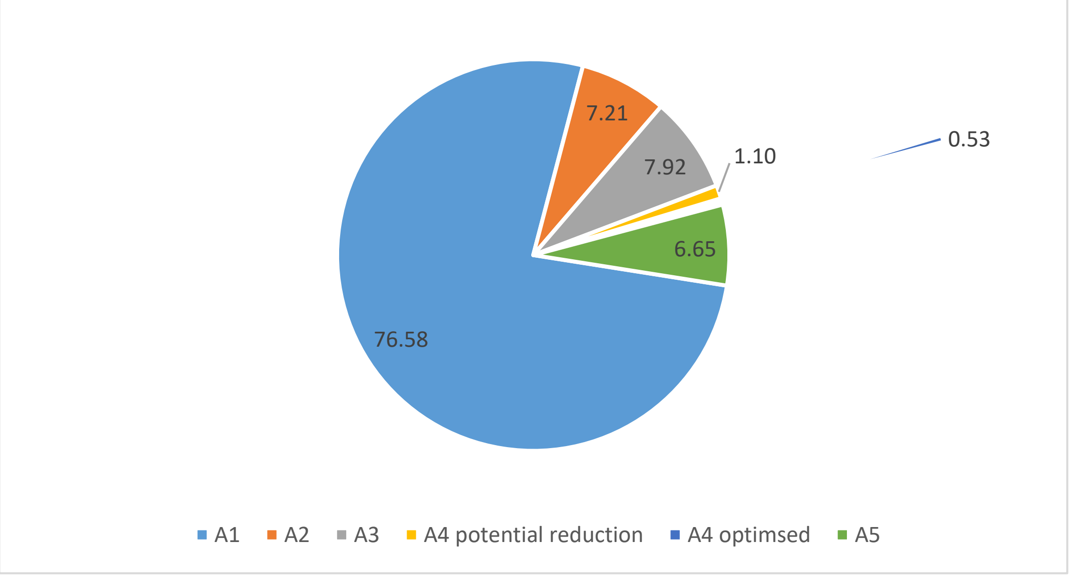

Figure 5.7 Theoretical phase A4 optimised emissions

5.5.5 Optimising phase A5

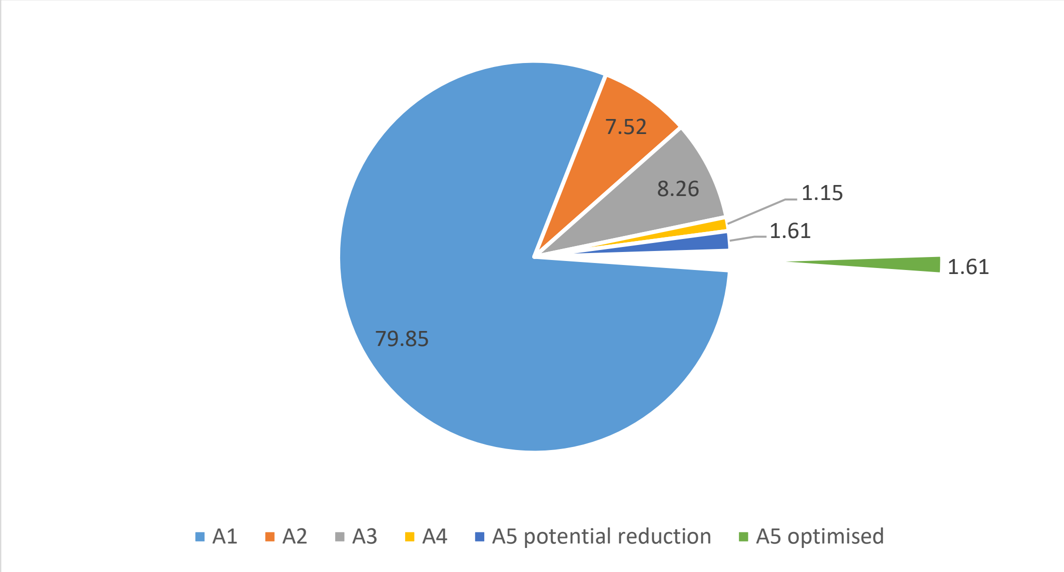

Figure 5.8 Theoretical phase A5 optimised emissions

5.6 Comparison to CLT and concrete

Research comparing emissions from concrete and CLT was conducted in the university of Washington in 2019. The thesis evaluates the life cycle CO_2 emissions for a hybrid cross-laminated timber (CLT) structure compared to a traditional reinforced concrete building, focusing on emissions at each phase of production, construction, and total CO_2 storage potential. [6]

