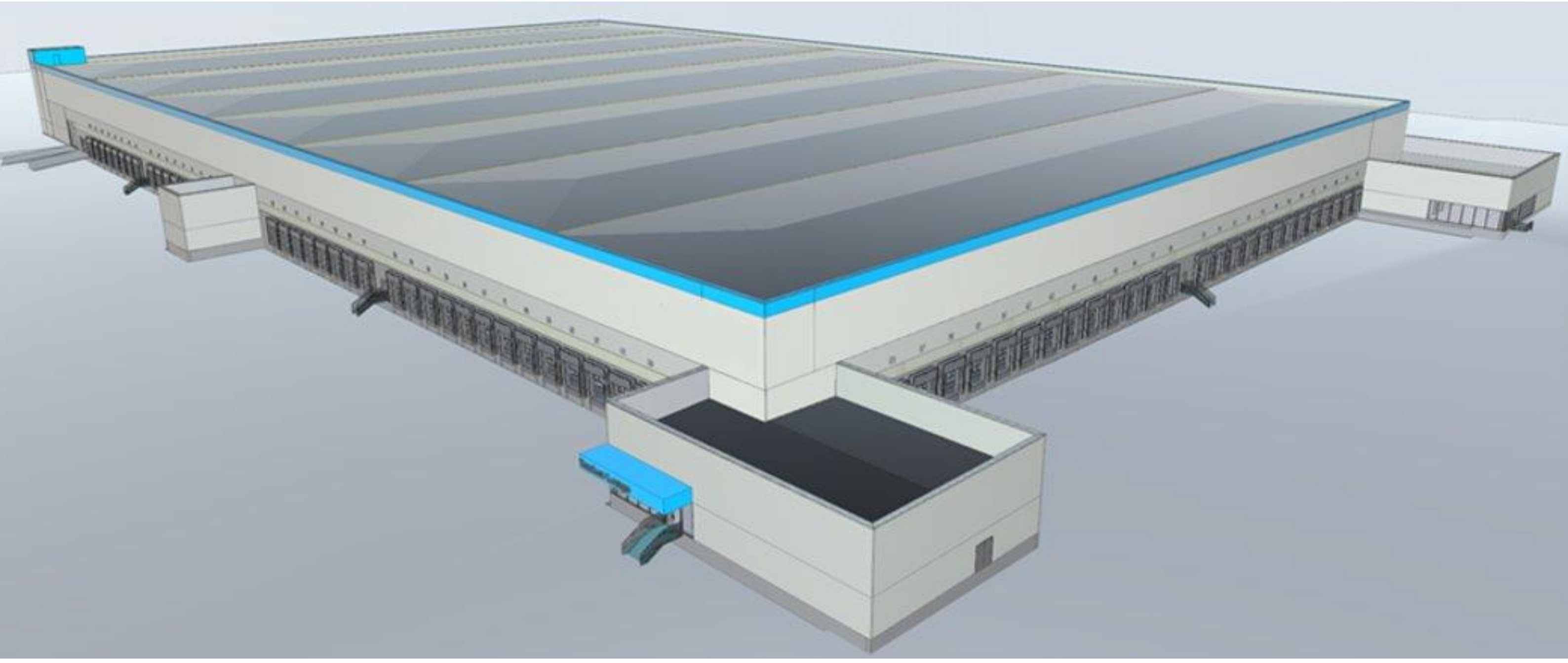
Master Thesis

Exploring the impact of the EU ETS allowance price on sustainable construction: a Dutch case study

Exploring the relation between the allowance price and the affordability of a wooden structure compared to conventional structures out of steel and concrete for a large distribution centre



Rinke de Jonge

March 2022

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By

R. J. de Jonge - 4383273

Master Construction Management and Engineering

Faculty of Civil Engineering and Geosciences

Delft University of Technology, The Netherlands

Graduation Committee:

Chair: Prof. Dr. Hans Bakker

TU Delft Supervisor: Dr. Ir. Martine van den Boomen

TU Delft Supervisor: Dr. Arjen Meijer

RH-DHV supervisor: Rudolf Scholtens

RH-DHV supervisor: Quirine Henry

Graduation company:

Royal HaskoningDHV - Amsterdam

Preface

This thesis has been written to finalise my master Construction Management and Engineering (CME). The CME master's programme made me interested in the possibility to create valuable business cases for sustainable choices within the construction sector. I am very happy that I was able to explore this topic within my thesis research, and I hope to learn more about this topic in the future.

I would like to thank my graduation committee members Hans Bakker, Martine van den Boomen and Arjen Meijer. Firstly, I would like to thank Hans Bakker for his leadership and focus on the end product. Secondly, I would like to thank Martine van den Boomen for her great willingness to provide feedback and her ability to create a friendly work environment. Thirdly, I would like to thank Arjen Meijer for his green view and knowledge about the LCA method.

I also want to thank Rudolf Scholtens and Quirine Henry from Royal HaskoningDHV for their support and advice during all the supervision sessions and the connections that they provided for me within the company. I want to thank Rudolf Scholtens for his excellent overview to identify the missing elements and improve the report's structure. I want to thank Quirine Henry for sharing her extensive knowledge about sustainability and everything related to this topic.

Lastly, I want to thank my girlfriend, family and friends for the support during my graduation process. The support helped me a lot to keep focusing and working for the end goal, although major events like the pandemic and the Ukrainian invasion had a big impact on me in the last six months.

I am very happy that I was able to carry out this research with the goal to improve sustainability in the construction sector, and I hope I can keep contributing to this goal in the future.

Rinke de Jonge

April 15 2022, Amsterdam

Executive summary

The global population is growing rapidly, so the construction sector must keep up by increasing the number of houses and improving the infrastructure. The construction sector is importance to support economic growth and social development within society. However, the conflict that arises here is that the activities of the construction sector are also responsible for a tremendous amount of greenhouse gas (GHG) emissions. This makes the construction sector a key player in the fight against global warming and its consequences. The construction sector can help reduce its emissions and slow down global warming by constructing more sustainable. Sustainable construction minimises the impact on the environment and assures safety and comfort while a financial profit is made. However, the most significant barrier to the implementation of sustainable construction is the affordability of sustainable projects. Sustainable construction often results in higher costs than conventional construction methods, which slow down the return on investment for the project owner. That is why the construction sector often sticks to its conventional construction behaviour.

In 2005, the European Union (EU) introduced the emissions trading system (ETS). The ETS is a policy measure aimed to lower the European emissions by letting the polluter pay for its emissions of GHGs. This policy measure could help overcome the barrier of affordability towards implementing sustainable construction. This research aims to find the ETS allowance price tipping point that financially stimulates the use of natural construction materials like timber over conventional materials like steel and concrete. The tipping point could stimulate the implementation of sustainable construction and help to slow down global warming. The report answers the research question:

“What is the European Union Emissions Trading System allowance price tipping point for a profitable business case for a timber constructed structure over a steel or concrete constructed structure in the Dutch built environment?”

To answer this research question, multiple steps have been executed. In the first step, a literature study presents the input for the rest of the research. In the second step, a theoretical framework is created and used as input to research the relation between the EU allowance price and the change in the steel and cement market price. In the third step, a life cycle analysis is performed on the selected case study to calculate the levels of embodied carbon for a steel, concrete and timber structural design of equal quality. In the fourth step, a costs analysis calculates the total realisation costs of the three structural designs. In the last step, the results of the second, third and fourth steps are combined to find the EU allowance price that results in the lowest total realisation costs for the most environmentally friendly design.

The research results showed that an ETS allowance price of € 7.174,54 makes the timber design besides the most environmentally friendly also the most affordable design under the expected market conditions. A maximum rise in the demand for steel and cement could bring the tipping point down towards an allowance price of € 4.864,43, while a maximum drop in the demand could lead the tipping point up towards an allowance price of € 13.746,36.

The results show that the allowance price could help lower the barrier of affordability because a higher allowance price increases the market price of carbon-intensive construction materials like steel and concrete. However, the found allowance price tipping point is unlikely to occur based on the current allowance price of around € 85. Therefore, the current ETS can be considered helpful but not decisive towards a financial favourable timber structure for buildings in the Dutch built environment.

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Abbreviations

BM = Benchmark Value

CLEF = Carbon Leakage Exposure Factor

CSCF = Cross Sectoral Correction Factor

ETS = Emissions trading system

EU = European Union

EUA = European allowance

GHG = Greenhouse gas

HAL = Historic Activity Level

PTR = Pass-through ratio

SQ = Sub question

1. Introduction

The activities of humankind have a significant impact on the changes in the earth's atmosphere, ocean, biosphere, and cryosphere. This was one of the conclusions in the recently published IPCC report (2021). Human activities are responsible for the emission of greenhouse gases (GHG) like carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) into the atmosphere. These emitted gases trap heat in the earth's atmosphere and, therefore, increase global temperature. Since 1981, the earth's temperature has risen by an average of 0.18 degrees Celsius per decade, while the increase was only 0.08 degrees Celsius per decade since 1880 (Lindsey, 2021). This extreme increase in global temperature has a significant impact on life on earth. Rising sea levels because of melting arctic ice cause floods in low lying areas. More frequent occurrences of extreme heat and agricultural droughts will result in unliveable places for humans, more forest fires, more extreme cyclones, more destroyed food productions and extinction for many species (IPCC, 2021). Unfortunately, the speed of global warming will only increase if humans do not change their behaviour.

The construction sector delivers the infrastructure and buildings to society, which are fundamental for economic growth and social development. This makes the construction sector of great importance, but the construction sector is also one of the big emitters of GHGs. Energy use in buildings, manufacturing of materials, transportation of materials and the need for construction equipment are all sources of GHG emissions from the construction sector (Yan et al. 2010). The emissions from the construction sector are divided into embodied and operational emissions. Embodied emissions are emissions arising from the material extraction, processing, manufacture, transportation, construction, maintenance, and demolition of a building. Operational emissions are emissions arising during the operation of the building like lighting, heating, ventilation, and the use of equipment of a building (Ibn-Mohammed et al, 2013). In 2016, iron and steel production was responsible for 7.2 percent (3.55 billion tonnes $CO2_{eq}$) of the global GHG emissions and the cement industry for 3.0 percent (1.48 billion tonnes $CO2_{eq}$), which are both part of the embodied emissions. The energy use in buildings, which equals the operational energy usage, was responsible for 17.5 percent (8.65 billion tonnes $CO2_{eq}$) of the global GHG emissions in 2016 (Ritchie & Roser, 2020). A more sustainable way of construction needs to be introduced to ensure that economic growth and social development can occur while GHG emissions from the sector are reduced. Sustainable construction can be the solution. Sustainable construction is defined as 'what we build today will provide the built environment of the future and will influence the ability of future generations to meet their needs' (Dickie & Howard, 2000). However, sustainable construction is not implemented regularly because it comes with higher initial investment costs (Zhang et al, 2011). The higher initial costs from sustainable construction can be earned back over time by lower operational costs. However, these costs are in general for the company that rents the office or the family that buys or rents the apartment. The extra costs make it financial unfavourable for the project owner to construct the project sustainably.

The Kyoto protocol and later the Paris agreement were both introduced in the fight against global warming, but within these agreements' countries are not forced to set specific emission goals. It is difficult to guide countries into the proper reduction measures without a legally binding agreement. Governments can use policy as a tool to create that legally binding agreement. Extra policy could push the construction sector into a more sustainable sector. In 2005, the European Union (EU) introduced the carbon emissions trading system (ETS) as a policy measurement in the fight against CO_2 emissions. This measure limits the European carbon emissions by allocating several tradable European union allowances (EUA). The allowances are sold on the European carbon market and given away for free to large emitters of GHGs. The total number of allowances decreases every year, which stimulates companies to invest in green production methods or pay a higher price for their emissions. Although

Bayer & Aklin (2020) concluded that the EU ETS saved 1.2 billion tonnes of $CO2_{eq}$ between 2008 and 2016 (3.8%), many observers remain sceptical about the price and effectiveness of the ETS. The Organisation for Economic Cooperation and Development (OECD) (2018) stated that EUA prices were too low to incentivise polluters to reduce carbon emissions and increase investments in low carbon technology. Bayer & Aklin and the OECD both agreed that a higher EUA price speeds up the reduction of carbon emissions and can contribute to overcome the barriers to sustainable construction. Carbon intensive construction materials like concrete and steel could be substituted for low carbon materials like timber if carbon prices increase significantly. This could make sustainable construction the best option from a financial and environmental perspective, driving all project owners to contribute to a futureproof construction sector.

This report will explore how the EU ETS price can stimulate sustainable construction in the Dutch built environment. In cooperation with Royal HaskoningDHV, a case will be selected to explore the possibilities to substitute carbon-intensive materials for natural materials within the design of a building. The goal is to find the ETS allowance price tipping point where the use of low-carbon materials within the structure of a building becomes financially favourable over the use of conventional construction materials like steel and concrete. This would create a big incentive for the construction sector to become more sustainable, which helps to slow down climate change. This research consists of a few steps. The first step is to focus on how the ETS currently affects sustainable construction and what barriers against sustainable construction can be identified. The second step is to create a theoretical framework that supports the relation between the EU allowance price and the price for carbon-intensive structural materials. The third step is to use that framework to identify the relation between EU allowance price and the steel and cement prices. The fourth step is to use a case study to come up with multiple structural designs of equal quality, consisting of steel, concrete and timber and calculate the levels of embodied carbon for the different designs. The fifth step is to calculate the realisation costs for the different designs under the current conditions. The sixth and final step combines the previous steps. It seeks to find the EU allowance price tipping point where the natural building material becomes financially favourable over the conventional materials, while it also reduces the negative impact on the environment. This price tipping point is the point where sustainable construction becomes financially and environmentally favourable for the project owner. European and national policymakers can use the results as input for effective climate policy.

The research consists of ten chapters. The second chapter describes the research design of this study. The third chapter presents the literature review. The fourth chapter presents the theoretical framework that can be used to explore the impact of the allowance price on the price of steel and cement. The fifth chapter uses the framework to present the relation between the allowance price and the price of steel and cement. The sixth chapter presents the levels of embodied carbon for the different designs based on a life cycle analysis. The seventh chapter presents the realisation costs for the different designs based on a realisation costs analysis. The eight-chapter presents the results of the tipping point calculations. The ninth chapter presents the conclusion of this research, and the tenth chapter presents the discussion that reflects on the found results.

2. Research Design

The research design will be presented in chapter 2. The research design explains how the research is set up. Section 2.1 presents the problem statement for this research. Section 2.2 presents the scope of this research. Section 2.3 presents the research question. Section 2.4 explains the methodology for this research and section 2.5 introduces the case that will be used within this research.

2.1. Problem statement

Based on the introduction, the following problem statement can be formulated:

The construction sector is a big emitter of greenhouse gasses which contributes to the process of global warming. The implementation of sustainable construction can slow this process down, but the higher costs for the project owner makes it often an unfavourable solution. This makes the project owner stick to carbon-intensive materials like concrete and steel instead of selecting a natural material like timber. The European emission trading system tries to stimulate the transition to a more sustainable Europe by creating a financial incentive to lower emissions, but this has not changed the material selection process in the construction sector. Not yet has been investigated at what European allowance price the use of timber becomes environmentally and financially favourable for the structure of a building in the Dutch built environment.

This research has the objective to find the solution to deal with the problem above. This solution requires a European allowance price which makes the structural design with the lowest environmental impact also the least expensive design.

2.2. Research scope

This section presents the scope of this research. The scope defines the boundaries of this research and what it focuses on.

The study's main goal is to find the European Union allowance price that will stimulate sustainable construction in the Dutch built environment. This concerns the impact of the European Union's Emissions trading system on the price of the carbon-intensive structural construction materials concrete and steel. The relation between the European allowance price and the price for cement and steel will be based on the Dutch production market. The impact of the allowance price on the cement price will be passed on into the concrete price. The conventional materials steel and concrete will be compared to timber, which is the third structural construction material of global importance. The use of timber is expected to lower the impact on the environment. The impact on the environment will be measured by the level of embodied carbon. The embodied carbon levels will be calculated for the structure of the building because the structure contains the highest share of embodied carbon. The structure includes the floors, foundation, columns, beams, and load-bearing walls of the building.

This study does not include the impact of the European ETS on the price of timber. This is done based on two reasons. The first reason is that the production of timber does not happen in a carbon-intensive way and is therefore not directly influenced by the ETS system. The second reason is that the Netherlands is a big importer of timber, which means that the Netherlands does not influence any price changes because these happen outside the Dutch borders. That's why the European market price will be followed for the timber price. This study does also not include other parts than the structure, because this increases the number of different materials which lowers the effectivity to measure the impact of the three selected structural materials. Finally, the Dutch carbon emission tax is also not included in the project scope, because the Dutch carbon tax can be neglected in case of a higher EUA price, which is currently the case.

2.3. Research questions

The research objective of this report is to find the EUA price that stimulates construction with materials that have a low negative impact on the environment. The problem is translated into a research question that will be solved in this report. The main research question of this report is:

What is the European Union Emissions Trading System allowance price tipping point for a profitable business case for a timber constructed structure over a steel or concrete constructed structure in the Dutch built environment?

The answer to the main question can be formulated on the bases of the answers to the following sub-questions:

Sub-question 1 (SQ1): *What are the main barriers to sustainable construction and how does the European emissions trading system affect sustainable construction?*

Sub-question 2 (SQ2): *What theoretical framework supports the determination of the relation between the European Union allowance price and material prices of steel and cement?*

Sub-question 3 (SQ3): *What is the relation between the European Union allowance price and the material prices for steel and cement as structural building materials in the Dutch construction market?*

Sub-question 4 (SQ4): *What is the level of embodied carbon for the steel, concrete, and timber structural designs of the selected project?*

Sub-question 5 (SQ5): *What are the realisation costs for the steel, concrete, and timber structural designs of the selected project?*

This report has the goal to find a solution on how the EUA price can impact the speed of the transition to more sustainable constructed projects. The main research question is formulated to find an answer to this problem. In order to find an answer to the main question, multiple smaller sub-questions have to be answered to construct the answer to the main question. First, the main barrier against sustainable construction must be identified to be able to find an effective counter measure to overcome this barrier. SQ1 does also identify how the ETS currently affects sustainable construction. The second sub-question creates a theoretical framework that standardises the relation between the allowance price and the final market price for steel and cement. SQ3 will use this theoretical framework to investigate the relation between the EUA price and the final market price for construction materials steel and cement. SQ4 uses the selected case study to calculate the levels of embodied carbon for the different structural designs. This question can confirm which structural material creates the design with the lowest negative environmental impact. SQ5 calculates the realisation costs for the different designs. This question confirms which design is financially the most attractive and the least attractive under the current market conditions. By combining SQ3, SQ4 and SQ5 a model can be made to find the EUA price which makes the design with the lowest level of embodied carbon also the least expensive. This EUA price tipping point is the answer to the main research question.

2.4. Research methodology

The research methodology explains what methods are used to find the answers to the different sub-questions. By combining the sub-question answers, an answer to the main research question can be formulated. This research exists out of five different sub-questions which are explained in the previous section and for all questions an explanation will be given on how the data will be sampled, how the data will be analysed and how the results will be validated. A method overview for the different questions is given in table 2-1. The first two sub-questions use qualitative methods to find their answers while sub-questions three, four and five use quantitative methods to find answers, so this study is a mixed-method study.

Table 2-1: Research method per sub-question

	SQ1	SQ2	SQ3	SQ4	SQ5
Data sampling	Literature study	Literature study	Literature study	Case study	Case study
Data analysis	Problem analysis	Theoretical framework	Scenario analysis	Life cycle analysis	Costs analysis
Results validation	Use of scientific literature and reports of acknowledges institutions	Use of scientific literature and reports of acknowledges institutions	ETS expert validation	LCA expert validation	Construction costs expert

Research method sub-question 1

The first sub-question will explore the barriers to sustainable construction and how the EU ETS impacts sustainable construction. The data will be sampled by a literature study because a literature study is a great method to gather and structure the existing literature about sustainable construction and the impact of the ETS on sustainable construction. The existing literature will be analysed and processed into a problem analysis, which will help to get a clear view of the current barriers of sustainable construction and the impact of the ETS on sustainable construction. The answer clarifies the relevance of the research and helps to structure the problem for the rest of the research. The results of SQ1 will be validated by only making use of scientific sources posted on Google Scholar and scientific reports which are published by reliable sources like public institutions or reliable organisations. This should result in reliable data for the problem analysis.