The comparative analysis reveals that the hybrid CLT building design achieves a 26.5% reduction in Global Warming Potential (GWP) compared to a concrete building. Two types of CLT solutions were analysed, differing in the fireproofing method. Replacing gypsum wallboard fireproofing with a charring design in CLT structures reduces impacts across all categories, demonstrating that an added CLT layer has a lower environmental impact than gypsum. The CLT building shows embodied carbon emissions of 334 kg CO_2 with fireproofing and 328 kg CO_2 with charring per square meter, compared to 450 kg CO_2 for concrete. When translating these figures to kg of CO_2 per kg of material, the figures are as follows: 2.07 kg CO_2 per kg of concrete, 4.21 kg CO_2 per kg of CLT (fireproofing method) and 2.03 kg CO_2 per kg of CLT (charring method). As these numbers reveal, in terms of CO_2 emissions per kg, steel in this case project is 13% more emissive than concrete, 80% less emissive than fireproofed CLT and 15% more emissive than charred CLT. But the important aspect to note here, is that a CLT load bearing system has a much smaller total mass than a steel load bearing system. For example, a 1 m³ section of CLT would weigh approximately 500 kg, whereas the same volume of steel would weigh 8000 kg, creating a difference of 16 and the density of concrete is 2400 kg/m^3, creating a difference of 3.33 times when compared to steel.[6]

To understand the practical implications of material usage in construction, it is essential to consider emissions on a volumetric basis using this formula 5.4.

$$CO_2(kg/m3) = CO_2/kg_{material}(kg) * \rho_{material} \quad (5.4)$$

Concrete has a density of 2,400 kg/m³, translating to 4,968 $kg/m3$ of CO_2

Steel has a density of approximately 8,000 kg/m³, translating to 18,720 $kg/m3$ of CO_2

CLT, has a density of 500 kg/m³, translating to 2,105 $kg/m3$ of CO_2 (using charring for fireproofing) and 2,655 $kg/m3$ of CO_2 (using gypsum-based fireproofing).

These results reveal that, when emissions are calculated per cubic meter, CLT demonstrates a much lower environmental impact relative to steel and concrete. Concrete is 73.5%, CLT (charred method) 88.8% lower and CLT (gypsum method) 85.8% lower than steel.

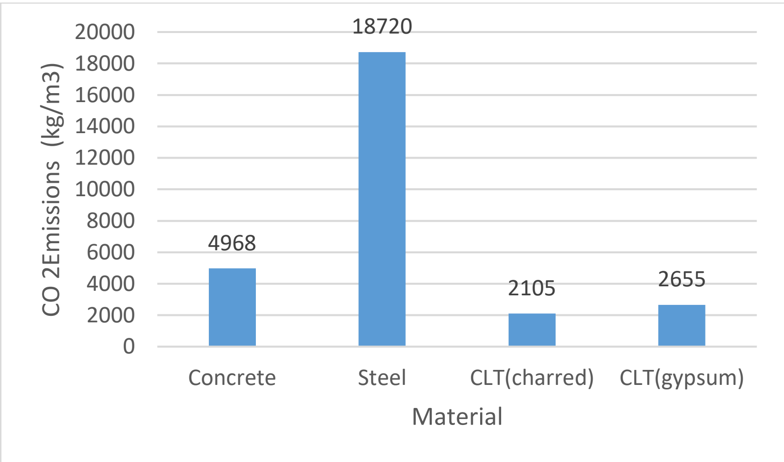

Figure 5.9 CO2 per m^3 emission comparison between load-bearing materials

Research from the Edinburgh Napier University examined environmental impacts associated with CLT, concrete and steel in construction. The three materials were examined in the context of a multi-storey building construction. A major finding of this study is the significant difference in material mass across the three structural systems. Concrete frames are found to be approximately five times heavier than timber frames and 50% heavier than steel frames for comparable structural designs. The main finding of this research was that timber frames have the lowest median emissions, at 119 kg of CO_2 per m^2, followed by concrete at 185 kg of CO_2 per m^2, and steel at 228 kg of CO_2 per m^2. [65]

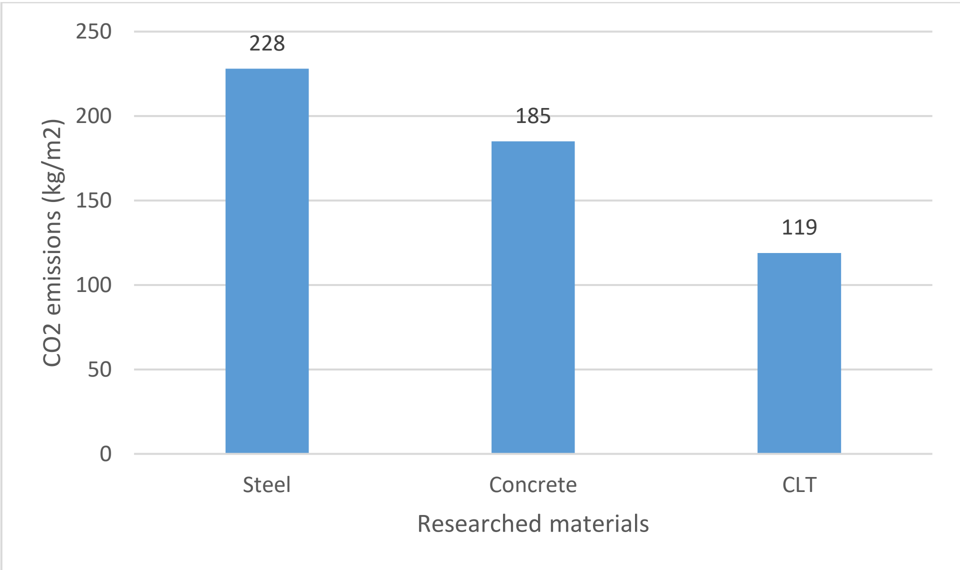

Figure 5.10 Comparison of CO2 emissions from steel, CLT and concrete

University of Washington found that steel is 73% more emissive than concrete and 86%-89% more emissive than CLT. Edinburgh Napier University findings indicate that steel produces 19% more emissions than concrete and 48% more than CLT. The 2 researches follow a similar trend of steel producing high amounts of CO_2 compared to concrete and CLT.

6. DISCUSSION OF FINDINGS

6.1 Comparisons to previous research

The findings from this study highlight the substantial carbon footprint of construction steel within the Estonian context, with a total estimated CO_2 emission of 218591 kg for the selected project. Which is 2.35 kg of CO_2 per kg of steel used. This total is divided across different life cycle phases, including raw material extraction(A1), transportation(A2), production(A3), and assembly(A4-A5). The most significant contributor to these emissions is the raw material extraction and initial refinement phase (A1), responsible for approximately 76.57% of the total emissions. This result aligns with previous studies, such as the work by the Institute of Energy and Petroleum Engineering, which emphasised that traditional Blast Furnace-Basic Oxygen Furnace (BF-BOF) processes are particularly carbon-intensive due to the heavy reliance on fossil fuels during steel production. Similarly, the International Energy Agency noted that BF-BOF processes are among the leading contributors to industrial CO_2 emissions globally. In the case of this thesis, the steel was sourced from a combination of European suppliers, with transportation emissions being a smaller yet notable factor, with phase A2 adding 7.21% to the total. [33]

The contribution of the production stage (A3) was relatively moderate, comprising 8.37% of the total CO_2 emissions. This percentage included producing steel elements, transporting them to the coating facility and the coating process. These findings are consistent with findings from The University of Surrey which observed that the emissions during the production stage are primarily influenced by the electricity mix used in manufacturing. In countries like Estonia, where oil shale still dominates the energy grid, with 62%, this stage has a higher carbon intensity. Estonia's reliance on oil shale for electricity generation impacts these figures, as a greener energy mix could potentially reduce emissions during steel production and assembly. For example, 1 kW of energy from oil shale generates 1 kg of CO_2 emissions, while wind generates 0.011 kg of CO2 per kW produced, representing a 98.9% difference. [57], [60], [66]