Research method sub-question 2

The second sub-question will collect all the literature around the ETS to create a theoretical frame that can be used to address the relation between the EU allowance price and the price of the final good. The data for this framework will be sampled from a literature study because a literature study is again a useful method to gather and structure the existing literature about the ETS mechanism and answer the question. The existing literature will be analysed and processed into a theoretical framework which will be used as a basis to answer the third sub-question. The second sub-question will be validated just like SQ1. This is again expected to result in reliable input data for the theoretical framework.

Research method sub-question 3

The third sub-question will investigate whether there is a relation between the EUA price and the price for the construction materials concrete and steel and how that relation is built up. The necessary data will be sampled by using available literature which does carry some degree of authority and expert consultations where necessary and available. Dutch producers of concrete and steel are private companies that are in general not willing to share internal data about the impact of the ETS on their product prices and their pricing strategy because this could weaken their competitive position in the market. After studying the literature, a distinction will be made between variables with an exact value and variables with multiple possible values. The variables that have exact values will be kept constant throughout the scenarios, while multiple scenarios will be made for the possible values of the unknown variables. A range of possible input values is used to create an in-depth analysis of all the possible outcomes under different circumstances. This method has an exploratory nature. The base scenario of the scenario analysis will be based on the average values of all included variables. The other scenarios will be based on the existing literature about the minimum and maximum possible values for the unknown variables. The results will be analysed and processed in excel. SQ3 will be validated by the consultation of an ETS expert. This expert is well known of all the rules and regulations around the ETS and can check whether the executed steps are complete and done correctly.

Research method sub-question 4

The fourth sub-question will calculate the levels of embodied carbon for the different structural designs of the selected project. The levels of embodied carbon will be measured for steel, concrete, and timber design. The data will be sampled from a selected case study. The materials and quantities can be extracted from the Revit model of the project. The extracted list will be used as input for the Life Cycle Assessment (LCA) method to calculate the levels of embodied carbon for each design. This method can measure the environmental impact over a product's entire life cycle by expressing the impact in a standardised unit. This study focusses only on the 'global warming potential' (GWP) as a standard impact unit. This category is expressed in kgCO_2-eq, and it describes the change in surface temperature which is caused by an increased concentration of greenhouse gasses in the atmosphere. Other GHGs like methane and nitrous oxide are converted into the effect of carbon dioxide to get one single impact value for the GWP. This category is selected because this research explores the impact of the ETS on lowering the CO_2 emissions of the construction sector and the ETS measures emissions in the same unit expression as the GWP. Therefore, only the results of the GWP category contribute to find the answer to the main research question. Only including one impact category in the analysis resulted in this LCA becoming a so called 'limited LCA'. A full LCA includes all impact categories.

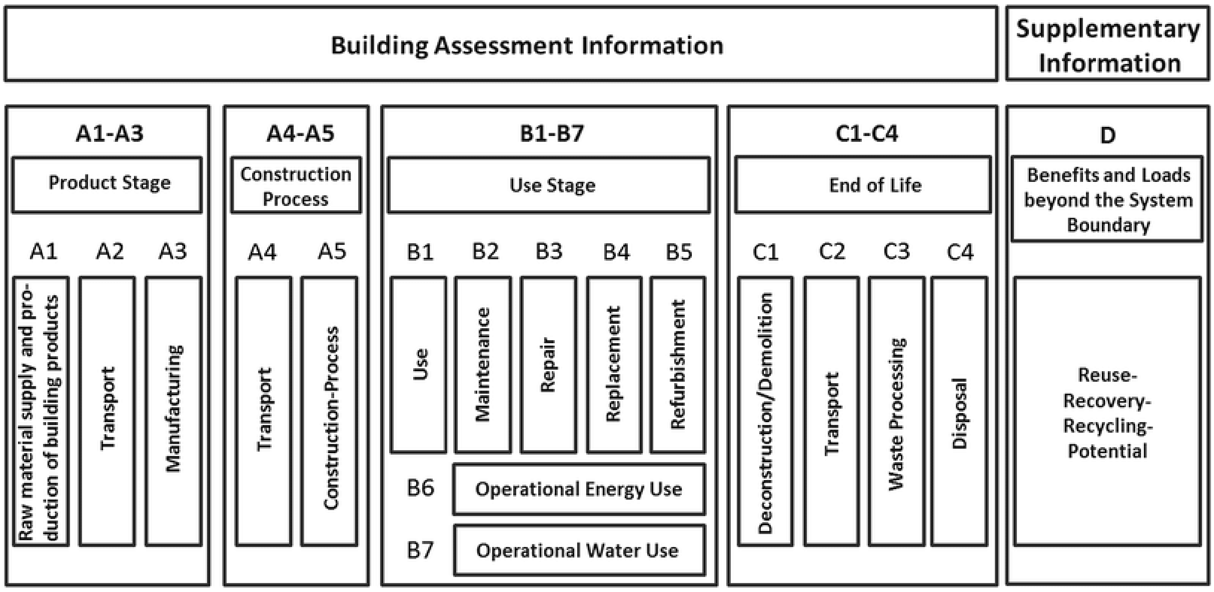

Figure 2-1: Overview of all life cycle assessment phases, EN15978 standard (Achenbach et al, 2018)

The stages and phases of a product's lifecycle are presented in figure 2-1. While this study only focuses on the levels of embodied carbon in the structure of the selected project, only the A1-A4 and C1-C4 phases will be included. A building's structure is assumed to be functional for at least 50-100 years, so this excludes the B1-B5 phases. A structure on its own doesn't tell much about the expected levels of energy and water consumption, so this excludes the phases B6 and B7. The D stage is also excluded because of the current debate of interpretation about this stage. For this stage is assumed that concrete can be fully recycled while timber cannot be recycled and is burned after use. This frames a very positive situation for concrete and very negative for timber usage while this is not the general vision on these materials.

The analysis will be performed with the help of an LCA tool, which is called One-click LCA. This tool can help to calculate the impact on the environment of a specific building. By entering the type and quantity of materials, this tool can help to calculate the level of a broad range of environmental impacts, amongst others embodied carbon for products based on the environmental information on products and activities from different environmental databases. All concrete, steel and timber volumes are expressed in m^3 as input to calculate the global warming potential. The analysis includes the life cycle phases of A1-A4 and C1-C4. The method of transport is kept on its default settings while the transportation distance is kept at its default value of 60 kilometres. This is average transportation distance for construction materials in the Netherlands according to One-click. The material manufacturing location is preferably set to the Dutch market as default production location, but the German market is used in the case that the Dutch market doesn't have the right product.

The LCA results will be validated by a review of an LCA expert. The LCA expert will check whether the LCA measures what it was designed to measure by checking if all the steps are included and if all the steps are executed in the right way.

Research method sub-question 5

The fifth sub-question will calculate the realisation costs for the steel, concrete, and timber structural designs of the selected project. The same list of materials and quantities as for SQ4 will be used to calculate the realisation costs for the different designs for SQ5. The costs will be calculated by using a costs analysis method. This method calculates the costs to realise the product which will be expressed in euros. The realisation costs will be calculated based on two costs components which are the material costs component and the installation costs component. The realisation costs will be calculated according to the costs calculations standards of Royal HaskoningDHV, which uses this standardised method to estimate the costs for a project that still has to be realised. The quantities for steel are expressed in kilo while the quantities for concrete and timber are expressed in cubic metres. The costs of concrete do vary per cubic metre. The stronger the concrete needs to be, the more expensive it will become. The realisation costs will be calculated and analysed in an excel model where the costs of the different project designs will be compared.

The fifth sub-question will be validated by the review of a cost expert. The costs expert will check whether the costs analysis measures what it was intended to measure by checking if all the steps are included and if all the steps are executed in the right way.

2.5. Case study

This research is executed in cooperation with Royal HaskoningDHV. Royal HaskoningDHV advises a client with their designs for a large distribution centre in Europe. The created designs are preliminary designs for a pan-European template. The contractor will adjust the template version to meet the requirements for the selected European location. A distribution centre is selected as a useful building type to compare the levels of embodied carbon because it has a purely functional use which comes with relatively low operational energy use and limited materials. This makes the share of embodied carbon relatively high compared to the total environmental impact over its entire life cycle and makes it easier to focus on the impact of one material.

Figure 2-2 displays the type of distribution centre which has been chosen. The building consists of three parts: the warehouse, the bump-outs and the office and welfare. The warehouse is the biggest part which covers the square in the middle of the building. This is marked by the red square in figure 2-2. This is the place where all the distribution activities take place. The bump-outs, sometimes called ancillaries, are the small blocks attached to two of the corners of the warehouse. This is marked by the 2 blue squares in figure 2-2. The bump-outs have the function to support the primary activity of product distribution, so this is the place where ICT, cleaning rooms and storage rooms could be located. The final part is the office and welfare part which is the rectangular part attached to one of the sides of the warehouse. This is marked by the green square in figure 2-2. The office and welfare part functions as office space contains toilets and has rooms for breaks.

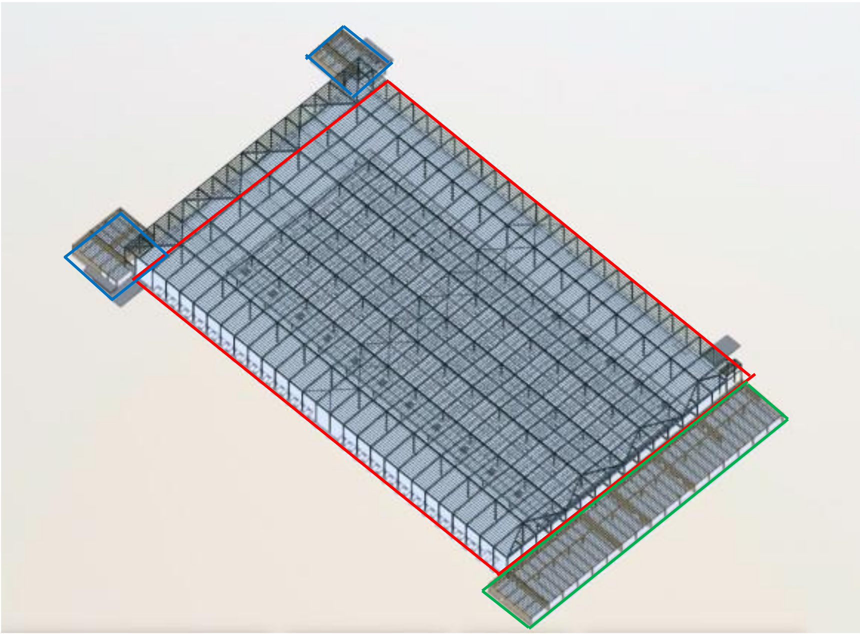

Figure 2-2: Overview of the 3D preliminary design of a large European distribution centre (Internal document Royal Haskoning-DHV,2020)

This distribution centre was selected as a suitable case to study because the office and welfare part of the building have been designed with a steel, concrete, and timber structure. The office and welfare part is selected as the scope instead of the entire distribution centre because the warehouse part could not meet the minimum safety standards for a distribution centre under a timber structure. The three selected structural designs for the office and welfare part are all of equal quality and safety due to the followed safety requirements of the client. But, the surface area size of the concrete design is slightly smaller compared to the steel and timber version. This difference exists because the concrete design was created before the client adjusted its design, so these adaptations have only been included in the more recent steel and timber structural designs. The concrete design has a surface area of 2.867,3 m^3, while the timber and steel designs have a surface area of 3.506,6 m^3, so the case study results of the concrete design will be compensated by a factor of 1,2229 to create an equal playing field for the different designs to be fairly compared with each other. The steel, concrete and timber designs for the office and welfare part are displayed in figure 2-3, 2-4 and 2-5.

Within the scope definition, the selection has been made to include the floors, foundation, columns, beams, and load-bearing walls of the building in the structure. In contrast to the steel design, do the concrete and timber designs contain load bearing walls, so that is why these two designs contain walls while the steel design does not.

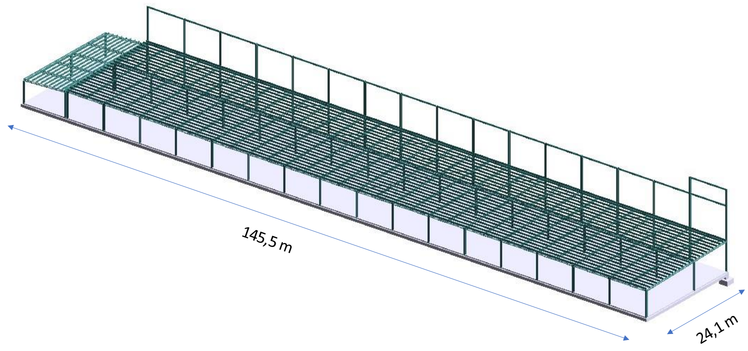

Figure 2-3: Steel structural design of the office and welfare (RHDHV internal document, 2020)

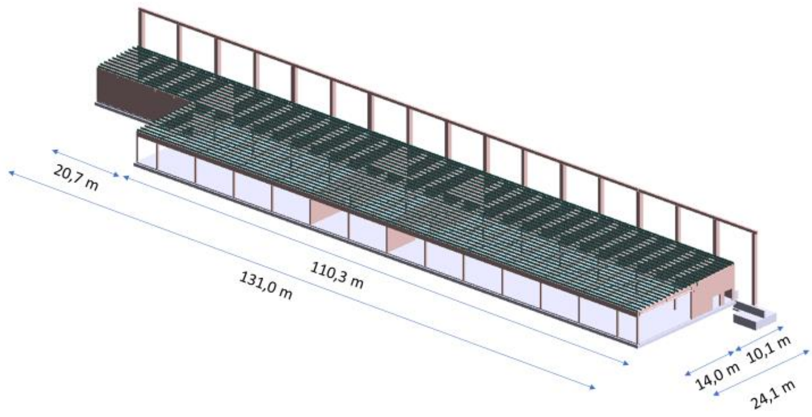

Figure 2-4: Concrete structural design of the office and welfare (RHDHV internal document, 2020)

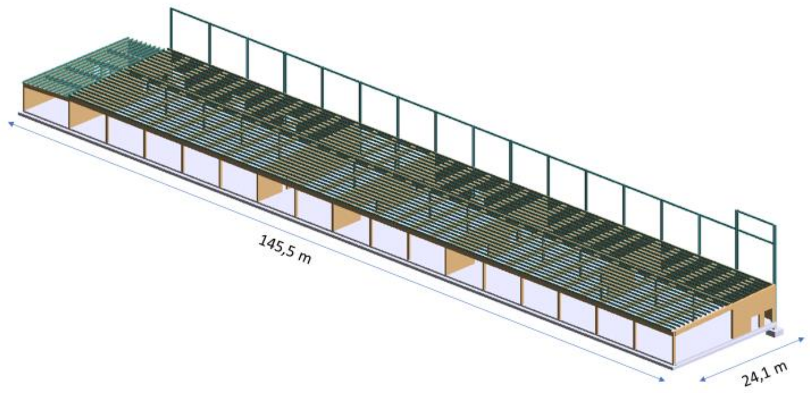

Figure 2-5: Timber structural design of the office and welfare (RHDHV internal document, 2020)

3. Literature review

A literature study is conducted in chapter 3 to answer the first sub-question: *What are the main barriers to sustainable construction and how does the European emissions trading system affect sustainable construction?* This literature study presents previous related research to get a better understanding of what is known and what is unknown about this topic. To answer this question, first, the definition of sustainable construction will be discussed in section 3.1. Once the definition is clear, the barriers against the implementation of sustainable construction will be identified in section 3.2. Section 3.3 will introduce the emissions trading system. Section 3.4 will discuss the evolution of the ETS. Section 3.5 will discuss the ETS impact on sustainable construction. Section 3.6 will summarize the findings of the literature review and form the answer to the first sub-question.

3.1. Sustainable construction

The construction sector must keep up with the growing global population by increasing the number of houses and improving infrastructure, but this increase in construction projects goes hand in hand with more human activities which result in more GHG emissions. Constructing our society more sustainable could help to reduce GHG emissions while still being able to develop as a society. Different definitions of sustainable construction are being used globally. This chapter shares the most important definitions of sustainable construction in current literature and the relation to sustainability and sustainable development. The definitions are presented in chronological order.

Dickie & Howard (2000), from the United Kingdom, used the definitions of sustainable development and sustainability to define sustainable construction. The most widely used definition of sustainable development was produced by the Brundtland Report as “development that meets the needs of the present without compromising the ability of the future generations to meet their own needs” (World commission on environment and development, 1987). Sustainability was defined by Chambers (1993) as “that which is capable of being sustained; in ecology the degree to which the earth’s resources may be exploited without deleterious effects”. The Construction Industry Research Information Association (CIRIA) (2006) defined sustainability as “the right balance between environmental responsibility, social awareness and economic profitability”. Dickie and Howard used both terms to define sustainable construction as ‘what we build today will provide the built environment of the future and will influence the ability of future generations to meet their needs’. This definition of sustainable construction was also used by Pitt et al (2009).

Abidin & Pasquire (2005), from the United Kingdom, formed a different definition for sustainable construction based on the sustainable development definition from Brundtland’s report. They defined the principle of sustainable construction as: “minimize damage to the environment and its resources, safeguarding future generations, evaluating benefits and costs to society and environment and improve quality of buildings and promote social cohesiveness “.

Shen (2010), from China, defined sustainability as ‘the interaction, integrations, and significant relationships among ecological, social and economic systems. This definition was used to form a new definition for sustainable construction as ‘contributing to an improved environment, an advanced society and gaining economic benefits and a competitive advantage’. This is comparable to the definition from Karji (2020) from the United States. “Sustainable construction considers the social and economic outcomes of construction in addition to its environmental impact”.

Noticeable for the definitions of sustainable construction in different regions and eras are the three dimensions that keep coming back. The economic, social, and environmental dimensions are generally acknowledged as the pillars of sustainability by researchers over time (Addis & Talbot., 2001, Schoormann et al., 2016). Economic sustainability concerns financial gains for the client for the implementation of the project (Bjorhovde., 2004, Abidin., 2007). Social sustainability concerns human feelings like security, comfort, and satisfaction (Parkin., 2000, Lombardi., 2001). Environmental sustainability concerns the extraction of natural resources (Addis & Talbot, 2001). Taking care of all the three dimensions within a construction project could make it a sustainable construction project. Sustainable projects are often mixed up with green and net-zero construction. That's why section 3.1.1. will explain how these definitions differ from each other.

Green construction and Net-zero construction

Green construction or net-zero construction are also frequently used when sustainable construction is being discussed, but they do have a slightly different meaning. The difference between these terms will be discussed to prevent misunderstanding.

Whereas sustainable construction serves all three pillars of sustainability, green construction only serves the social and environmental pillars of sustainability. This means that green construction ensures quality, safety, and other basic requirements while it maximizes the conservation of resources and reduces negative environmental activities (Shi et al, 2013). Green construction is defined by Kenji (2020) as "creating the built environment by minimizing its footprint on the natural or existing setting". This differs from sustainable construction because there is no goal of making a financial profit, but it just focuses on a qualitative project while minimizing negative environmental impact.

Net-zero construction is considered a form of sustainable construction. The Royal Institute of British Architecture (RIBA) (2019) defined net-zero construction as "the amount of carbon emissions associated with a buildings production and construction stage up to practical completion is zero or negative, through the use of offsets or the net export of on-site renewable energy". This means that the building generates at least as much energy on-site to compensate for the realisation of the building to be considered net-zero. This net-zero construction can even be expanded to net-zero operations in case of annual operational energy consumption that is lower than the annual on-site generation of renewable energy. This means that the building generates at least as much energy as it uses on an annual basis. Net-zero construction reduces the operational emissions of a building because it can generate its own energy, but initial costs will be higher due to the use of more advanced technology and more material (Peterson et al, 2015). So, net-zero construction is a form of sustainable construction with an extra constraint. This constraint is that the project needs to generate a minimal amount of on-site energy to compensate for the emissions from the realisation of the project. This results in net-zero projects having higher initial costs, but lower operational costs and higher initial carbon impact, but a lower operational carbon impact on the environment.

3.2. Barriers to sustainable construction

Now it is clear how a sustainable constructed project is defined, but it is still unclear why it is not implemented that often. This section will introduce the main barriers that hold back the implementation of sustainable projects.

The global status report found that the construction and operations of buildings account for 39 percent of the global energy-related carbon dioxide (Abergel et al, 2018). This makes the buildings and construction industry a key player in the fight against global warming. Constructing more sustainably can help to slow down global warming, but sustainable construction still faces many implementation barriers and that's why the construction sector sticks to its conventional behaviour. This section will explain all the different barriers that sustainable construction faces according to the existing literature.

Construction projects are led by project owners. From the beginning, they shape their project and process by their willingness and needs (Pitt et al, 2009). This makes the project owners the decision-makers whether a project is going to be constructed sustainable or not. From an owner's perspective, the adoption of sustainable construction must deal with a few critical factors (Gan et al, 2015). The critical factors can be placed in five different categories: economic, resources, consciousness, process and policies and regulations.