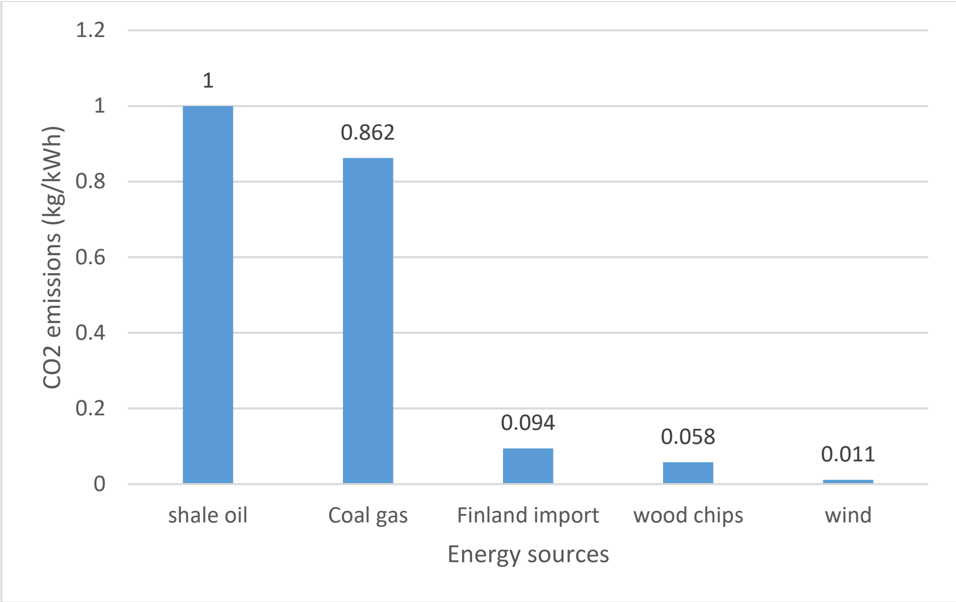

Figure 6.1 CO2 emissions from different energy sources

Study from the Graz University of Technology also corroborate these findings, demonstrating that regions with renewable energy sources such as Sweden or Norway report significantly lower emissions during the production of steel due to their greener electricity grids.[2]

The transportation of steel elements to the construction site, calculated in Phase A4, resulted in a total emission of 2410 kg of CO_2 for the selected project. This includes both the trips to the site and the return journeys with lower load factors. The transportation phase contributes a relatively small percentage of 1.10% to the overall carbon footprint. These findings align with previous research which has shown that road transport, especially over long distances, contributes to the carbon footprint of construction projects. For example, a study from Minho University demonstrated that road transport is generally more carbon-intensive than alternative methods such as rail or sea freight, which emit far fewer grams of CO_2 per tonne-kilometre. In the context of this project, using trucks for long-distance transport increased emissions, especially considering that steel is a heavy material, which further strains fuel efficiency.[23]

The assembly stage (A5), which includes diesel-powered machinery and electric equipment, was the next source of emissions, contributing approximately 6.75% of the total. This finding is in line with research conducted by Mid Sweden University, which highlighted that construction machinery contributes significantly to overall CO_2 emissions, especially in large-scale projects where operations extend over longer periods. Furthermore, University of Michigan found that emissions from on-site activities, such as welding and the use of heavy machinery, can contribute up to 20% of a building's total carbon footprint, supporting the conclusions drawn in this study. [37], [67]

In the case of optimising each phase in terms of emissions, the total CO_2 emissions came down to 43579 kg, making it 175012 kg less than the real emissions from the project. This marks an 80% decrease in the total emissions. These calculations prove that through a total system overhaul and massive infrastructure development, an environmentally friendly way of producing construction steel can be achieved. This requires a great sum of investments to the production industry and a greater planning of logistics. When cutting down on emissions, the total cost and construction times tend to increase. For example, transporting materials by ships from Italy to Estonia takes longer than transporting the same materials by trucks. Additionally acquiring all of the required EAF machinery requires high amounts of investments. Europe is slowly moving towards a more environmentally sustainable production network, with more and more EAF production facilities appearing all around the continent. These infrastructure changes take time, and it is up to the EU to keep the emission regulations and plans in place.[68], [69]