Economic

Financial profit has normally the highest priority for a project owner, but sustainable construction can make it harder to create a profitable business case due to higher initial investment costs (Zhang et al, 2011). Sustainable construction often increases the pay-back time, increases the capital cost of equipment, and requires a more skilled staff while the benefits mostly appear in the long-term. These benefits can appear in the form of reduced operational costs, improved corporate image, improved local environmental performances, and increased job opportunities (Yung & Chan, 2012). Reduced operational costs can boast the profitability for the operator of the building, but the project owner is often not the final operator of the building which makes it financially unfavourable for the project owner to implement sustainable construction. Increased project costs and a longer payback period increases project risk which reduces financial support from institutions and therefore reduces the implementation of sustainable construction in the sector (Elmualim et al, 2012). Sustainable construction has the potential to grow, but as long as prices aren't comparable, project owners will continue building the conventional way (Karji et al, 2020). Pitt (2009) also concluded that the affordability of sustainable construction is the biggest barrier for the industry, but fiscal incentives or penalties can reduce this barrier and stimulate the implementation of sustainable construction in the future.

Resources

For the implementation of sustainable construction, resources like qualified employees and advanced technology are demanded. Not having skilled employees is one of the biggest barriers to the implementation of sustainable construction (Zhang et al., 2011, Zhang et al., 2012). This results in the need to outsource the sustainability part of the project which increases the risk and costs of the project (Pinkse & Dommisse, 2009). The use of advanced technology increases the difficulty of the project and increases the total construction time which is unfavourable for the project owner from an economical perspective (Elmualim et al, 2012). The absence of certification, codes and standards for materials and technologies in developing countries is another barrier. This lack of certainty about product performances discourages the implementation of sustainable construction (Wong & Yip, 2004).

Consciousness

Consciousness and awareness about the urge for sustainable construction is the starting point for a change in stakeholder behaviour towards sustainable construction (Pitt et al, 2009). The consumer demand for the more expensive sustainable construction projects is currently not strong enough to make a shift towards sustainable construction (Tseng et al, 2013). Consciousness by the project owners is expected to stay low if market demand for sustainable constructed projects stays low. The lack of acceptance and understanding is caused by a knowledge gap and the lack of education and training of employees (Wong & Yip, 2004). The low level of consciousness also has to do with the culture of the construction industry. The profit-driven culture clashes with the principles of sustainable construction (Mukherjee & Muga, 2010). Prioritizing minimal costs over sustainable construction will remain if demand stays low, but a better understanding of the importance can change this perception (Shi et al, 2013). The Dutch government introduced the energy performance certificate for each new building. This regulatory change is an example of increased awareness of the climate change problem (Pinkse & Dommisse, 2009).

Process

The process category is related to the project management activities of the project. The biggest challenge is the successful cooperation of all project stakeholders during the process of a sustainable construction project (Hwang & Ng, 2013). Sustainable construction relies on various methods and technologies, so it is important that all the involved stakeholders cooperate to centralize the more spread-out knowledge. This is especially important at the beginning of the project process because incorporation of sustainable construction is more likely to be used if it is introduced in an early phase (Abidin, 2010). The second important barrier is that construction companies prefer to hold on to their business traditions. Bigger companies tend to be less flexible due to their size and they tend to have a low willingness to change their behaviour. This makes them stick with the well-known business models for different phases of the project. Innovations like sustainable construction are therefore hard to implement (Rwelamilla et al., 2000, Karji et al., 2020).

Policies and regulations

The government plays a significant role in the implementation of sustainable construction (Gan et al, 2015). Sustainable construction is not implemented voluntarily, so the government should sharpen policy measurements to enforce the construction sector to become more sustainable. Local policy can be used as a tool to effectively mitigate negative environmental activities within the construction sector, but these measurements must enforce people to change their conventional behaviour. The lack of enforcement in policy and regulations in China results in a conservative attitude from the construction sector (Zhang et al, 2011). For the Dutch construction sector, van Bueren (2002) found that incremental institutional changes can result in radical changes over time. This could also be the case for sustainable construction where a small institutional change could result in a radical change for the implementation of sustainable construction in the sector.

Both project owners and project consumers consider affordability as the biggest barrier to the implementation of sustainable construction, but there are ways to overcome this financial barrier. The first step could be to create competitive prices for sustainable construction to make it more attractive for project owners. Policy measures like climate regulated rules or subsidies and taxes can be used to achieve competitive prices if the market doesn't regulate itself. Advanced sustainable technology could be another solution to overcome the affordability barrier. Technology becomes cheaper and more accessible once production increases. This speeds up the implementation of sustainable technology in the construction sector (Pitt et al, 2009., Karji et al, 2020). The resource barrier could be overcome by offering sustainability training to workers and hiring qualified employees. The consciousness barrier can be overcome by a change in culture and attitude in the sector and the creation of social awareness. The process barrier could be overcome by supportive and stable administration of the project and the policies and regulations barrier can be overcome by sharpening the climate-related rules and regulations for the sector (karji et al, 2020).

3.3. Embodied and operational carbon

Whether a building has a high or low impact on the environment can be determined by the levels of embodied and operational carbon. This section explains both definitions and how it can be measured.

Buildings consume 30 percent of the global energy consumption (Abergel et al, 2018). This large share of energy consumption goes hand in hand with a lot of GHG emissions. The GHGs come from two different sources: embodied carbon and operational carbon. This section will explain the two sources of carbon in the construction sector, discusses strategies that could be used to lower the emissions from these sources and explains a method of how these levels of carbon can be measured. Lowering the emissions from these sources reduces the environmental impact and could contribute to the environmental pillar of sustainable construction.

Embodied carbon and operational carbon are two sources of emissions from buildings. Embodied carbon is carbon that is emitted during the raw material extraction, material processing, manufacturing, transportation, construction, maintenance, and demolition of a building. This could be seen as the carbon that's emitted during realisation, maintenance, and demolition of a building. The other source is operational carbon. Operational carbon is carbon that is emitted during operations of a building like lighting, heating, ventilation, and the use of equipment of a building (Unalan, 2016).

The definitions of embodied carbon and embodied energy are often interchanged but it is important to understand the difference. Embodied carbon relates to the real amount of carbon emissions during all the individual life cycle phases which are expressed in CO_2 equivalent, while embodied energy relates to the real amount of energy expressed in joule for the same life cycle phases. The same amount of embodied energy can have different values of embodied carbon because it depends on how the energy is generated (Hammond & Jones, 2008). Burning fossil fuels can generate the same amount of energy like wind and solar panels can do, but the carbon emissions will be completely different. That makes it easier to compare embodied carbon values with each other because it is not dependable on the source of energy.

During the entire life cycle of a building, around 80 percent of the carbon is used for operational purposes while only 20 percent is used as embodied carbon (Smith & Fieldsin, 2008). Although the share of operational energy is significantly bigger, recent research has shifted focus to the embodied energy consumption of buildings. Technological improvements in renewable energy technology, energy efficiency and changes in energy consumption behaviour offered promising reductions in the operational emissions of the future. The expectation of more renewable energy generation is also in line with the prediction from the 'Rijks Energiestrategie'. They predict that the Dutch goal of 75 percent renewable electricity generation in 2030 is likely to be within reach (NOS, 2021). Reducing the level of operational carbon often results in the use of more material and more energy consumption during production, so the balance must be found between operational and embodied reduction measures (Ibn-Mohammed, 2013).

The materials within the structure of a building account for more than 60 percent of the total embodied carbon of a building. This makes the structure the largest contribution to the embodied carbon of a building (Dimoundia & Tompa, 2008; Zhang & Wang, 2016). Changing the materials that are being used in the structure of a building can change the level of embodied carbon up to 40 percent (Ji et al, 2014). The exact reduction in embodied carbon depends on the originally used materials (grade of concrete, regular or reinforced concrete, etc), but reducing material usage or finding alternatives for concrete and steel could change the level of embodied carbon significantly.

Global warming potential

Assessing and analysing the embodied carbon for a product can best be done by using the so-called life cycle assessment method (LCA) (Hill, 2011). This method measures and quantifies the environmental impacts of a product. This is done by breaking down a product's lifecycle into all the individual phases and quantifying the environmental impact per phase expressed in tonnes or kilos of CO_2 equivalent. Expressing the impact in CO_2 equivalent is known as the global warming potential

(GWP) of a product which is also known as 'carbon footprint'. The LCA method according to the ISO 14040 (environmental management) standard breaks the system down to the stages of production, processing, usage and end-of-life and these are again split up into individual phases. These phases are displayed in figure 2-1 of the research design.

Previous studies provided information about the differences in embodied carbon of buildings structure by using an LCA analysis. De Wolf et al. (2020) found that the median embodied carbon value for timber frames was the lowest compared to steel and concrete. The timber frame had a global warming potential (GWP) value of 200 kg CO_2eq/m^2 compared to a value of 350-380 kg CO_2eq/m^2 for steel and concrete frames. Hart et al. (2021) compared several non-residential, single, whole building LCA studies and found that eight of the eight timber frames resulted in a lower GWP compared to the concrete frames and five out of the six cases had the timber frame a lower GWP compared to the steel frame. Eliassen et al. (2019) compared a concrete and steel apartment building with a timber apartment building and found that the timber building had 25 percent less GHG emissions compared to the concrete and steel building when looking at the production phase and 13 percent less GHG emissions looking at all phases. This suggests that the construction sector could become more environmentally friendly if carbon-intensive materials like concrete and steel would be replaced for timber structures. Other embodied carbon reduction strategies are material minimization, material recycling, transport minimization and construction optimization strategies. The EU also introduced a policy measure to stimulate the use of low carbon materials. This measure will be explained in section 3.4.

3.4. The emissions trading system mechanism

The EU introduced in 2005 the Emissions Trading System (ETS) which is a policy measurement that was aimed to lower the European emissions by making the polluter pay. This section will explain how the EU ETS is set up and how it functions.

The EU emissions trading system is called a 'cap and trade' system where a maximum (cap) is set on the total amount of GHG emissions for all EU member states (27) plus Norway, Lichtenstein, and Iceland. The cap of the system decreases every year to slowly phase out all the GHG emissions within Europe. The set cap for a year is divided over a few European union allowances (EUA) which all equal the right to emit 1 ton of CO_2 equivalent. This is a metric measure that can be used to compare various GHGs based on their global warming potential. Other important GHGs are methane and nitrous oxide which respectively have a factor of 25 and 298 CO_2 equivalents (IPCC, 2007). This means that 25 allowances are needed to compensate for the emissions of one tonne of methane. The allowances are partly allocated for free and are partly sold on auctions. Allowances are allocated for free to prevent European companies from having a competitive disadvantage due to their higher production costs. This risk could lead to businesses moving outside the EU which is known as carbon leakage. The part of the allowances that are not given away for free can be bought on auctions or the ETS market. The ETS market is a place where businesses can sell their surplus of allowances or buy allowances to repair their deficit. Allowances are traded freely on the ETS market, and the price will be determined by demand and supply. The current ETS phase is phase four (2021-2030). The European Union decided to increase their reduction target for 2030 from 43 percent to 55 percent in comparison to the emission levels in 1990 (European Commission, 2021a). This goal is in line with the objective of the Paris agreement, and it encourages international partners to increase their ambitions as well.

Businesses that are obligated to operate under the ETS are businesses with a net heat excess of 20 megawatts or more. The participants of the ETS are often energy-intensive businesses from the electricity, oil refinery, chemical or metal industry. The Netherlands has around 430 businesses that participate under the ETS while Europe in total has around 11.000 participants. Dutch cement producer ENCI IJmuiden and Dutch steel producer Tata Steel IJmuiden are both obligated to participate under the ETS. The 11.000 European participants are responsible for 45 percent of the total European emissions (Bayer & Aklin, 2020). The other emissions come from smaller companies and activities which don't fall under the ETS, but under the Effort Sharing Regulation (ESR) system. The ESR system applies to smaller and more fragmented businesses and is regulated by the rules and regulations from the local government of EU member states. A member state is individually responsible to reduce the total emissions from the ESR sector. The reduction target for an individual member state is based on its GDP per capita, so wealthier countries are expected to be able to achieve emission reduction more easily. This research will just focus on the ETS because the ESR impact falls outside the scope of the research.

Dutch ETS participants need to monitor the GHG emissions of their company and submit enough allowances for all the emitted GHGs at the 'Nederlandse Emissieautoriteit' (Nederlandse Emissieautoriteit, 2015). Businesses who exceed their emissions will need to buy extra allowances while businesses who reduced their emissions can hold on or sell their allowances. Businesses that don't hand in enough allowances receive a fine. The objective of the ETS is to stimulate energy-intensive companies to make the transition to a more sustainable production method. The costs of production increase if the production method is kept the same while the total number of allowances reduces. At some point, the emitter must reduce their emissions to make sure that production costs don't become inescapable.

3.5. Evolution of the emissions trading system

In 2021, the ETS entered the fourth phase, and a lot has changed since the introduction of the system. This section will explain the evolution and background of the system to get a better understanding of the system functionality and the possible directions in the future.

The idea for a cap on emissions arose during the Kyoto protocol. The failed introduction of an effective EU carbon tax in 1990 led to the idea for emission allowances during the 1997 Kyoto Protocol (Convery, 2009). The Commission started the design of the EU ETS system in 2000, which was adopted in 2003. The EU ETS launched in January 2005 with the first phase of the system. This pilot phase ended in December 2007 and had the objective to learn and prepare for the second phase. The first phase only covered CO_2 emissions from energy generating companies and energy-intensive businesses. The absence of historical data about European emissions resulted in a supply of emission allowances that exceeded total European emissions which resulted in the price dropping to zero. The price development in the first phase is displayed in figure 5. This first phase didn't have a significant impact because almost all the allowances were given away for free to prevent business from carbon leakage (European Commission, 2021c).

The second phase took place from January 2008 to December 2012. The cap was reduced by 6.5 percent in comparison to the first phase and the price was set at 20 euro per tonne to stimulate the system, but the market still did not function by itself. The set allowance reduction did not result in an allowance shortage due to the economic crisis of 2008 which reduced European emissions more than expected. In 2008, the price started at 20 euro per allowance, but the price slowly decreased to 5 euro per allowance at the end of 2012. This is displayed in figure 5. With allowance prices between 5 and 20 euros and free allocation of 90 percent of the allowances, the system was still not contributing to its goal of European emission reduction (European Commission, 2021c).

The third phase took place from January 2013 to December 2020. The cap for 2013 was set on the average quantity of allowances issued during phase 2 and is linearly reduced by 1.74 percent per year

(European Commission, 2020b). Auctions became the standard method to allocate allowances, but despite this measure, most allowances were still given away for free to protect the local economy. These measures did not do much against the huge oversupply of allowances from the previous phases. That's why the market stability reserve (MSR) was introduced in 2018 as the most significant change. In 2018, the MSR start to control the number of allowances in the market to increase the effectiveness of the system. The unallocated allowances at that moment were all transferred to a EUA reserve with a lower and higher threshold of releasing allowances to the market. The MSR releases allowances from the reserve into the market if the number of allowances gets below 400 million and market allowances are added to the reserve if the number of allowances in the market exceeds 833 million. The ETS improved its resilience to demand shocks and the allowance price started to rise again when the MSR was introduced (European Commission, 2020a). The extensive oversupply in the market is eliminated and the price increased from 5 euro per EUA to around 30 euro per EUA. The phase 3 price development is displayed in figure 5.

The fourth phase of the ETS started in January 2021 and will end in 2030. The European Parliament and European Council agreed to an increased rate of reduction of EUAs. The cap will annually be reduced by 2.2 percent during the fourth phase to speed up the reduction of European GHGs (European Commission, 2020b). The increased rate of allowance reduction and the introduction of the MSR resulted in a huge allowance price increase. The allowance price increased from 30 euro to 80 euro per allowance within a year. This is displayed in figure 5. The real reason behind the price increase is hard to state, but the next section will further investigate what factors influence the EUA price.

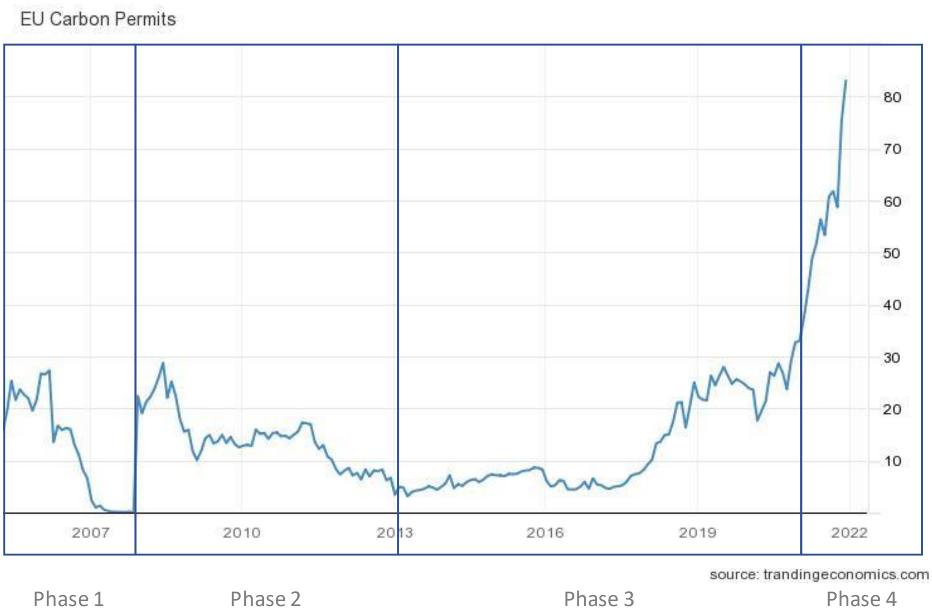

Figure 3-1: European allowance price development from Jan 2005 - Dec 2021 (Trading economics, 2021)

3.6. The ETS impact on sustainable construction

The EU presented the ETS with the idea to make the polluter pay. This could financially reduce the attractiveness of carbon-intensive materials and help to overcome the barrier of affordability. This section will discuss whether the ETS has influenced sustainable construction and if it is able to create competitive prices for sustainable construction.

The implementation of regional CO_2 reducing policies like the EU ETS system raised fear for disruption of international competition which could result in carbon leakage and a loss in regional employment and welfare due to the output decrease. The EU tries to keep the impact low to make sure that European producers don't get disadvantaged too much, by giving out free emission allowances to producers at risk. The impact of the ETS is especially important for carbon-intensive manufacturing products like concrete and steel because these prices are expected to be influenced the most by the allowance price. Branger (2016) found that there was no significant effect of the carbon price on the net imports of steel and cement in the European Union during the first two ETS phases. This means that final consumers did not shift to suppliers outside Europe due to the ETS price. Branger also found that there was no evidence for carbon leakage in the short run because of the ETS. The same was concluded by Naegele and Zaklan (2019), who also did not find evidence for carbon leakage as a consequence of the ETS in the first two phases. Naegele and Zaklan also found that for 95 percent of the total European manufacturing sector less than 0,65 percent of the total material costs came from emission costs during the first two phases. This means that the ETS allowance price barely influenced the output price of products produced under the ETS.

The Carbon Market Watch (2021) concluded that the ETS did not succeed in its goal of reducing the total European emissions because emissions did barely change over the last decade. They argue that too many industries are placed on the list for high carbon leakage risk, while there is no proven risk of carbon leakage. These industries do get more allowances for free to protect the sector against the unfair global market competition, but the free allowances lower the incentive to change their polluting production process. CE Delft (2016) did even conclude that the European industry received additional profits of around 8 billion euros because of the over-allocation of allowances between 2008 and 2014. The Dutch industry earned over 230 million euros of additional profits because of the excess of 50 million allowances in the same period. The Dutch cement industry did receive the largest number of free allowances relative to its emissions while it is one of the biggest contributors to large emissions from the construction sector.

3.7. Conclusion literature study

Multiple definitions for sustainable construction have been presented in section 3.1, but in the definitions from different regions and different eras, the three pillars of sustainability always returned. The social, economic, and environmental pillars are the most evident in the definition of Shen (2010) who defined sustainable construction as 'contributing to an improved environment, an advanced society and gaining economic benefits and a competitive advantage'. This means that a project will be considered sustainable if human feelings like safety and comfort can be assured. The project owner can make a financial profit and the impact on the environment is minimized. An LCA analysis can analyse the levels of embodied carbon and confirm whether the environmental impact is minimized in comparison to other designs. Section 3.2 presented multiple barriers to the implementation of sustainable construction, to identify the biggest barrier which is the affordability of sustainable construction. Possible solutions to lower this barrier are to implement policy measures which result in more competitive prices for sustainable construction or by lowering the prices of sustainable technology by increasing the levels of production. The ETS is a European policy measure that was aimed to speed up the transition by increasing the production costs for polluting products. This policy measure is starting to become more effective over time due to the lower supply and higher price per allowance, but this is not the case for every product that is produced under the ETS. For the first two phases, Naegele and Zaklan concluded that production costs barely changed because of the ETS introduction. This can also explain why the net imports of steel and concrete did not change. This means that the ETS was not able to increase the price of carbon-intensive materials. This could have to do with the low effectiveness of the system during the first two phases or with the free allocation of allowances that compensated for the emissions costs. Allowances are allocated for free because of the risk of carbon leakage, but multiple sources couldn't prove the risk of carbon leakage as a consequence of the ETS. This does not incentivise the polluter to change their polluting production process. The Dutch polluting industries were even able to make an additional profit between 2008 and 2014 due to the excess of free ETS allowances.

So far, the ETS did not lower the barrier of affordability. Prices didn't change up to 2016 which did not result in a stimulation of sustainable construction. Literature about the ETS impact in the most recent years is not yet available, but it has not led to significant European emission reductions, so the impact is not assumed to be significantly different. This low impact on carbon-intensive materials and sustainable construction could be the result of the allocation of free allowances to polluting sectors to protect their market position. The allocation of free allowances will be further investigated in chapter 4.

4. Theoretical framework

Chapter 4 will create the theoretical framework that will be used in chapter 5 to identify the relation between the EU allowance price and the price for steel and cement. This chapter will answer the sub-question: *What theoretical framework supports the determination of the relation between the European Union allowance price and material prices of steel and cement?* Section 4.1 discusses the construction materials steel and concrete and why they are selected as materials to explore the allowance price impact. Section 4.2 explains what factors influence the ETS allowance price. Section 4.3 explains how the number of free allowances for an ETS participant can be calculated. Section 4.4 discusses how the extra production costs are passed through to the final consumer. Section 4.5 presents the conclusion to sub-question 2 and section 4.6 presents the concept that explains how all the sub-question built up to the answer to the main question.

4.1. Structural construction materials

Different strategies could be applied to reduce the embodied carbon emissions from a building. Selecting materials with a low level of embodied carbon over carbon-intensive materials is an option to reduce the environmental impact. This section will discuss three of the most important structural construction materials on a global scale which are concrete, steel and timber.

Steel

Steel is another carbon-intensive building material that is used in the worldwide construction industry while the iron and steel industry is responsible for 7.2 percent of the global GHG emissions (Ritchie & Roser, 2020). Steel can be produced in two ways which are displayed in figure 4-2. The first and primary method uses iron ore and a blast furnace on coal. This method is used for 70 percent of global steel production. The other 30 percent is produced by the secondary method which uses steel scrap and an electric furnace (WSA, 2012). The blast furnace method produces 1.5-2.5 tonnes of CO_2 per tonne of steel, while the electric furnace method only produces 0.4 tonnes of CO_2 per tonne of crude steel (de Bruyn et al, 2015). This makes the blast furnace method roughly five times more polluting, but the electric furnace method depends upon the availability of scrap.

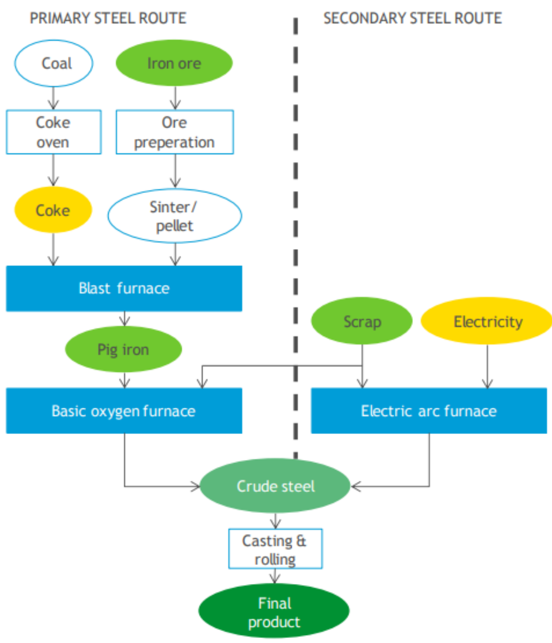

Figure 4-1: Primary and secondary steel production route (de Bruyn et al, 2015)

Concrete

Concrete is a mixture of cement, fine and coarse aggregates, and water. Although concrete is used worldwide, it is also starting to become controversial. The cement content is responsible for 88 percent of the carbon dioxide emissions of concrete in the case of the standard 3000 PSI mix (Nisbet et al, 2000). This results in approximately 0.9-tonne CO_2 to produce one-ton cement. 0.53 tonne CO_2 comes from the decarbonisation of limestone and 0.39 tonne CO_2 comes from burning fossil fuels for heating (Habert et al, 2010).

The usage of large quantities of concrete around the globe result in cement production being responsible for 3 percent of the global carbon emissions (Ritchie & Roser, 2020). The use of cement in concrete results in an average level of embodied carbon of 0.073 tonne CO_2 per tonne concrete. Concrete is often reinforced in bigger construction projects because of its weak tensile strength. In general, this means that steel is added to strengthen the concrete which makes the structure more carbon-intensive (0.08 CO_2 per tonne reinforced concrete) (The Concrete Centre, 2019).

Limestone, the raw material of cement, can be found all over the world in great quantities which makes cement relative cheap (45-150 $/tonne). This results in cement being produced in almost all countries in the world and moderately traded on an international scale. The cement production process out of limestone is displayed in figure 4-1.

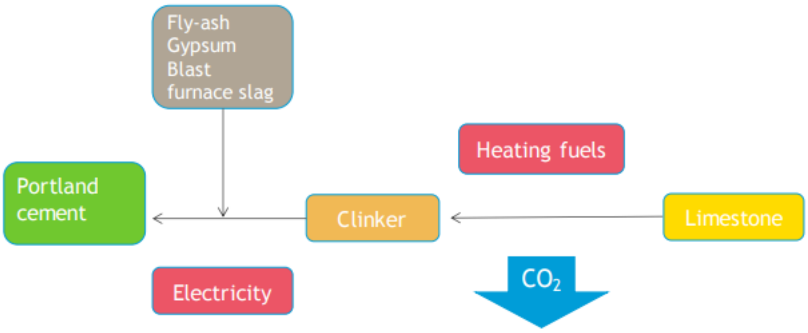

Figure 4-2: Cement production route (de Bruyn et al, 2015)

Timber

Timber is a natural building material, which has the advantage to be able to store carbon during its growth process. This creates a lot of opportunities for timber as a construction material to contribute to a more sustainable construction sector. The great majority of the life cycle assessments (LCA) of timber did show that the stored amount of carbon is larger than the emitted emissions coming from the processing of the material (Hill & Dibdiakova, 2016). This means that as long as the timber isn't burned, timber a negative carbon footprint has. This proves that the use of timber could significantly reduce GHG emissions and mitigate climate change. Timber remains a very important building material that has been used for many centuries and many structures because it is easily available, simple to transport, handle and repair and shock and sound-absorbing (Cabeza et al, 2021).

4.2. Exogenous allowance price factors

In 2020, economist Van Cleef did two EUA price predictions for 2030. His first prediction had a moderate price increase from 30 euro to 50 euro per allowance in 2030. His second prediction had a stronger price increase. He predicted an increase from 30 euro to 80 euro per allowance in 2030. One year after Van Cleef's prediction, an allowance price of 80 euros was already achieved. This confirms that futuristic allowance price predictions are very insecure and hard to make. That is why this section will indicate and discuss individual factors that influence the allowance price. These factors can give a better understanding of how the allowance price is built up and how it could develop in the future.

Van Cleef (2020) identified policy changes, technological development and subsidies as the main EUA price influencing factors. The impact of futuristic policy changes is very uncertain. A new policy can drive the allowance price in both directions. Increased technological development helps businesses to speed up their transition to a more environmentally friendly production process. This helps to lower the demand and lower the price for allowances. The local government often subsidises sustainable production techniques in the industry to speed up the transition, but too much subsidy often contributes to a low ETS price. Van Cleef stated that the government is probably giving too much subsidy if sustainable production techniques for the industry get better, but the ETS price remains low.

Aatola et al. (2013) researched exogenous factors that influenced the EUA price. His study found a relatively high correlation between the energy price and the carbon price. This is not very surprising because 73 percent of the global GHGs are produced by the energy sector (Ritchie & Roser, 2020). The electricity sector is the largest single energy sector. A higher electricity price results in power plants willing to produce more electricity. The increased production comes in most cases with increased pollution, so demand for allowances rises and the price increases. Coal and natural gas are the main fuels for electricity production. One-third of Europe's electricity generation comes from coal (Friedrich, 2020). Coal is a very carbon-intensive fuel, so when coal prices rise, electricity will be generated out of other fuels like natural gas or biomass which are less polluting. Therefore, a high coal price is expected to reduce emissions which lowers the demand and price for allowances. The opposite is the case for natural gas. Natural gas is a less polluting fuel in comparison to coal, so a high natural gas price will stimulate the shift to use coal as a fuel for power plants. Coal usage is very carbon-intensive, so the demand and price for allowances will rise. The massive rise of the European gas price over 2021 is one of the reasons for the huge EUA price increase in the fourth phase of ETS.

Besides the already mentioned factors, Friedrich (2020) also found a relationship between the EUA price and the economic activity and weather conditions. An increase in economic activity stimulates production. Higher levels of production increase production emissions and that will result in increased demand and price for allowances. Weather conditions can push the allowance price in both directions. More wind and sun stimulate the electricity generation out of solar panels and wind turbines which lowers the demand for electricity generated out of fossil fuels. These weather conditions lower the demand and price for allowances. Extreme temperatures result in the opposite effect. Electricity usage is higher under extreme temperatures because of the need to cool or warm the area. The electricity production increases due to the higher demand, and this requires more allowances which drive the price upwards.

Table 4-1 summarises the impact of the discussed exogenous factors that influence the allowance price. An increase in the value of a factor with a positive impact increases the allowance price, while an increase in the value of a factor with a negative impact lowers the allowance price. Policy change is placed on both sides because the actual impact depends on the kind of policy change.

Table 4-1: Summary of the impact of exogenous factors on the allowance price

Positive impact on the allowance price (+)	Negative impact on the allowance price (-)
The electricity price	Technological Development
The natural gas price	Subsidies
The Economic activity	The Coal price
Extreme temperatures	Windy and/or sunny weather conditions
Policy changes (+/-)	Policy changes (+/-)

4.3. Free allocation of allowances

In the literature study, it became clear that prices of steel and concrete did not change under the ETS. The free allocation of allowances to producers of polluting goods was a possible explanation for the low-price impact. The EU allocates these for free to protect producers against unfair global market competition. These free allowances help the producer to lower production costs so that European producers can keep competing on a global scale. This section will explain which factors influence the number of freely received allowances and how it is calculated.

The number of free allowances per producing installation is determined by the following formula (European Commission, 2011):

$$FA = BM * HAL * CLEF * CSCF$$

FA is the number of free allowances per year (EUA's/year), BM is the benchmark value (EUA's/unit of production), HAL is the historic activity level (units of production/year), CLEF is the carbon leakage factor (*unitless*) and CSCF is the cross-sectoral correction factor (*unitless*). The meaning of all four factors will be explained below. A unit consists of 1 tonne of the produced product.

The Benchmark value (BM)

Since the third phase of the ETS, a benchmark approach was used for the free allocation of allowances. The benchmark value is a value that reflects the average emissions of the top 10 percent best performing installations of a specific product in the EU. This means that the methodology to calculate this BM value does not vary according to the type of fuel usage, technology, location, or size of the installation. The installations that meet the BM value are among the most efficient in the EU. These most efficient installations receive in principle all the allowances for free to cover their emissions. Installations that do not meet the benchmark value receive fewer allowances than needed, which means that they must reduce their emissions, buy extra allowances on the market or combine both options. This reduces their output or increases their production costs.

The Historical Activity Levels (HAL)

The HAL value is an output value based on the average of a 5-year reference period which is known as the baseline period. The HAL for the first half (2021-2025) of the fourth phase will be based on the activity levels between 2014-2018 and the HAL for the second half (2026-2030) of the fourth phase will depend on the activity levels between 2019-2023 (European Commission, 2019b). The HAL value is every year compared with the average activity level (AAL) from the last 2 years and if the AAL differs more than 15 percent from the HAL, an adjustment will be made in the amount of freely allocated allowances.

Table 4-2: Example of a change in activity level (European Commission, 2021f)

Year	HAL	2019	2020	2021	2022
Activity Level	100 000	80 000	90 000	79 000	110 000
Average Activity Level (AAL)				85 000	84 500
(AAL-HAL)/HAL [%]				-15,00%	-15,50%
Preliminary free allocation (BM=1)				100 000	84 500

Table 4-2 shows an example of how the free allocation of allowances is calculated. The HAL in this example is set at 100.000 units. The AAL in 2021 of 85.000 units is calculated by taking the average output from 2019 and 2020. The number of freely allocated allowances will be adjusted if the difference between the AAL and HAL is more than 15 percent. This is not the case for 2021, so the number of free allocated allowances will equal the HAL value in 2021. In 2022 is the AAL 84.500 units, which is the average activity level over 2020 and 2021. The difference between the output of the AAL and HAL is 15.5 percent. This means that the number of freely allocated allowances will be lowered by 15.5 percent for the year 2022.

The Cross-Sectoral Correction Factor (CSCF)

The maximum number of free allowances is a fixed percentage of the total number of emission allowances. The current value lies around 40 percent. This maximum helps to predict the total revenue from allowance auctions for the European Union. Every country that participates under the ETS has to submit an annual number of free allowances for the industry of their country. If the sum of all participating countries exceeds the supply of free allowances, a cross-sectoral correction factor will be introduced. This factor reduces the number of demanded free allowances to the agreed maximum of free allowances. This means that the maximum CSCF value is 1 and the smallest value approaches 0. The European Commission wanted to limit the use of the CSCF in the fourth ETS phase, so the difference between the demand and supply of free allowances is first going to be compensated with a reduction in the total amount of auctioned allowances. The auctioned allowances can be reduced up to 3 percent of the total quantity of allowances if the sum of all countries exceeds the maximum annual number of free allowances. This creates a little bit more flexibility for the CSCF to stay at 1 until 2025.

The Carbon Leakage Exposure Factor (CLEF)

The CLEF value is a factor that is based on industries at risk of carbon leakage. The European Union made a list of sectors and subsectors that are deemed at high risk and a list for sectors which are at low or no risk. The industrial sectors that do have a high risk of leaving the EU do receive a CLEF value of 1. The low or no risk industries receive a CLEF value of 0.3. The factor for the low and no risk industries will linearly decrease to 0 in the period between 2026 and 2030 (Carbon Market Watch, 2021). The European Commission (2019a) placed the steel and the cement industries both on the list for industries that are exposed to a significant risk of carbon leakage. This list is applicable for the entire fourth ETS phase (2021-2030), which means that both cement and steel producers get a CLEF value of 1.

4.4. The pass-through ratio

In case of higher production costs, due to extra emission costs, the final consumer could experience a price increase. The height of the price increase depends on the producers pass-through ratio (PTR). The PTR is expressed in a percentage and quantifies the output price change relative to a change in production costs. The extra emission costs, due to the ETS, could change the production costs which could be passed through to the final consumer. For example, a PTR of 0.6 means that the final market price will increase by 0.60 euro for every 1.00 euro increase in production costs. This section researches the pass-through ratios for the cement and steel industries based on the literature.

It is now known that producers of polluting products receive free allowances to protect the European market against unfair competition. This results in two different scenarios which can play out according to the carbon costs pass-through ratio. The European Union had the intention to allocate free allowances to producers so that they would directly use the free allowances to compensate for their annual emissions. In this order, the price increase of steel and concrete will be relatively small because most producers receive almost all their allowances for free which compensates for the extra production costs in the form of carbon.

But under the second scenario, firms do use the free allowances as opportunity costs to maximize their profit. Firms normally produce up to the point where marginal costs equal marginal revenues if the economic theory is followed. This means that a producer increases its production until it is not profitable to do so. This means that ENCI and Tata Steel do not necessarily use the free allowances to compensate for their production. If the benefit of selling an allowance exceeds the benefit of producing an extra unit of output, firms will strive for profit-maximizing. That is why the neoclassical theory predicts that firms do pass through allowance costs into their product prices even though they did not pay for the allowances. This is known as 'windfall profits' (Sijm et al., 2012). This scenario suggests that the free allowances are seen as opportunity costs to increase the final market price and increase their profit.

The literature shows that the exact PTR is highly method-dependent, so different rates are found in different studies. McKinsey did research on the PTRs of Portland cement and steel in 2006 and found a PTR between 66 and 80 percent on steel and a PTR between 35 and 70 percent for the cement industry. CE Delft and Öko Institut (2015) did research on the PTR in the steel and cement sectors under the European ETS during the first three phases of the system. They concluded that steel production is driven by demand, so the higher the demand for steel the higher the PTR on CO_2-related costs can actually be. The found PTR for the Nort-European steel sector ranges from 75 percent for hot-rolled coil to 85 percent for cold-rolled coil. This means that the steel price increases by 0.80 euro for every euro that the allowance price increases. The cement industry is a relatively protected sector with limited competition from producers outside the EU. This creates the expectation that a high PTR would be applicable within the cement sector, but they found a relatively low PTR of 20 to 40 percent for the total cement production in Germany and France. For the Portland cement product, a PTR of 90 to 100 percent was found in Czech and Poland and for clinker production, a PTR of 35 to 40 percent was found in France, Poland and Germany.

The cement's low PTR could be the result of a few sector characteristics. The cement industry works with long term contracts and spot prices. Having Long term contracts reduces the possibility to implement the emission costs directly in the market price. The cement industry is also an oligopoly that tries to maximize profit. The PTR is based on the demand in comparison to the supply. If demand exceeds supply, a 100 percent pass-through is likely, but if supply exceeds demand, companies may decide to regain market share by lowering their prices by lowering the PTR. The demand for cement was lacking during the second and third ETS phase, which could have played a role in the relative low PTR. During the third ETS phase, a cement oversupply occurred because producers didn't want to lower production. After all, that would lead to a lower HAL value and a loss of free allowances. The PTR is likely to be lowered during an oversupply to maintain or regain market share.

CE Delft revised their PTRs in 2016 in their new report on additional profits of firms and sectors from the EU ETS. This report selected an average PTR of 75 percent for steel (55-100) and an average PTR of

39 percent for cement (20-58). These values will be used in the rest of the research because these are the most recent values based on the Dutch market and they have been selected by CE Delft after revisioning.

4.5. Conclusion theoretical framework

Based on the findings in the theoretical framework chapter and the literature review chapter, two frameworks have been created to explore the relation between the EUA price and the market price for steel and concrete. The first framework is presented in figure 4-3 which assumes that the free allowances are directly used to compensate for the emissions coming from the production of the product.

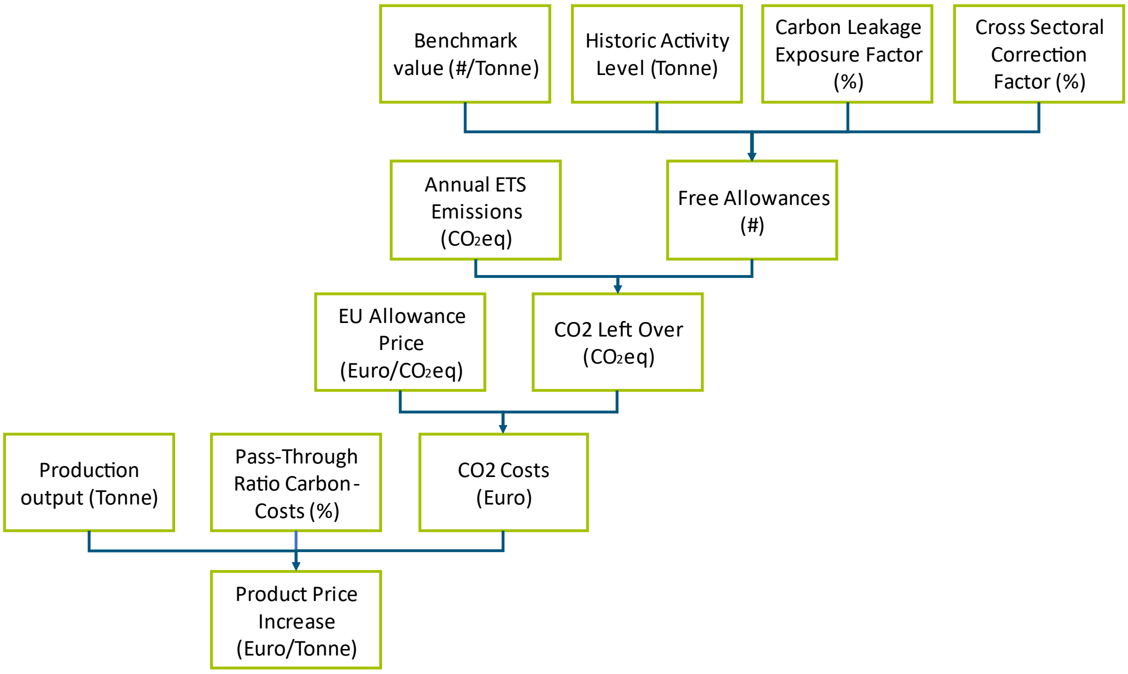

Figure 4-3: Theoretical framework for the relation between the allowance price and the price of steel and cement under reduced opportunity costs circumstances.