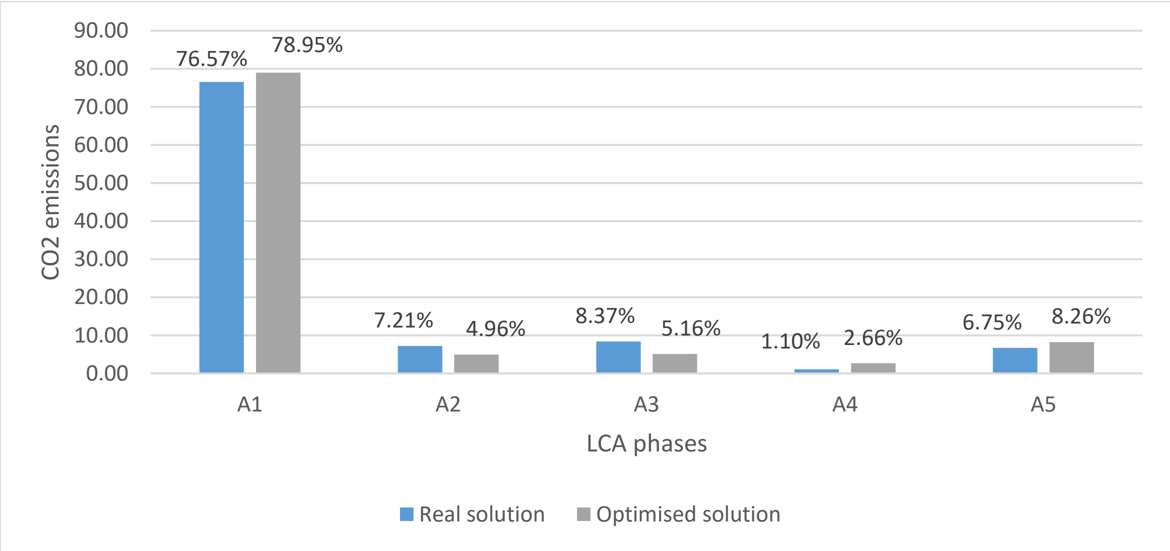

Figure 6.2 CO2 emissions in percentage comparison between real and theoretical solutions

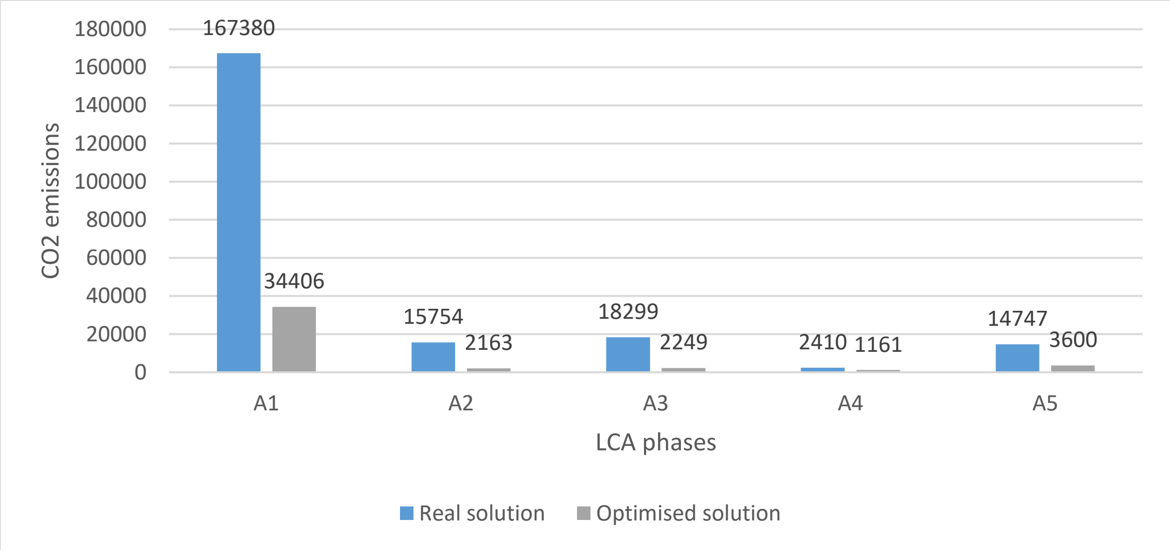

Figure 6.3 CO2 emissions in kg comparison between real and theoretical solutions

6.2 Suggestions for optimisation

One of the most immediate ways to reduce CO_2 emissions in construction is by selecting steel from sources that utilise low-emission production processes. Electric Arc Furnace (EAF) steel production, which relies heavily on recycled steel, generates far fewer emissions than the traditional BF-BOF process. As this study has shown, sourcing steel from countries with a greener energy mix, such as Sweden, where hydropower is widely used, could significantly reduce the carbon footprint of steel construction in Estonia. Additionally, increased use of recycled steel should be encouraged, aligning with the circular economy principles advocated by the European Commission.[2]

Another major area for improvement is the energy mix used in both the production and construction phases. Estonia's electricity grid, which is largely dependent on fossil fuels, contributes heavily to the emissions from processes like steel cutting, welding, and coating. A shift towards renewable energy sources for these processes could drastically cut emissions. Moreover, adopting hydrogen-based steel production, as explored in Lund University, could further lower emissions by up to 95%. However, implementing such technologies would require significant investment and policy support at the national level.[30]