Every Dutch company that is obligated to participate under the ETS must register its annual emissions at the 'Nederlandse emissieautoriteiten' (NEA). These emissions need to be compensated by handing in European emission allowances. The producer receives these allowances partly for free. The exact number depends on the benchmark value, the historic activity level, the carbon leakage exposure factor, and the cross-sectoral correction factor. Every allowance compensates for the emissions of one tonne CO_2eq, so the CO_2 leftover can be calculated by reducing the annual ETS emissions by the received number of free allowances. The CO_2 leftover can be multiplied by the EUA price to calculate the CO_2 costs of the total production. The producing business can decide itself what share of the CO_2 costs are passed through to the consumer in the market price by setting a pass-through ratio. Multiplying the CO_2 costs with the applied pass-through ratio and dividing it by the total production output results in the product price increase per tonne of produced output.

The second framework is presented in figure 4-4 which assumes that the number of free allowances does not influence the final market price change because the emission costs are completely used as opportunity costs to maximize profits.

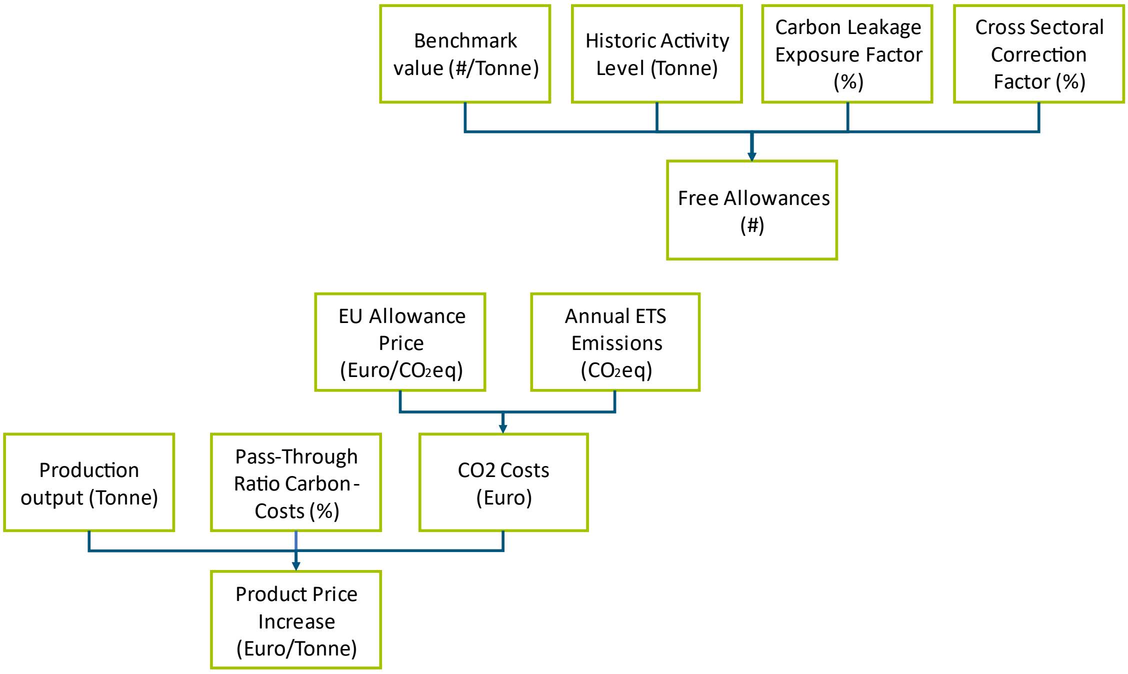

Figure 4-4: Theoretical framework for the relation between the allowance price and the price of steel and cement under profit maximization circumstances.

In this situation, the annual ETS emissions are not directly compensated by the allocated free allowances and have therefore no link with the 'free allowances' variable. Firms do not directly compensate their emissions because they seek profit maximization and hope to pass through more of the CO_2 costs as production costs in the form of opportunity costs. The CO_2 costs are calculated by multiplying the allowance price with the registered ETS emissions. These CO_2 costs are multiplied by the pass-through ratio and divided by the production output to calculate the product price increase per tonne of output.

The relation between the EUA price and the product price increase will be stated based on these two theoretical frameworks.

4.6. Conceptual model

This report has the goal to find the EU ETS allowance price tipping point for a profitable business case for a timber structure in the Dutch built environment. This information can help to speed up the transition to a more sustainable construction sector. In order to find an answer to the main question, multiple smaller steps have to be taken to build the answer to the main question. This conceptual model shows how this problem is built up and what part of the problem is covered by which sub-question. The first sub-question is not included because the answer to this question was the impetus and introduction to this research. SQ2 and SQ3 cover the same part of the problem, but SQ2 presents the framework which will be used to answer the question while SQ3 gives the answer to this question. SQ 4 calculates the levels of embodied carbon for the selected designs and SQ5 calculates the realisation costs for the selected designs. By combining all the sub-questions, an answer to the main question can be formulated. This conceptual model shows how the answers to the individual questions built up to the main research question.

These research questions will all be answered within the scope of this research which is discussed in section 2.2.

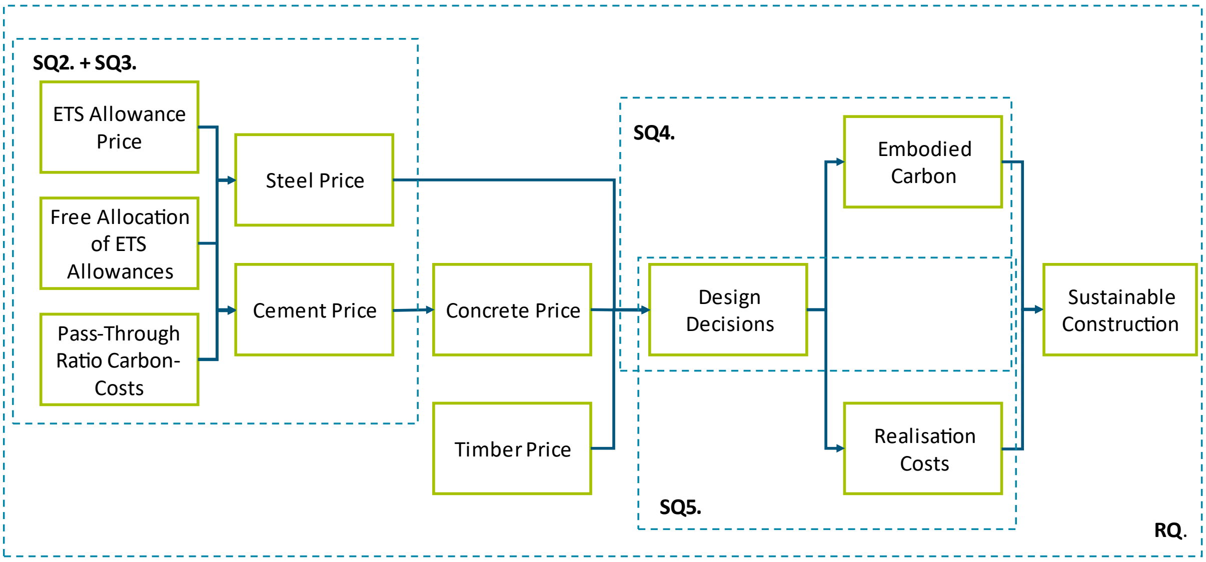

Figure 4-5: The conceptual model with research question definition

5. ETS impact on material prices

Chapter 5 will explore the relation between the European allowance price and the steel and cement prices in the Dutch construction market. This chapter will answer the sub-question: *What is the relation between the European Union allowance price and the material prices for steel and cement as structural building materials in the Dutch construction market?* Section 5.1 discusses what variables from the theoretical framework are known and unknown and how this results in the different scenarios. Section 5.2 presents the results from the different scenarios and section, 5.3 presents the answer to the third research question.

5.1. Framework variables

The two frameworks presented in section 4.5 will be used to identify the relation between the allowance price and the market price for steel and cement because the ETS policy directly impacts the production of these two materials. The found relation between the allowance price and the cement price will be used in the remainder of the report to determine the allowance price impact on the price of concrete. This section will identify the values of the different variables which are present in the framework to be able to explore the relation between the allowance price and the material price.

Dutch steel market

Tata Steel IJmuiden is the only Dutch steel producer. Tata Steel IJmuiden has a maximum production capacity of 7.5 million tonnes of steel per year, but recent production levels have not exceeded the 7 million tonnes (Keys et al, 2019). In 2020, Tata Steel published their crude steel production output and their registered annual emissions for their facility in IJmuiden in their sustainability report (Tata Steel, 2020). The recent production values are displayed in table 5-1. The expected ETS emissions and crude steel production output for 2022 are based on the average of these values between 2017 and 2019. The expected average is based on these three years because it is the most recent available data about the output values and therefore expected to be the most representative for the future.

Table 5-1: Tata Steel IJmuiden historical crude steel production (Tata Steel, 2020)

	2017	2018	2019	Average
CO_2eq emissions (million tonnes)	6.93	6.59	6.35	6.62
Crude steel production (million tonnes)	6.90	6.90	6.62	6.81

The number of allowances that Tata Steel receives for free is not publicly shared, so an estimation for the number of free allowances must be made. The number will be calculated by filling in the formula for free allowances, which is shared in section 4.3. In 2021, the benchmark value for hot metal was 1,288 allowances per produced tonne output. This value will reduce by 0,2% per year based on the possibilities for technological innovations in the steel sector, which could reduce the emissions per unit of output. This results in a BM value of 1,285 allowances per tonne of output for 2022 (European Commission, 2021h). The historic activity level for 2022 is based on the average produced output between 2014 and 2018. This results in a HAL value of 6,888 million tonnes, which is calculated and presented in table 5-2. The producer's HAL value will only be adjusted if a minimum difference of 15 percent in the production output is realised compared to the current HAL. An adjustment of Tata's HAL value is very unlikely to happen because a 15 percent increase is not possible because of the maximum production capacity of 7.5 million tonnes, and a 15 percent decrease would be highly unlikely while the European steel market is expected to grow the next few years (World steel association, 2022)

Table 5-2: HAL calculation Tata Steel IJmuiden (Keys et al., 2019, Tata Steel., 2020)

Tata Steel HAL	**2014**	**2015**	**2016**	**2017**	**2018**	**HAL**
Crude steel production (million tonnes)	6.87	6.92	6.85	6.90	6.90	6.888

The cross-sectoral correction factor is set to 100 percent for the period between 2021 and 2025 (European Commission, 2021g). The carbon leakage exposure factor is also set to 100 percent for the period between 2021 and 2030 because the steel sector is considered at high risk of carbon leakage (European Commission, 2019a). This factor should protect the European steel market against unfair competition.

This last missing variable is the pass-through ratio of carbon costs into the steel market price. This value is hard to select precisely because the price-setting strategies are not being shared in the open by private companies. This report accounts for multiple possible PTR values and creates multiple scenarios based on the average, minimum and maximum PTR value extracted from the literature. This results in an average steel PTR of 75 percent, a minimum of 55 percent and a maximum of 100 percent (CE Delft, 2016).

Having two different frameworks and three different PTR values results in 6 different scenarios. These scenarios will all be researched to explore the impact of the allowance price on the steel price. The input values of the different variables for the different scenarios are displayed in table 5-3 and represent the values for 2022.

Table 5-3: Overview of the input variables for the scenario analysis of the allowance price impact on the steel market price

	Reduced opportunity costs			**Profit maximisation**		
	Average	**Minimum**	**Maximum**	**Average**	**Minimum**	**Maximum**
Benchmark value (Allowance/Tonne)	1.285	1.285	1.285	-	-	-
Historic activity level (mil. Tonne)	6.888	6.888	6.888	-	-	-
Carbon leakage exposure factor	1.000	1.000	1.000	-	-	-
Cross sectoral correction factor	1.000	1.000	1.000	-	-	-
Annual ETS emissions (mil. Tonne)	6.62	6.62	6.62	6.62	6.62	6.62
Annual production output (mil. Tonne)	6.81	6.81	6.81	6.81	6.81	6.81
Pass through ratio carbon costs (%)	75	55	100	75	55	100

Dutch Cement market

The Netherlands has only one cement producer who has the name ENCI (Eerste Nederlandse Cement Industrie). At this moment, ENCI produces cement in IJmuiden and Rotterdam. ENCI also owned another cement plant in Maastricht, but this one has been closed recently. The production facility in IJmuiden has an annual production capacity of 1.4 million tonnes cement. The production process for this site is displayed in figure 5-1. The facility in IJmuiden dries the blast furnace slag from the neighbouring steel producer Tata Steel. The clinker is imported from outside the Netherlands and ground together with the dried slag and limestone into cement. ENCI IJmuiden produces for 89 percent CEM 3 blast furnace slag cement. This type of cement contains, on average, 35 percent clinker (Xavier and Oliveira, 2021). The ENCI Facility in Rotterdam has an annual production capacity of 0.6 million tonnes cement. It uses the same production process as the one in IJmuiden, but this facility does not participate under the ETS and does not have to compensate for its emissions. That is why this facility will not be included in this analysis any further.

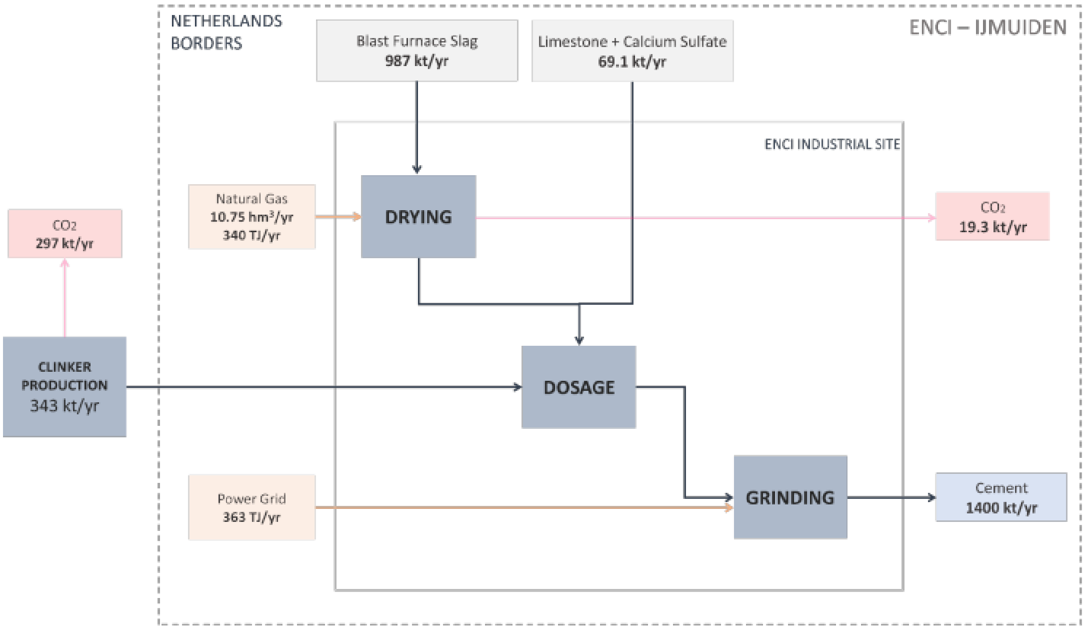

Figure 5-1: Production Process ENCI IJmuiden in full capacity (Xavier & Oliveira, 2021)

A barrier towards exploring the impact of the allowance price on the cement price is that ENCI does not completely execute the cement production chain. This is, for example, different compared to the steel production chain of Tata Steel, which executes the entire process. ENCI only executes the drying, dosage and grinding process, but it does not produce the polluting clinker. Because ENCI only dries and grinds the materials in their process, they have very low emissions compared to other cement sites with coupled production. This results in the assumption that ENCI does not receive any free allowances for their drying and grinding production process because these production processes are not at risk of carbon leakage. So, the free allowances within the cement production chain are allocated to the clinker producers because the EU identified clinker production as an activity at risk of unfair competition under the ETS. European clinker producers can obtain free allowances to mitigate the risk of unfair competition.

Therefore, the calculation will be done by combining the 2 individual steps into one cement production chain. A distinction will be made between the clinker production and the activities carried out by ENCI. The clinker production determines the received number of free allowances within the cement production chain. However, the annual emissions of the chain will be based on the combined emissions of the clinker production and the production activities of ENCI. This results in a situation where it is possible to measure the impact of the allowance price on the price of cement because it represents the entire production chain of cement. The emissions from the clinker producer relative to the total emissions from the cement production chain define the share of the total carbon costs, which can be used as opportunity costs by the clinker producer to change the market price for the clinker. The emissions produced by ENCI relative to the total emissions from the cement production do define the share of the total carbon costs, which can be used as opportunity costs by ENCI to change the market price for cement.

ENCI has not publicly published any data related to their production numbers, but as an ETS participant, they are obligated to publish their annual emissions at the 'Nederlandse emissieautoriteit'

(NEA). The data handed in at the NEA is used to estimate the production output. The historical annual ENCI emissions is divided by the maximum annual emissions of 19.3 Kt/year at the IJmuiden facility to estimate the historical output. The relative share is multiplied by the maximum production capacity of 1,400 Kt/year to estimate the historical production values. The same principle will also be used to calculate the number of clinkers that is used as input to produce cement. This method assumes that there have not been any efficiency improvements in their production process since 2014. Table 5-4 displays the calculated values.

Table 5-4: ENCI's cement production and clinker usage, based on the relative emissions (Nederlandse emissieautoriteit, 2021)

ENCI B.V., facility IJmuiden	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
CO_2eq emissions ENCI (Kilo tonnes)	8.47	11.44	15.26	15.35	13.23	13.76
Relative output to maximum	0.44	0.59	0.79	0.80	0.69	0.71
Cement production (Kilo tonnes/year)	614.62	829.77	1,106.80	1,113.25	959.69	997.92
Clinker producer, facility unknown						
Clinker input (Kilo tonnes/year)	150.58	203.29	271.17	272.75	235.12	244.49
CO_2eq clinker production (Kilo tonnes/year)	130.39	176.03	234.80	236.17	203.59	211.70

The Benchmark value to produce cement clinker is 0.693 allowances/tonne output for 2021. This rate has an annual reduction rate of 0.63 % based on the opportunities for technological development (European Commission, 2021h). This results in a BM value of 0.689 for 2022. The HAL value is the average clinker production between 2014 and 2018. This value is calculated based on the production values in table 5-4, which results in 226.58 Kt/year. The cross-sectoral correction factor is set to 100 percent for the period between 2021 and 2025 (European Commission, 2021g). The clinker production sector is considered at high risk of carbon leakage, resulting in a 100 percent carbon leakage exposure factor for grey cement clinker (European Commission, 2019a).

The expected emissions for the 2022 Dutch cement production chain are predicted based on the combined average emissions of ENCI and the clinker production between 2017 and 2019. The expected cement output for the Dutch market in 2022 is also based on the average cement output between 2017 and 2019. The period between 2017 and 2019 is taken as a reference period to predict the cement output and cement emissions. The same reference period is taken to estimate the steel output for 2022.

The pass-through ratio is the last missing variable to calculate the relation between the allowance price and the price increase of cement. This is again a variable with a very uncertain value, due to the private price setting strategies of private companies'. Based on the different PTRs found in the literature, multiple scenarios will be explored with different values for the PTR variable. CE Delft (2016) found an average PTR for the cement production industry of 39 percent, a minimum of 20 percent and a maximum of 58 percent, so these values are the values that will be used in the different scenarios.

The two frameworks and the three PTRs also create six scenarios for the cement production chain. These scenarios will be explored to research the impact of the allowance price on the cement price. The input values of the different variables are displayed in table 5-5 and represent the values for 2022.

Table 5-5: Overview of the input variables for the scenario analysis of the allowance price impact on the cement market price

	Reduced opportunity costs			Profit maximisation		
	Average	**minimum**	**maximum**	**Average**	**minimum**	**maximum**
Benchmark value (Allowance/Tonne)	0.689	0.689	0.689	-	-	-
Historic activity level (kilo Tonne)	226.58	226.58	226.58	-	-	-
Carbon leakage exposure factor	1.00	1.00	1.00	-	-	-
Cross sectoral correction factor	1.00	1.00	1.00	-	-	-
Combined annual ETS emissions (kilo Tonne)	231.26	231.26	231.26	231.26	231.26	231.26
Annual cement output (kilo Tonne)	1,023.62	1,023.62	1,023.62	1,023.62	1023.62	1023.62
Pass through ratio carbon costs (%)	39	20	58	39	20	58

5.2. Results scenario analysis

This section presents the results of the relation between the allowance price and the material price for steel and concrete for the different scenarios. First, the impact on the steel price will be presented and discussed. After that, the impact on the cement price will be presented and discussed.

The EU allowance price impact on the steel price

Figure 5-2 presents the results of the impact of the EU allowance price on the price per tonne of steel under both frameworks. These results are obtained by following the first and second theoretical frameworks, presented in figure 4-3 and figure 4-4. First, the results of the reduced opportunity costs framework will be discussed. The first framework assumes that the freely received allowances are directly used to compensate for the production emissions of Tata Steel IJmuiden. This reduces the product's carbon costs, which automatically reduced the opportunity costs to make product price adjustments.

A carbon pricing analysis from oil company Shell assumes that an allowance price of more than 200 euros per allowance is necessary to deliver and sustain the emission cuts of the EU to reach climate neutrality in 2050 (Hatherick, 2020). This report displays the relation up to an allowance price of 250 euros per allowance to assure that the allowance price that could reach climate neutrality is included. This graph range will also be applied to the following graphs within this report that consider a relation with the allowance price.

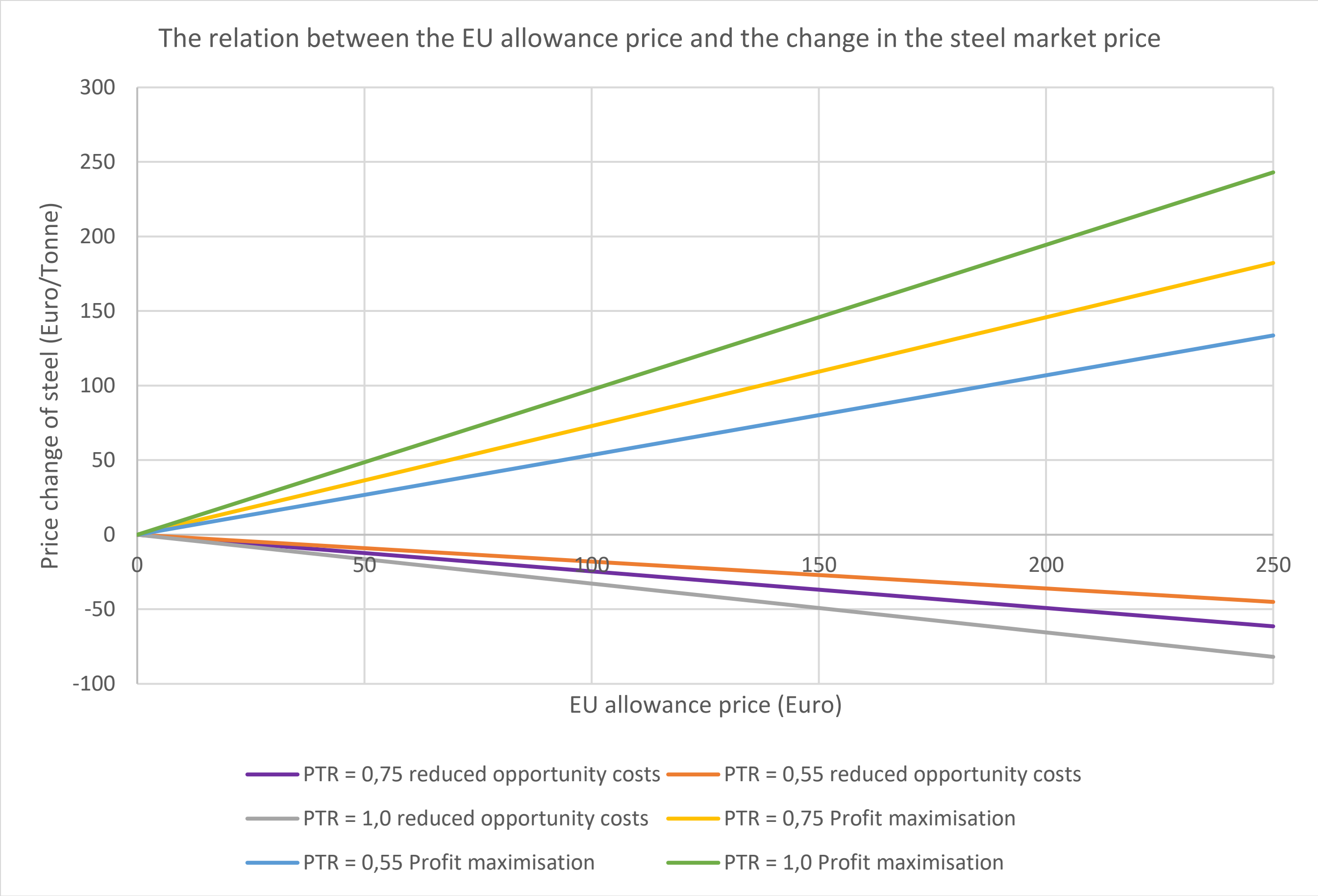

Figure 5-2: Relation between the EU allowance price and the price change of steel under the reduced opportunity costs and profit maximisation circumstances

The first thing to notice about the results from the reduced opportunity costs framework in figure 5-2 is that a negative relation is found between the allowance price and the price of steel under the reduced opportunity costs framework. The negative relation means that the price per tonne of steel drops when the allowance price increases. The negative relation under this framework can be explained because Tata Steel receives more allowances for free than it needs to hand in to compensate for its annual emissions. This creates an allowance surplus under these three scenarios. The allowance surplus has a value on the ETS market where Tata can sell their allowance surplus and use the profit to reduce their production costs and lower the final steel price. The higher the allowance price, the more value the surplus has, so the stronger the steel price can be lowered. A higher applied PTR also contributes to a lower steel price under the reduced opportunity costs framework. The higher the PTR, the bigger the share of the surplus-value that is passed through into the steel product price, and the stronger the final price reduces.

Figure 5-2 also presents the relation between the impact of the EU allowance price and the price per tonne of steel under the profit maximisation framework. This framework assumes that the number of freely received allowances does not influence a change in the steel price. The extra production costs in the form of emission costs are entirely used as opportunity costs by the producer to justify an increase in their product price. The producer will use the free allowances after the price has been changed to lower their own production costs and increase their margin of profit.

A positive relation can be noticed between the allowance price and the price for steel under the profit maximisation framework. Once the allowance price increases, the production costs increase as well.

This creates the opportunity for Tata to use these extra production costs as opportunity costs and raise their product prices. The height of the applied PTR influences the speed of the price increase. A higher applied PTR results in a larger share of the production costs being used as opportunity costs, which justifies a stronger increase in the steel price.

The gradient of the lines under the maximized opportunity costs framework is much steeper than the lines under the reduced opportunity costs framework. This is the consequence of the direct use of the free allowances, which dampens the opportunity to use the carbon costs as opportunity costs and justify a price increase towards the market.

The EU allowance price impact on the price of cement

Figure 5-3 presents the results of the impact of the EU allowance price on the price per tonne of cement under both frameworks and the different PTRs. The reduced opportunity costs framework assumes that the freely received allowances are directly used to compensate for the production emissions from the cement production chain. This reduces the product's carbon costs, which automatically reduces the opportunity costs for the clinker producer and cement producer to adjust the product price.

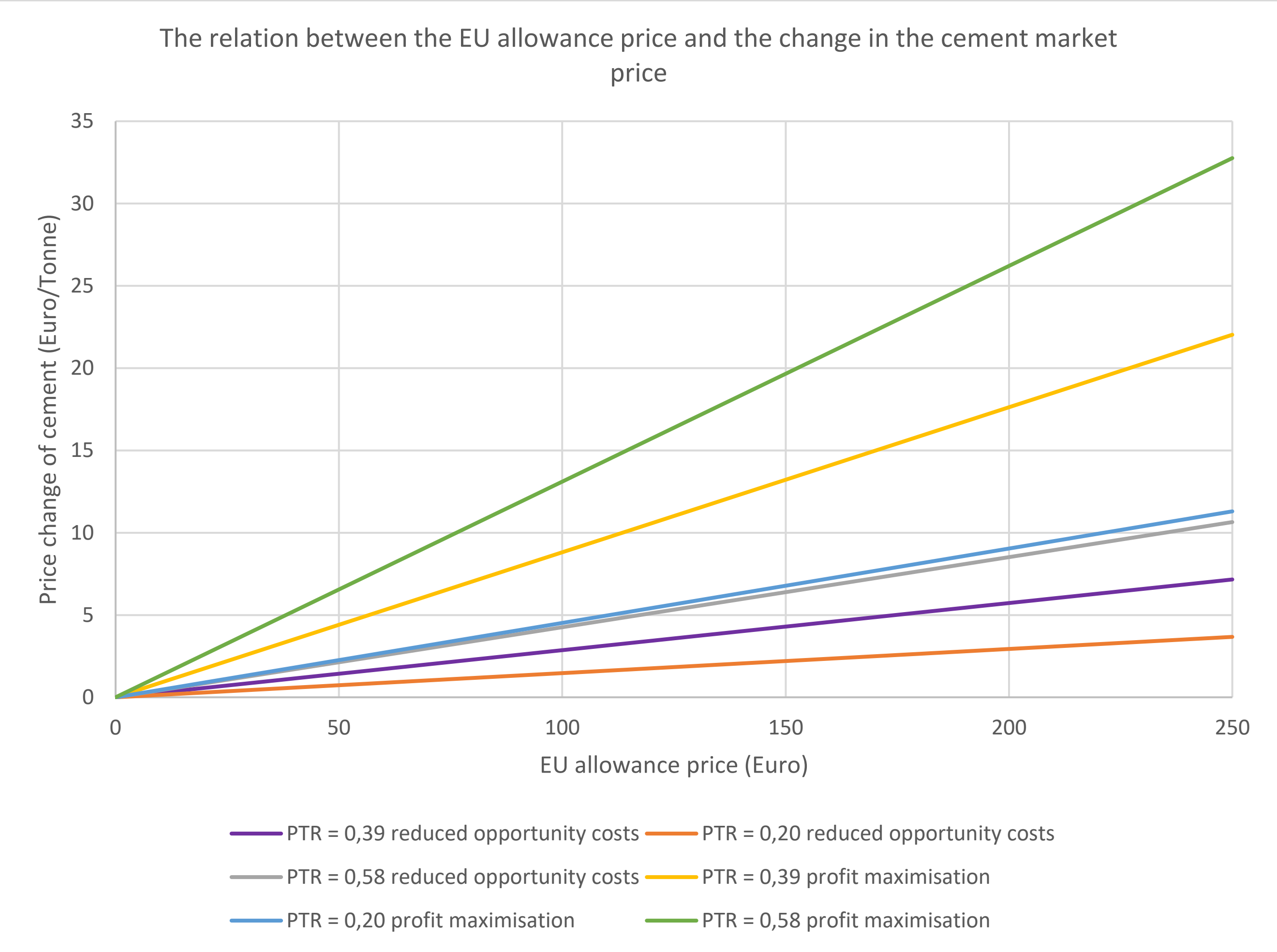

Figure 5-3: Relation between the EU allowance price and the price change of cement under the reduced opportunity costs and profit maximisation circumstances

The results in figure 5-3 show a positive relation between the allowance price and the product price increase of cement under the reduced opportunity costs framework. The positive relation means that the number of allocated free allowances did not fully cover the total emissions made in the cement production chain. The results also show that a higher PTR increases the size of the change in the cement price. The higher the applied PTR, the more carbon costs that are passed through into the cement market price.

Figure 5-3 also shows the relation between the impact of the EU allowance price and the price per tonne of cement under the profit maximization framework. This framework is presented in figure 4-4. This framework assumes that the number of freely received allowances does not influence any changes in the market price of cement. The extra production costs in the form of emission costs are entirely used as opportunity costs by the producer to justify an increase in their product price. The clinker producer will use the free allowances after the price has been increased to lower their production costs and increase their margin of profit.

A positive relation can be noted between the allowance price and the increase in the cement price. The gradient of the lines under the profit maximisation framework is around three times steeper compared to lines under the reduced opportunity costs framework. This means that the price of cement increases around three times faster for every euro increase in the allowance price under the profit maximisation framework compared to the reduced opportunity costs framework. The increased impact of the allowance price on the cement price can be explained because the total carbon costs are used as opportunity costs. This allows the producers of clinker and cement to justify an increase in their product prices. The PTR decides how much of the carbon costs are passed through into the market price, so a higher PTR results in a stronger positive relation between the allowance price and the market price for cement.

Looking at the results from the different scenarios, especially one thing is noteworthy. The negative relation between the allowance price and the price per tonne of steel under the reduced opportunity costs circumstances is remarkable. Figure 5-4 presents the development of the EU allowance price on the left and the development of the global steel price on the right over the last five years. In this situation, the global steel price is assumed to represent the Dutch steel market. This figure shows that, in contrast to the results in figure 5-2, the steel price can increase along with an increase in the allowance price. A positive relation would also make more sense based on one of the private companies' goals, which is to maximise financial profit. Making a profit is essential for a private company to continue to exist. This contradicts the results in figure 5-2, where an increase in the allowance price decreases the steel price.

Figure 5-4: Development of the EU allowance price over the last three years (Left) next to the development of the Steel price over the last 5 years (Right) (Trading economics, 2022)

5.3. Conclusion on the allowance price impact on steel and cement

This section will answer the third research question, which is: *What is the relation between the European Union allowance price and the material prices for steel and cement as structural building materials in the Dutch construction market?*

The answer to this question is based on the two presented frameworks in chapter 4. The first framework directly uses the free allowances to compensate for their production emissions. This reduces the carbon costs in the production process reducing the opportunity to use the ETS carbon costs as opportunity costs to adjust its product price. This framework shows that Dutch steel producer Tata Steel receives more allowances for free than it needs in total to compensate for its emissions in 2022. Tata Steel can use the surplus in allowances to lower their production costs by selling the allowances to other ETS participants on the allowance market. This results in a relation where a 1 euro increase in allowance price decreases the price per tonne of steel by 0,246 euro under the average applied PTR of 75 percent. The uncertainty about the real applied PTR made it necessary to explore the boundaries of the relation between the allowance price and the steel price by testing a minimum and maximum PTR. This resulted in a minimum decrease of 0,180 euro/tonne steel (PTR = 0,55) and a maximum decrease of 0,328 euro/tonne steel (PTR = 1,0) for every euro that the allowance price increases.

The same framework has been used to explore the relation between the allowance price and the price of Dutch cement. The results show that the cement production chain does not receive more allowances for free than it needs to compensate for its production emissions. So, there is no allowance surplus within the cement production chain, so an increase in the allowance price also increases the cement market price. This results in a relation where a 1 euro increase in allowance price increases the price per tonne of cement by 0,028 euro under the average applied PTR of 39 percent. The uncertainty about the real applied PTR made it necessary to explore the boundaries of the relation by also testing the minimum and maximum PTR. This resulted in a minimum increase of 0,015 euro/tonne cement (PTR = 0,20) and the maximum increase of 0,043 euro/tonne cement (PTR = 0,58) for every euro that the allowance price increases.

The second framework uses all the emission costs from the ETS as opportunity costs to justify higher production costs and increase their product price. The producer still receives free allowances, but they do not influence the size of the price increase. They are only used to lower their own production costs after adjusting the price. This framework shows that the Dutch steel producer Tata Steel increases its product price along with an increase in the allowance price. This results in a positive relation where a 1 euro increase in the allowance price increases the price per tonne of steel by 0,729 euro under the average applied PTR of 75 percent. The boundaries of the relation have also been tested by the maximum and minimum PTR. This resulted in a minimum increase of 0,535 euro/tonne steel (PTR = 0,55) and a maximum increase of 0,972 euro/tonne steel (PTR = 1,0) for every euro that the allowance price increases.

The same framework has been used to explore the relation between the allowance price and the Dutch cement price. This framework shows that the Dutch cement production chain increases the product price of cement along with an increase in the allowance price. This results in a positive relation where a 1 euro increase in the allowance price increases the price per tonne of cement by 0,088 euro under the average applied PTR of 39 percent. The boundaries of the relation have also been tested by the maximum and minimum PTR. This resulted in a minimum increase of 0,045 euro/tonne steel (PTR = 0,20) and a maximum increase of 0,131 euro/tonne steel (PTR = 0,58) for every euro that the allowance price increases.

The negative relation between the allowance price and the price for steel under the reduced opportunity costs framework is in contrast with the historical data about the allowance price development and the steel price development. The data from the last five years have shown a positive trend between the allowance price and the steel price. The positive trend is also supported by a private company's goal of profit maximisation to be able to continue existing. The goal of profit maximisation does also apply to cement producers. Therefore, the decision has been made to exclude the results from the reduced opportunity costs framework from any further calculations in the rest of this report. This means that the ETS allowance tipping point for an affordable timber structure will be found with the help of the results from the profit maximisation framework.

6. Life cycle assessment results

Chapter 6 will calculate the global warming potential of the different office and welfare designs by executing a life cycle analysis. This chapter answers the fourth sub-question: *What is the level of embodied carbon for the steel, concrete and timber structural designs of the selected project? A* list of materials is extracted and used as input for the LCA analysis for every design. The individual materials are added up into simplified lists, which are used as input for the one-click tool. These lists are presented in appendix A. Section 6.1 explains how the materials from the office and welfare design are translated into materials that are available in the one-click tool. Section 6.2 presents the LCA results for all three designs. Section 6.3 formulates a conclusion to the fourth research question.

6.1. One-click material selection

The one-click material database consists of thousands of materials, but the selected materials within the office and welfare designs are not always 1:1 applicable. This section explains how the translation from office and welfare materials is made into the available materials in the one-click tool.

To be consistent and transparent in the material selection process, a criteria order is made to select the most suitable materials in the one-click tool. These criteria are implemented based on the following order:

1. Correct material type
2. Correct available unit
3. Origin of the product

The most important criterion is that the correct type of material is selected. This starts with the correct material and is followed by the correct applicability of the material. The second criterion is that the correct unit must be available for the selected material in One-click. This means that the one-click unit has to match the material unit that has been exported from the office and welfare design. All the material volumes are expressed in cubic meters, so the One-click material has to have the same unit. This prevents unnecessary unit translations, which reduce the effectiveness of the outcome. The last criterion focuses on the production origin of the material. The production process of construction materials can have a different environmental impact based on the country that has produced the product. This research scope focuses on the impact of the ETS on the Dutch construction market, so that is why the Netherlands is the preferred origin for the product. Suppose the first two criteria cannot be combined with the third criteria. In that case, a German product is selected because the German production process is assumed to be the most comparable to Dutch production processes. The precast concrete elements are the only elements with a German origin because no suitable Dutch material could be found for this element. Appendix A presents how all the design materials are translated into one-click materials.

All material volumes are entered with four decimal places to be consistent in the input variables. The travel distance is set to 60 kilometres because this is also set as the default travel distance for Dutch materials in One-click. This value is in line with the CBS data (2013), where the median travel distance for construction materials is around 50 km per trip. This substantiates the average travel distance of 60 kilometres for construction materials within the Netherlands. The mode of transport is kept at its default choice for the selected materials, and this resulted in two different modes of transport. The trailer combination is selected for precast materials like steel, timber and precast concrete, and a concrete mixer truck is used for on-site casted concrete.

6.2. LCA results

This section presents the results of the LCA analysis performed on the different office and welfare designs. First, the overall levels of embodied carbon will be presented and discussed. After that, the embodied carbon per life cycle phase per design and the embodied carbon per structural element per design will be presented and discussed.