Transportation emissions, while not the largest contributor, present opportunities for optimisation. Switching from road-based transport to rail or sea transport for steel elements, where feasible, could substantially reduce emissions, particularly for long-distance imports. Minho University calculated that sea transport emits only 3-10 grams of CO_2 per tonne-kilometre, compared to road transport which generates up to 120 grams per tonne-kilometre. [23]

On-site operations, particularly the use of diesel-powered machinery, also present an area for optimisation. Reducing machinery operation times, transitioning to electric-powered equipment, or using biodiesel could mitigate the emissions impact during the assembly phase. Research from Mid Sweden University suggested that careful planning and optimisation of construction logistics could reduce machinery-related emissions by up to 15%. [37]

7. CONCLUSION

7.1 Summary

This thesis focuses on quantifying CO_2 emissions associated with construction steel production and use in Estonia, Life Cycle Assessment (LCA) methodologies to evaluate environmental impact. Estonia's construction sector, a substantial contributor to national greenhouse gas (GHG) emissions, is faced with environmental challenges due to its reliance on fossil-fuel-intensive production methods. This study particularly evaluates the CO_2 emissions of an actual steel-framed warehouse/office project in Estonia, analysing data across all phases of steel's lifecycle—raw material extraction, manufacturing, transportation to Estonia, further production in Estonia, and on-site assembly. The phases researched are A1 - A5.

Key findings from the research underscore the high carbon footprint associated with construction steel, where the bulk of the emissions, 76.57%, comes from material extraction and initial manufacturing in phase A1. This phase takes place outside of Estonia in other European countries. In terms of this case study project, 92% of the steel imported is manufactured using the BOF method, which results in higher CO_2 emissions. 1.8 kg of CO_2 is emitted per kg of steel in this phase. BOF method is predominantly used due to its economic efficiency and simplicity, as it relies on fossil fuels and there is no need for recycled steel.

The rest of the phases account for 23.43%, with phase A2(material import to Estonia) contributing 7.21%, phase A3 (steel detail manufacturing and coating), contributing 8.37%, phase A4 (transportation to construction site), contributing 1.10% and Phase A5 (assembly process) contributing 6.75%. As shown figure 5.1.

When optimising each LCA stage, it is possible to bring down the emissions by 80% according to the examples and calculations brought out in this thesis. Though this production overhaul would require copious amounts of investments and a more precise system for planning each project and each LCA phase. The results are brought out on figure 5.3.

As the comparisons to different load bearing materials show, steel is the highest pollutant out of concrete, steel and CLT according to two different researches. With the emissions being 73.5% lower for concrete, 85.8% to 88.8% for CLT when compared to structural steel on a cubic meter basis when compared to findings from Delft University of Technology. Edinburgh Napier University concludes that steel produces 19% more CO_2 emissions than concrete and 48% more CO_2 than CLT. [64] [65]

But the emission difference does not mean that steel should instantly be replaced by CLT in every scenario, as each material has unique qualities and therefore specific uses. Steel is prized for its exceptional tensile strength, durability, and flexibility, allowing for tall and slender structures with complex designs. It can withstand high loads and is ideal for structures such as skyscrapers or bridges. Concrete, offers remarkable compressive strength and versatility, making it the main material in foundations, floors, and load-bearing walls. Its fire resistance, durability, and capacity for mass production make it ideal for infrastructure projects. Meanwhile, CLT is a renewable and lighter alternative, boasting natural carbon storage and energy efficiency. CLT is easy to work with, offers high strength-to-weight ratios, and provides aesthetic warmth and acoustic insulation, making it popular in mid-rise buildings and sustainable construction projects. CLT, though strong for timber, does not match steel's strength and would require significantly larger sections to support equivalent loads, which isn't practical at large scales. In addition, CLT is less resistant to weather and fire resistance.

7.2 Recommendations for industry practice

Implementation of Electric Arc Furnace (EAF) Technology: Increasing the adoption of EAF methods in, supported by a more circular economy approach to recycling steel, could drastically reduce CO_2 emissions in construction. EAF technology, especially when combined with renewable energy sources, can cut emissions by up to 75% compared to BF-BOF processes. However, policy and industry incentives are essential to stimulate investment in EAF infrastructure and facilitate a reliable supply of scrap steel.