Table 6-1: Levels of the embodied carbon of the three different office and welfare designs

	Global warming potential (tonne CO_2)			
	A1-A3 phase	**A4 phase**	**C1-C4 phase**	**Total GWP**
Steel design	1,020.00	17.60	7.76	1,045.36
Concrete design (compensated)	1,222.90	36.56	28.98	1,288.45
Timber design	436.00	16.40	50.50	502.90

Table 6-1 presents the total levels of embodied and levels per phase for the three different office and welfare designs. The LCA results for the concrete design have already been multiplied by 1.2229 to compensate for the smaller size of the concrete building compared to the steel and timber building. The results show that the timber design has a significantly lower impact on the environment than the steel and concrete design, with a GWP of 503 tonne CO_2. The steel design is the second-best option with a GWP of 1,045 tonne CO_2, while the concrete design has the most significant negative impact on the environment with a GWP of 1,288 tonne CO_2.

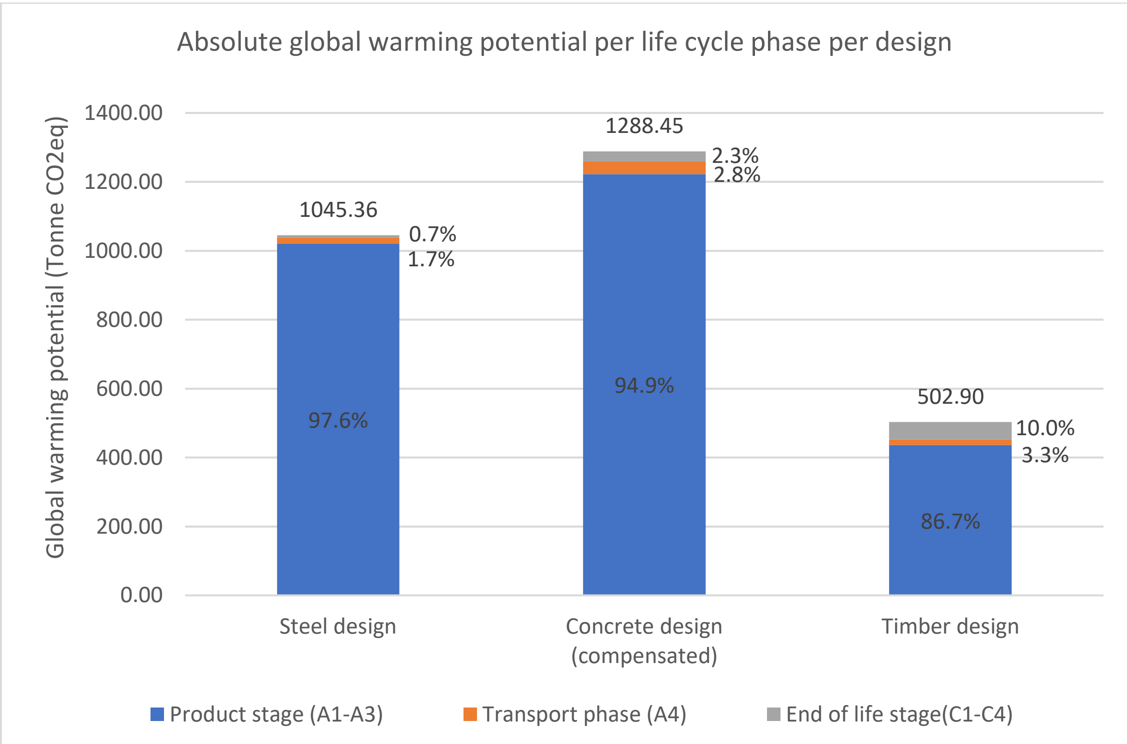

Figure 6-1: Absolute global warming potential per life cycle phase per design

The most significant contribution to the total GWP comes from the production stage (A1-A3). The percentual shares of the GWP per life cycle phase are presented relative to the total GWP in figure 6-1. This figure shows that 86,7-97,6 percent of the global warming potential comes from the production stage. This stage includes the raw material extraction, transport to the manufacturer and the manufacturing phases. The percentual contribution of the transportation phase (A4) is more significant for the concrete and timber design than for the steel design because they must transport bigger volumes of material to the construction site. The end-of-life stage (C1-C4) consists of a project's demolition, transport, waste processing and disposal phase. The percentual contribution of the end-of-life stage to the total GWP is the biggest for the timber design. One-click assumes that the quality of the timber has declined to such an extent that it can no longer meet the minimum quality requirements for reuse. This results in the assumption that timber is used as biofuel and burned after usage. The burning process emits carbon dioxide, which increases the GWP for the end-of-life stage. At the same time, One-click assumes that concrete is crushed and recycled after usage, making the GWP for concrete small compared to timber for the end-of-life stage. For steel is assumed that steel structures could directly be re-used in other projects because there is no loss of quality after usage. Therefore, steel results in a very low GWP in the end-of-life stage for the use of steel.

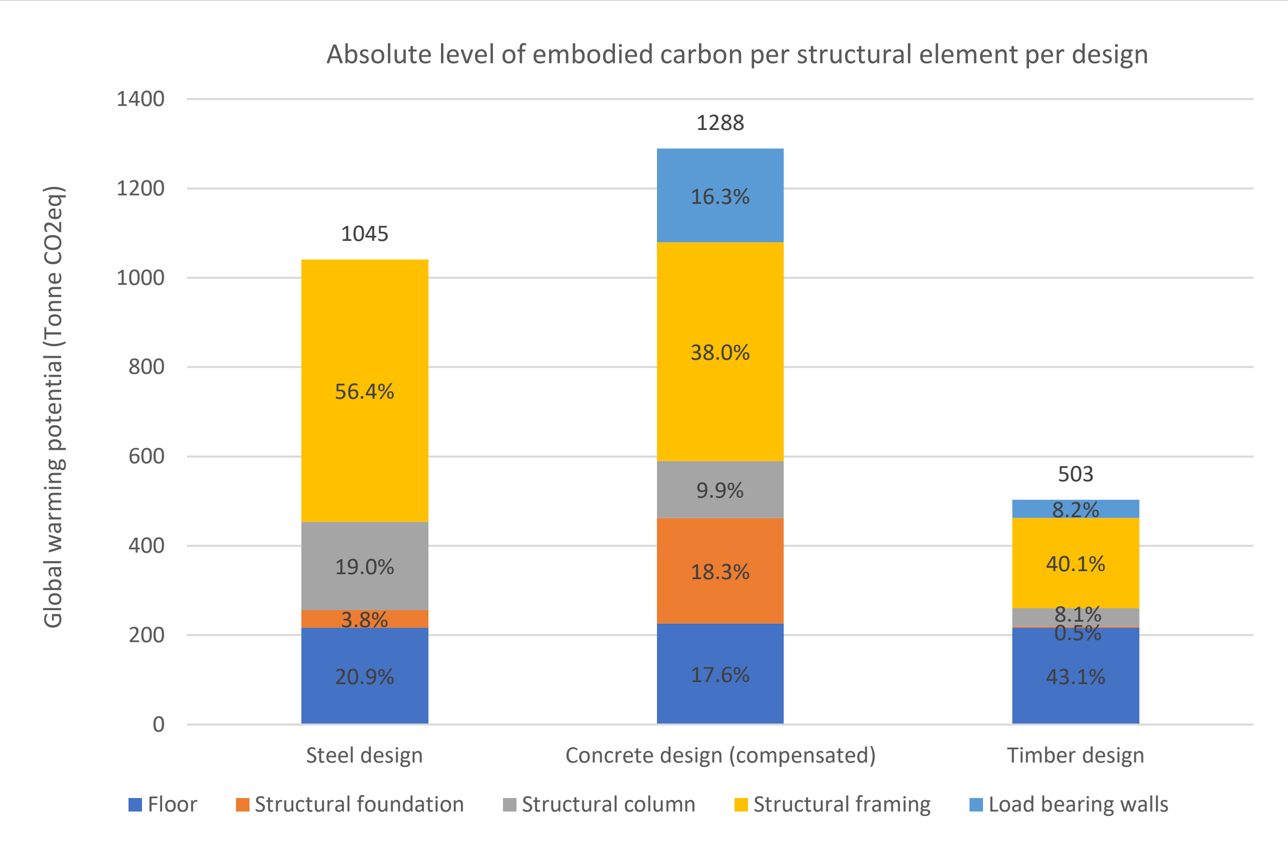

Figure 6-2: Absolute contribution to the global warming potential per structural element per design

Since the results of the total GWP per design are known, it is also essential to gain insights into how the individual structural parts contribute to the total GWP. Figure 6-2 presents the exact contribution to the global warming potential for every structural element within the three designs. The exact GWP contribution of the floor is equal for the three designs because they all present the same floor size. The structural framing is the most significant contributor to the total GWP for the steel and concrete designs due to large quantities of steel within this element. Timber is partly used as a building material in three structural elements of the design: the structural columns, structural framing and load-bearing walls. The use of timber within these three elements has significantly lowered the GWP of the timber design compared to the steel and concrete designs. The timber design has a GWP of 284 tonnes CO_2eq over these three elements, while the steel design has a GWP of 785 tonnes CO_2eq, and the concrete design has a GWP of 827 tonnes CO_2eq measured over the same elements. This is a reduction of around 65 percent, which can be attributed to the use of timber instead of steel or concrete. This confirms that the use of timber in the structure of a building lowers the negative impact on the environment. The percentage of 65 percent could be even higher if the non-timber components in the timber design were substituted for timber components.

6.3. Conclusion embodied carbon

This section will answer the fourth sub-question: *What is the level of embodied carbon for the steel, concrete, and timber structural designs of the selected project?*

The answer is based on the LCA analysis that has been performed on the three different material lists. The level of embodied carbon is reported in the form of the global warming potential, which is expressed in CO_2eq. The results showed that the timber design has the lowest total global warming potential, which was 502,9 tonnes CO_2eq. The steel design has the second-lowest global warming potential, which was 1045,4 tonnes CO_2eq, which is 108 percent higher than the timber design. The concrete design has the highest global warming potential with a value of 1288,4 tonnes CO_2eq, which is 156 percent higher compared to the timber design. This means that the life cycle analysis has confirmed that the timber design has the least negative impact on the environment followed by the steel and concrete designs. The usage of timber has shown that a minimum reduction of 65 percent in the level of embodied carbon can be achieved by selecting the timber design instead of the steel or concrete design. The actual percentage could even be significantly higher if the non-timber elements were substituted for timber elements in the timber design. Therefore, using timber as a building material in the structure of a building contributes to a more sustainable construction sector.

Of the different life cycle stages, the production stage (A1-A3) has the highest contribution to the embodied carbon of the three cases. This stage consists of the raw material extraction, the transport to the manufacturer and the manufacturing phases. This stage contributes at least 86,7 percent to a structural design's total global warming potential. The structural framing element contains the most significant share of embodied carbon for the steel and concrete designs. In contrast, the floor element contains the biggest share of embodied carbon for the timber design. The structural framing element had a minimum contribution of 38 percent to the total global warming potential. Lowering the emissions in the material production process or the structural framing could therefore have the most significant reduction in the total level of embodied carbon.

7. Realisation costs

Chapter 7 will calculate the realisation costs for the different office and welfare designs by performing cost analysis. This chapter answers the fifth sub-question: *What are the realisation costs for the steel, concrete and timber structural designs of the selected project?* The extracted material lists (appendix A) will be used as input for the cost analysis. The costs will be calculated for every individual material, and the sum of all materials will be added up to the total realisation costs. Section 7.1 explains how the realisation costs are calculated for the different input materials. Section 7.2 presents the results of the cost analysis. Section 7.3 formulates the conclusion to the fifth sub-question.

7.1. Realisation costs calculations

The costs for all parts of the design have to be combined to calculate the total realisation costs for the different designs. The realisation costs can also be seen as the total costs. The differences in total costs will be analysed to investigate which design is the least and the most expensive. This gives insights into the most crucial barrier towards the implementation of sustainable construction projects, the barrier of affordability. This section will present how the costs for all the individual parts are calculated that are present in one of the designs.

The total realisation costs consist of two components. The material costs component and the installation costs component. The material costs component is the component that represents the costs to acquire the necessary material. In contrast, the installation component represents the costs that are made to install the material at the construction site. The way that both components are built up depends on the type of material. The cost differences will be analysed per component per design and for the total realisation costs. This three-step analysis helps to understand how the total costs per design differ per cost component. This is important because of the absence of a standardised formula for the installation costs of the different materials. The absence of a standardised formula increases the uncertainty about whether the realisation costs of the three designs could be compared on an equal scale. The material costs are calculated in the same way for the different materials, so these costs can be compared fairly.

This research uses constant values for the variables used in the cost calculations formulas. These values are based on the values which Royal HaskoningDHV uses at the start of 2022 to make cost estimations for new construction projects. Some of the used variables do contain a time (t) component, and this indicates that the value of this variable could fluctuate over time. The covid pandemic is an example that recently impacted the volatility of material prices within the construction sector (Kightliner, 2022). This research applies the variable values applicable at the start of 2022, but these values could have to be reconsidered under different market circumstances in the future.

Steel costs calculations

The steel realisation costs are calculated by adding the material costs (euro) to the installation costs (euro). The realisation costs formula is the same for all calculated materials. The material costs for steel are calculated by multiplying the steel price per kilo (euro/kg) by the mass per linear meter of the beam (kg/m) and the length of the beam (m). The installation costs for steel are calculated by multiplying the installation factor (#) by the material costs (euro).

1. $Realisation\ costs_{steel,t} = Material\ costs_{steel,t} + Installation\ costs_{steel,t}$
2. $Material\ costs_{steel,t} = Price_{steel,t} * \frac{Mass}{Linear\ meter} * Length$
3. $Installation\ costs_{steel,t} = Installation\ factor_{steel,t} * Material\ costs_{steel,t}$

Concrete in situ costs calculations

The material costs for concrete in situ are calculated by multiplying the concrete volume (m3) by the concrete price per cubic meter (euro/m3). The installation costs consist of worker costs and pump costs. The worker costs are calculated by the time that the worker needs to control the pump (hour) times the costs for the worker (euro/hour). The time that the worker needs to control the pump can be calculated by dividing the total concrete volume (m3) by the pump's capacity (m3/hour). The costs for the pump are calculated by multiplying the concrete volume (m3) by the price for the pump (euro/m3).

4. $Realisation\ costs_{concrete,t} = Material\ costs_{concrete,t} + Installation\ costs_{concrete,t}$
5. $Material\ costs_{concrete,t} = Volume * Price_{concrete,t}$
6. $Installation\ costs_{concrete,t} = \left(\frac{Volume}{Capacity_{pump}} * Price_{worker,t}\right) + (Volume * Price_{pump,t})$

Precast concrete costs calculations

The material costs for prefab concrete elements are calculated by multiplying the prefab volume (m3) by the prefab concrete price per cubic meter (euro/m3). The installation costs per individual prefab element are calculated by the sum of the costs to set the beam and attach the beam. The costs to set the beam is calculated by multiplying the labour to adjust the beam (hour) by the costs for the worker (euro/hour). The costs to attach the beam are calculated by multiplying the labour for the beam attachment (hour) by the costs for the worker (euro/hour). These costs are the costs for installing one individual beam, so the installation costs must be multiplied by the number of prefab elements to calculate the total installation costs.

7. $Realisation\ costs_{prefab\ concrete,t} = Material\ costs_{prefab\ concrete,t} + Installation\ costs_{prefab\ concrete,t}$
8. $Material\ costs_{prefab\ concrete,t} = Volume * Price_{prefab\ concrete,t}$
9. $Installation\ costs_{prefab\ concrete,t} = Labour_{beam\ adjustment} * Price_{worker,t} + Labour_{beam\ attachment} * Price_{worker,t}$

Timber costs calculations

The material costs for timber are calculated by multiplying the timber volume (m3) by the price per cubic meter of timber (euro/m3). The installation costs are calculated by multiplying the volume (m3) by the installation costs (euro/m3).

10. $Realisation\ costs_{timber,t} = Material\ costs_{timber,t} + Installation\ costs_{timber,t}$
11. $Material\ costs_{timber,t} = Volume * Price_{timber,t}$
12. $Installation\ costs_{timber,t} = Volume * Price_{installation,t}$

Constant variables

The formulas for the material and installation costs can be simplified by filling in all the values of the constant variables. The constant variables and their values are presented in table 7-1. The variable values are based on Royal HaskoningDHV's used values for their cost estimations since the beginning of 2022. The average ETS allowance price over January 2022 was 85 euros per allowance, so the values of the variables are assumed to be affected by an allowance price of 85 euros. This assumption is essential in the continuation of the study because this allowance price is the starting point for the calculations to answer the main research question.

Table 7-1: Constant variables for the realisation cost calculations (RHDHV, 2022; Betonhuis, 2018)

Material	variable	value
Steel	$Price_{steel,t}$	4.5 euro/kg
Steel	$Installation\ factor_{steel,t}$	0.1
Concrete	$Capacity_{pump}$	100 m3/hour
Concrete	$Price_{worker,t}$	49.0 euro/hour
Concrete	$Price_{pump}$	9.0 euro/m3
Concrete	$Labour_{beam\ adjustment}$	2.5 hours
Concrete	$Labour_{beam\ attachment}$	1.0 hour
Timber	$Price_{timber,t}$	1,190 euro/m3
Timber	$Price_{installation}$	510 euro/m3

The mass per linear meter is needed to calculate the costs for the different steel parts. Appendix B presents the mass per linear meter values for all the different types of steel.

In contrast to the steel and timber price, the price per cubic meter of concrete is not constant. This concrete price depends on the type and composition of the product. ENCI IJmuiden produces 89 percent CEM III cement, also known as blast furnace slag cement. Blast furnace slag cement can be produced efficiently because ENCI uses the furnace slag from their neighbouring company Tata Steel. The exact used type of cement in concrete is important because it affects the density of the concrete mix and the necessary share of cement within the concrete mix. This report assumes that ENCI's CEM III A 42,5 N is used as a cement component within the concrete parts constructed for the office and welfare design. The capital A of this type indicates a share of 34-64 percent clinker within the cement mix. This is in line with the average clinker content of 46 percent in the Netherlands (Xavier & Oliveira, 2021). The 42,5 N is selected over the 32,5 N or 52,5 N types because the 42,5 is the most versatile in its applicability. This makes the 42,5 N type the favourite pick for the multiple applications like foundations, floors and columns which have to be constructed for the office and welfare part.

Now that the type of cement is known, a table can be made to state the densities for the different concrete types and the shares of cement within the different concrete types. These values are displayed in table 7-2. The stronger the type of concrete, the bigger the share of cement needs to be. This bigger share of cement is compensated by reducing the share of sand and gravel. The data for these concrete compositions were compiled in collaboration with a concrete specialist from Royal HaskoningDHV.

Table 7-2: Concrete material characteristics per type under CEM III A 42,5 N usage (concrete specialist constructor RH-DHV)

Concrete type	Density (kg/m3)	Cement (kg/m3)	Price (Euro/m3)
C25/30	2,375	215	78.5
C28/35	2,379	257	86.5
C35/45	2,385	305	96.5
C45/55	2,392	365	106.5

7.2. Cost analysis results

This section will present the results of the cost analysis. First, an overview of the different costs per component is presented in table 7-3. This table displays the exact material, installation, and realisation costs per office and welfare design. The costs for the concrete design have already been compensated for its smaller size compared to the other two designs by multiplying all cost components by 1,2229. The cost calculations of all the individual material parts per design are presented in Appendix C.

Table 7-3: Overview of the total costs per cost component per design

	Material costs	Installation costs	Realisation costs
Steel design	€ 1,108,776.81	€ 111,747.72	€ 1,220,524.53
Concrete design (Compensated)	€ 1,274,724.32	€ 65,664.44	€ 1,340,388.75
Timber design	€ 1,273,802.89	€ 430,588.01	€ 1,704,390.90

The steel design has the lowest total material costs of € 1,108,777. This means that the costs of purely the materials are the lowest for the steel design. The total material costs for the concrete and timber designs are almost the same and are approximately 15 percent more expensive. The differences in the total realisation costs are much more significant. The concrete design has the lowest total installation costs of € 65,664. This means that the costs of constructing the office and welfare building out of the materials is the least expensive for the concrete design. The installation costs for the steel design are 70 percent more expensive, while the timber design is 555 percent more expensive. The total realisation costs exist out of the sum of the total material costs and the total installation costs. This results in the lowest total realisation costs for the steel design, which are € 1,220,525. The concrete design follows with a 9 percent more expensive design. The most expensive is the timber design, with a design of almost 40 percent more expensive. The cost analysis results show that the steel design the least expensive design to realise.