Transition to Renewable Energy: The study emphasises that a shift from oil shale—currently a dominant energy source in Estonia—to renewables in electricity generation could reduce emissions from both steel production and on-site assembly. Renewable energy sources, such as wind and hydropower, generate minimal CO_2 emissions, compared to oil shale's 1 kg of CO_2 per kW produced. The research advocates for national energy policy adjustments to incorporate greater renewable sources, especially as the EU Green Deal mandates a 2050 climate neutrality target.

Optimised Logistics: Employing low-emission transportation methods for raw materials and steel products—such as rail and sea transport instead of road—can significantly reduce transportation emissions, which currently contribute 8.36% of the total project emissions. Rail and sea transport are far less emissions-intensive than road transport. Additionally, optimising routes and consolidating loads could further minimise emissions from transportation.

For construction sites, prioritising electric or hybrid machinery and reducing diesel usage is recommended. Additionally, efficient scheduling and reduction of idle times for machinery can cut emissions. Strategic planning in equipment usage during peak construction phases can decrease emissions from the assembly phase, which accounts for over 6.69% of total project emissions. Using electric-powered lifts and cranes, where feasible, could yield substantial emissions reductions in projects with high steel demands.

7.3 Recommendations for further research

To expand on the findings of this study, further research could explore alternative energy sources for steel production in Estonia, such as integrating renewable energy into the steel manufacturing process to reduce carbon dependency on fossil fuels. Conducting a case study on a project, for which steel is sourced from only EAF facilities and manufactured in Estonia using green energy such as wind or solar could put into perspective the effects of green policies and green energy. Additionally, examining the lifecycle emissions of other construction materials like concrete, Cross-Laminated Timber (CLT), and innovative composites in Estonia could provide a comparative analysis to guide more sustainable material choices within Estonia’s construction sector.

The cost implications of CO_2 emissions reduction measures are multifaceted, affecting both upfront investments and long-term savings. Transitioning to low-carbon technologies, such as renewable energy integration, carbon capture and storage, or advanced manufacturing processes, would require significant initial capital expenditure. For steel production, implementing Electric Arc Furnaces powered by renewable energy or transitioning to hydrogen-based production can incur high costs in infrastructure development and energy supply adjustments. However, these investments can lead to reduced operational costs over time. In addition to operational costs, regulatory frameworks, such as carbon pricing and emissions trading systems, further impact costs, potentially incentivizing early adopters. Companies that proactively implement emissions reduction measures may also gain a competitive advantage through enhanced market appeal and compliance with emerging sustainability standards, offsetting some of the upfront costs.

8. KOKKUVÕTE

Käesolev magistritöö keskendub Eestis ehitusterase tootmise ja kasutamisega seotud CO_2 saaste arvutamisele, kasutades elutsükli hindamise (LCA) metoodikat keskkonnamõjude hindamiseks. Eesti ehitussektor, mis on märkimisväärne riikliku kasvuhoonegaaside emissioonide tekitaja, seisab silmitsi keskkonnaalaste väljakutsetega, sõltudes fossiilkütustemahukatest tootmismeetoditest. Antud uurimistöö analüüsib eelkõige reaalse Eestis asuva terasraamil lao- ja büroohoone projekti CO_2-heitmeid, uurides andmeid terase elutsükli faasides—alates tooraine kaevandamisest ja tootmisest kuni transpordini Eestisse, edasise töötlemise ja ehitusobjektil monteerimiseni. Uuritud on LCA A1 kuni A5 etappe.

Uuringu põhitulemused rõhutavad ehitusterase kõrget süsinikujalajälge, kus suurem osa emissioonidest (76.57%) pärineb tooraine kaevandamisest ja esmase tootmise faasist A1. See faas toimub väljaspool Eestit, teistes Euroopa riikides. Selle juhtumiuuringu raames on 92% imporditud terasest toodetud BOF-meetodil, mis põhjustab kõrgemaid CO_2-heitmeid võrreldes EAF meetodiga. Selle faasi saastekogus on 1.8 kg CO_2 ühe kilogrammi terase kohta. BOF-meetodit kasutatakse peamiselt majandusliku efektiivsuse ja lihtsuse tõttu, kuna see tugineb fossiilkütustele ega nõua terase taaskasutust.

Ülejäänud faasid moodustavad kokku 23.43%, millest A2 (materjali import Eestisse) panustab 7.21%, A3 (terasdetailide tootmine ja katmine) 8.37%, A4 (transport ehitusplatsile) 1.10% ja A5 (monteerimisprotsess) 6.75%. Need tulemused on esitatud graafikul 5.1.

Optimeerides iga LCA faas, on võimalik heitkoguseid vähendada kuni 80%, mida väljendavad käesolevas töös toodud näited ja arvutused. Selline tootmise ümberkorraldamine nõuab suuri investeeringuid ja põhjalikku süsteemi iga projekti ja iga LCA-faasi planeerimiseks. Tulemused on esitatud joonisel 5.3.

Võrdlused erinevate kandevkonstruktsioonide materjalidega näitavad, et teras on suurim saastaja betooni, terase ja CLT (ristkihtpuit) vahel kahe erineva uuringu kohaselt. Leidude põhjal on emissioonid betoonil 73.5% madalamad ning CLT-l 85.8% kuni 88.8% madalamad kuupmeetri kohta võrreldes terasega Delfti Tehnikaülikooli uuringus. Edinburghi Napieri Ülikool järeldab, et teras toodab 19% rohkem CO_2 kui betoon ja 48% rohkem kui CLT. [64] [65]

Siiski ei tähenda emissioonide erinevus, et teras tuleks igas olukorras koheselt CLT-ga asendada, kuna igal materjalil on unikaalsed omadused ja spetsiifilised kasutusvaldkonnad. Teras on hinnatud oma erakordse tõmbetugevuse, vastupidavuse ja paindlikkuse poolest, võimaldades ehitada kõrgeid ja saledaid struktuure keeruliste disainidega. See suudab taluda suuri koormusi ja on ideaalne pilvelõhkujate või sildade ehitamiseks. Betoon seevastu pakub suurepärast survekindlust ja mitmekülgsust, muutes selle peamiseks materjaliks vundamentide, põrandate ja kandevate seinte jaoks. Selle tulekindlus, vastupidavus ja võime massiliseks tootmiseks muudavad selle ideaalseks infrastruktuuriprojektideks. Samal ajal on CLT taastuv ja kergem alternatiiv, pakkudes looduslikku süsiniku sidumist ja energiatõhusust. CLT on lihtne töötlemiseks, pakub suurt tugevuse ja kaalu suhet ning annab esteetilist soojust ja akustilist isolatsiooni, mis muudab selle populaarseks keskkonnasõbralike ja keskmise kõrgusega hoonete puhul. Kuid CLT, kuigi tugev puidu kohta, ei vasta terase tugevusele ja vajaks samade koormuste kandmiseks oluliselt suuremaid ristlõikeid, mis pole suuremahulistes projektides praktiline. Lisaks on CLT vähem vastupidav ilmastiku ja tulekindluse poolest.

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10. APPENDIX

Appendix 1: Alternative methods ferry logistics routes

Poland: Gdansk harbour – Muuga harbour, 600 km

Italy: Venice harbour – Muuga harbour, 8900 km

Denmark: Grenaa harbour – Muuga harbour, 1180 km

Czech Republic: Hamburg harbour – Muuga harbour, 1500km

Turkey: Istanbul harbour – Muuga harbour, 9400 km

Appendix 2: Alternative methods train logistics routes

Poland: Warsaw (Poland) – Bialystok (Poland) – Kaunas (Lithuania) – Riga (Latvia) – Tallinn (Estonia) – Muuga Harbour (Estonia), 1200 km

Italy: Milan (Italy) – Verona (Italy) – Innsbruck (Austria) – Munich (Germany) – Berlin (Germany) – Warsaw (Poland) - Bialystok (Poland) – Kaunas (Lithuania) – Riga (Latvia) – Tallinn (Estonia) – Muuga Harbour (Estonia), 2800 km

Denmark: Copenhagen (Denmark) – Malmö (Sweden) – Stockholm (Sweden) – Ferry to Tallinn (Estonia) – Muuga Harbour (Estonia), 1200 km

Czech Republic: Prague (Czech Republic) - Warsaw (Poland) - Bialystok (Poland) – Kaunas (Lithuania) – Riga (Latvia) – Tallinn (Estonia) – Muuga Harbour (Estonia), 1500 km

Turkey: Istanbul (Turkey) – Sofia (Bulgaria) – Bucharest (Romania) – Budapest (Hungary) – Bratislava (Slovakia) - Warsaw (Poland) - Bialystok (Poland) – Kaunas (Lithuania) – Riga (Latvia) – Tallinn (Estonia) – Muuga Harbour (Estonia), 3800 km