Figure 7-1 shows the ratio between the material and installation costs relative to the total realisation costs. Notable is the big difference in the share of installation costs for the timber design compared to the steel and concrete design. The total timber realisation costs exist for 25 percent of installation costs, while the steel and concrete realisation costs only exist for 9 and 5 percent of installation costs. This big difference indicates that not the entire timber design is more expensive to install, but that especially the installation of the timber elements is more expensive. This can be concluded because the floor, foundation and some columns and beams are built up out of the same materials as the used materials in the steel and concrete designs, but that did not result in those high installation costs. The big difference comes from the use of timber, which represents over 90 percent of the total installation costs of the timber design.

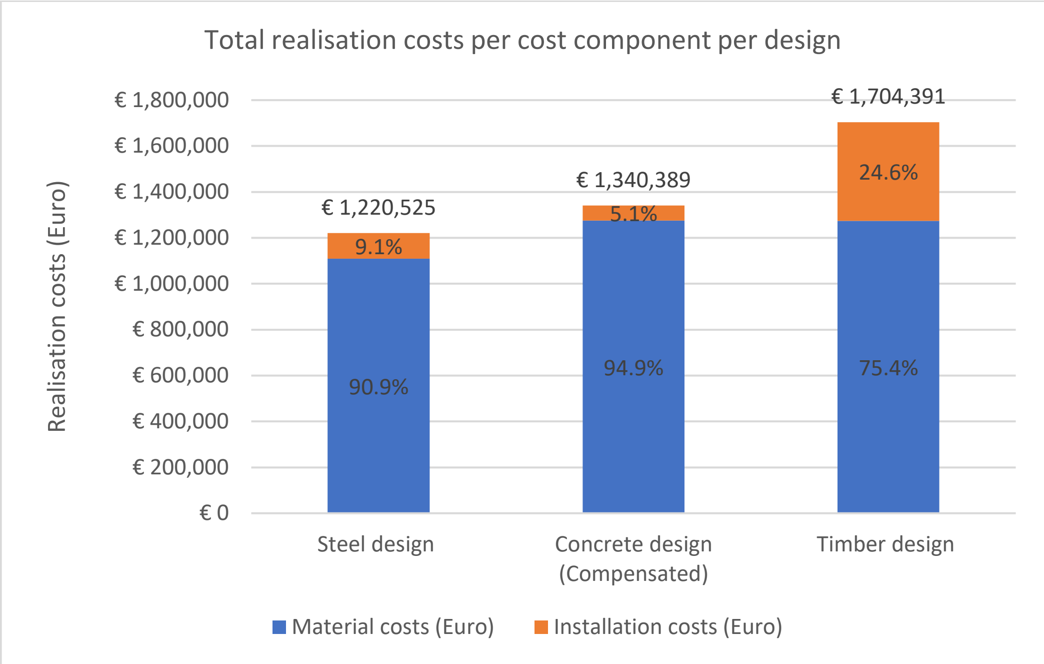

Figure 7-1: Total realisation costs per cost component per design

Figure 7-2 shows the realisation costs per structural element for the different designs. Notable is the big contribution of the structural framing to the total realisation costs per design, but this contribution is not significantly different for any of the three designs. The biggest difference in the outcome of the total realisation costs are made by the costs of the load-bearing walls. The steel design does not contain any load-bearing walls because the structural columns are already strong enough to hold the roof's weight, so no costs for any walls have to be made in this design. This is entirely different for the other two designs. The load-bearing walls of the concrete design cost over 400 thousand, while the load-bearing walls in the timber design approximately cost 800 thousand euros. These costs come from the big volumes of material that are used for the walls in both designs. The difference in the costs of the concrete and timber walls indicates that the current costs for timber are higher than the costs of concrete.

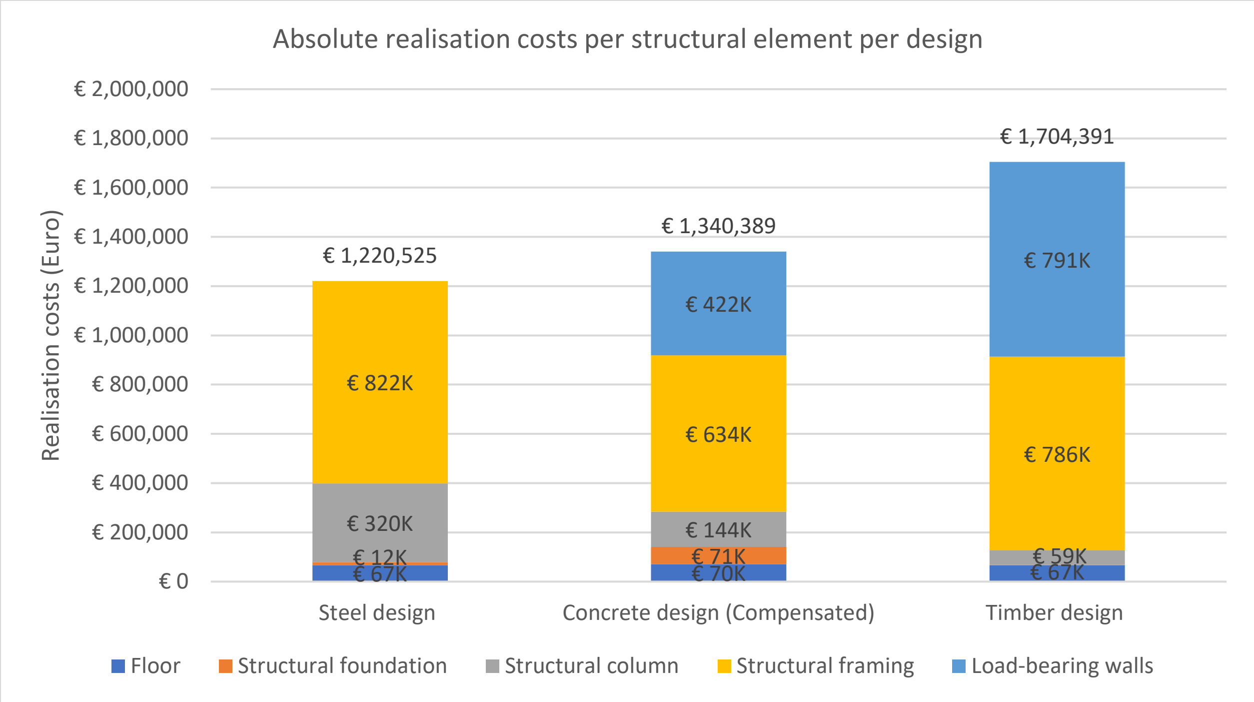

Figure 7-2: Absolute realisation costs per structural element of the design

7.3. Conclusion realisation costs

This section will answer the fifth sub-question: *What are the realisation costs for the steel, concrete and timber structural designs of the selected project?*

The answer to this question is based on the performed costs analysis on the steel, concrete and timber designs of the office and welfare building. The material list per design has been used as input for these cost analyses. The costs have been calculated based on the cost variable values that Royal HaskoningDHV has used since the beginning of 2022 to make costs estimations for new projects.

The steel office and welfare design has the lowest total realisation costs of the three designs, with a total cost of € 1,220,525. This makes the steel design financially the most favourable design to realise under the current market conditions. The concrete office and welfare design is financially the second-best option, with total realisation costs of € 1,340,389. This makes the concrete design 9 percent more expensive to realise compared to the steel design. The timber office and welfare design is financially the least attractive option to realise, with total realisation costs of € 1,704,391. This makes the timber design 40 percent more expensive to realise compared to the steel design.

The total realisation costs consist of a material costs component and an installation costs component. The steel design has the lowest total material costs out of the three designs. This means that the costs of all needed materials are the lowest for the steel design. The concrete design has the lowest total installation costs out of the three designs. This means that the total cost to install all the construction elements on site is the lowest for the concrete design. The combination of the large volumes of timber that are used in the structural framing and walls of the building and the high installation costs per cubic meter of timber resulted in total installation costs, which are 555 percent higher than the total installation costs for the concrete design. The significantly higher installation costs of the timber design resulted in much higher total realisation costs than the realisation costs of the steel and concrete design. This makes the use of timber in the office and welfare design financially unattractive compared to conventional building materials like steel and concrete.

The affordability barrier is the biggest barrier to the implementation of sustainable construction projects. The results of the costs analysis confirm that constructing a low carbon timber structure still faces significantly higher total costs than the use of steel or concrete under the current market conditions. This delays the transition towards a more sustainable construction sector.

8. ETS price tipping point

Chapter 8 will present how possible changes in the ETS allowance price would impact the total realisation costs of the different office and welfare designs and whether it could lead to a profitable business case for the timber design. This chapter will present the results to the main research question: *What is the European Union Emissions Trading System allowance price tipping point for a profitable business case for a timber constructed structure over a steel or concrete constructed structure in the Dutch built environment?* The results of sub-question 3 and 5 will be used as input to find the tipping point for a profitable business case for the low environmental impact timber design. Section 8.1 explains how the tipping point will be found and section 8.2 presents the tipping point analysis results.

8.1. Tipping point calculations

To find the ETS allowance price tipping point that results in the lowest realisation costs for the timber design, we must understand how the ETS price influences the material costs of steel and concrete. Chapter 5 has presented how the ETS allowance price influences steel and cement prices within the Dutch construction market. The results from this analysis are used to see how the price of steel and the different types of concrete will change due to a change in the ETS allowance price. A change in the material price will also change the total realisation costs per design that have been calculated in chapter 7. Therefore, it is crucial to find the allowance tipping point. The tipping point is the point where the ETS allowance price results in the lowest realisation costs for the design with the lowest environmental impact, which is the timber design. The tipping point could help to speed up the transition to a more sustainable construction sector.

8.1.1. Relation between the allowance price and the steel and concrete price

Table 8-1 presents an overview of the scenario analysis results on the relation between the EU allowance price and the price for steel and cement. The minimal, average or maximum increase depends on the applied pass-through ratio of the producer. The applied material prices for the costs analysis in chapter 7 have been based on the material prices at the start of 2022. The average allowance price in January 2022 was 85 euros per allowance, so this price is used as starting position to calculate how the material prices change due to a change in the allowance price.

Table 8-1: Overview of the relation between the EU allowance price and the price for steel and cement

	Material price increase per euro increase in the EU allowance price (Euro/Tonne)		
	Minimal increase	**Average increase**	**Maximum increase**
Steel	0.535	0.729	0.972
Cement	0.045	0.088	0.131

Steel

The steel price at the start of 2022 has been 4.5 euros per kilo. Knowing that the allowance price was 85 euros at the exact moment, a graph can be made based on this starting point on how the steel price changes due to a change in the allowance price. The following formula calculates this change in the steel price:

$$Price_{steel,t} = ((Price_{EU\ allowance,t} - 85) * \frac{Steel\ price\ increase_{PTR,t}}{1000}) + 4.5$$

The active EU allowance price (euro) at point t in time has to be reduced by 85 to compensate for the current impact of the allowance price on the steel price. The allowance price difference is multiplied by the increase in the steel price and divided by a thousand (euro/kg) to equal the units. This value is added to the currently applied steel price of 4.5 euro per kilo. The relation between the allowance price and the steel price is displayed in figure 8-1. All three lines intersect at the same point because this is the only known value as well as our starting point. The development of the real-life relation depends on the applied PTR by the producer of the steel. The PTR of 0.75 is the average PTR, which produces the expected relation between the allowance and steel prices. The other two PTRs produce the boundaries of the relation between the allowance price and the steel price.

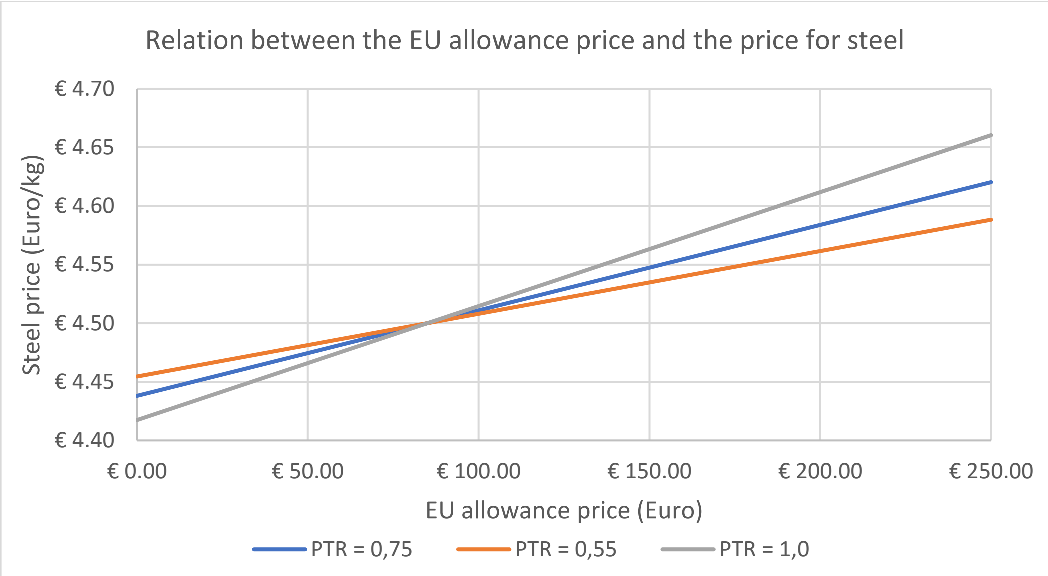

Figure 8-1: relation between the EU allowance price and the price for steel

Concrete in situ

The relation between allowance price and concrete is slightly different because the results in chapter 5 give the relation between the allowance price and the price for cement instead of concrete. Therefore it is necessary to know the shares of cement in the different types of concrete. This is presented in table 7-2. The cement shares within the different types of concrete are based on the assumption that CEM III A 42,5 N cement has been used. The stronger the concrete needs to be, the bigger the share of cement becomes within the mix. At the start of 2022, concrete prices varied between 78,50 euros per cubic meter and 106.50 euros per cubic meter for concrete in situ. The price for prefab concrete was 800 euros per cubic meter during the same period. These prices were active under an 85-euro allowance price during that period. A change in the allowance price realises a change in the cement price, which changes the price of the concrete. The drop in the use of water and gravel under a larger cement component is not included in the price because it is assumed that these slightly lower water and gravel costs are negligible. The price per cubic meter of concrete can be calculated by the following formula:

$$Price_{concrete\frac{C25}{30},t} = ((Price_{EU\ allowance,t} - 85) * (\frac{Cement\ price\ increase_{PTR,t}}{1000}) * 215) + 78.50$$

The active EU allowance price (euro) at point t in time has to be reduced by 85 to compensate for the current impact of the allowance price on the concrete price. The allowance price difference is multiplied by the increase in the cement price (euro/kg) and multiplied by the number of kilo’s cement that is mixed into one cubic meter of C25/30 concrete (kg/m3). This total is added to the current price of 78.50 (euro/m3) for C25/30 concrete. The relation between the allowance price and the price for

C25/30 concrete is displayed in figure 8-2. The real-life relation depends on the applied PTR within the cement production chain. The PTR of 0.39 is the average PTR which produces the expected relation between the allowance price and the C25/30 concrete price. The other two PTRs produce the boundaries of the relation between the allowance price and the C25/30 concrete price.

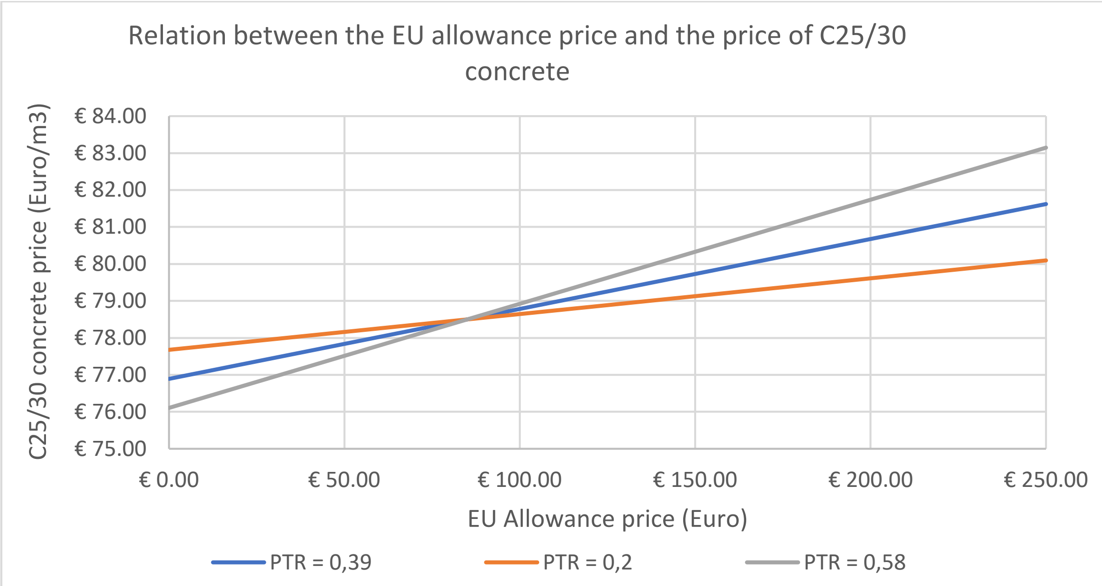

Figure 8-2 relation between the EU allowance price and the price for C25/30 concrete

The formulas for the other types of concrete in situ are calculated as followed:

$$Price_{concrete\frac{C28}{35},t} = ((Price_{EU\ allowance,t} - 85) * (\frac{Cement\ price\ increase_{PTR,t}}{1000}) * 257) + 86.50$$

$$Price_{concrete\frac{C35}{45},t} = ((Price_{EU\ allowance,t} - 85) * (\frac{Cement\ price\ increase_{PTR,t}}{1000}) * 305) + 96.50$$

$$Price_{concrete\frac{C45}{55},t} = ((Price_{EU\ allowance,t} - 85) * (\frac{Cement\ price\ increase_{PTR,t}}{1000}) * 365) + 106.50$$

The figures that display the relation between the allowance price and the price for C28/30, C35/45 and C45/55 concrete are presented in appendix D.

Prefab concrete

Prefab concrete is only applied to the walls and structural beams, and columns of the concrete design. These structural elements require a high level of strength, therefore is assumed that prefab concrete uses the same share of cement as the C45/55 concrete in situ. This results in the following formula to calculate the price per cubic meter of concrete:

$$Price_{Prefab\ concrete,t} = ((Price_{EU\ allowance,t} - 85) * (\frac{Cement\ price\ increase_{PTR,t}}{1000}) * 365) + 800$$

The figure that presents the relation between the allowance price and the price for prefab concrete is presented in appendix D

8.1.2. Tipping point scenarios

The changes in the realisation costs per design depend not only on the change in the allowance price, but also on the applied PTRs of the material producers. The actual applied PTRs are unknown, so three scenarios will be used to explore how the realisation costs of the three designs could change due to a change in the allowance price. The scenario built up is presented in table 8-2.

Table 8-2: Scenario built up for the allowance price tipping point

	Steel	Cement
1. Expected price development	PTR = 0.75	PTR = 0.39
2. Economic welfare	PTR = 1.0	PTR = 0.58
3. Construction crisis	PTR = 0.55	PTR = 0.2

The first scenario assumes that the average PTRs are used for steel and cement production. This could be the case when demand and supply are in equilibrium. This scenario will result in the expected relation between the allowance price and the total realisation costs per design using the average input values. The second scenario assumes that there is a lot of economic welfare in the Dutch economy. This results in demand exceeding supply for new buildings and new construction materials, which justifies higher applied PTRs for material producers within the Netherlands to maximise profits. The third scenario assumes a construction crisis that lowers the demand for construction materials while supply is held constant. Producers of construction materials try to maintain their market share by lowering their prices by reducing their carbon costs PTR. This scenario will display the slightest change in the realisation costs per design for every change in the allowance price.

8.1.3. Tipping point equation

The increase in the total realisation costs for the different designs will happen linearly because the material price increases with a fixed amount for every increase in allowance price. Therefore, the exact tipping point can be calculated with the help of the starting positions and the slope of the relation. The starting position presents the total realisation costs under an allowance price of zero. The slope presents the increase in the total realisation costs for every euro that the allowance price increases. The actual allowance price tipping point can be found by setting two of the linear equations equal to each other and solving them. This can be done by solving for X in the following formula:

$$Starting\ position_{design\ A} + Slope_{design\ A} * X = Starting\ position_{design\ B} + Slope_{design\ B} * X$$

8.2. Tipping point results

This section will present the results on the impact of the EU allowance price on the total realisation costs and the total material costs of the three different office and welfare designs for the three different scenarios. These results will find the price tipping point for a financially favourable timber design compared to the steel and concrete design. The exact values of the total realisation costs, material costs and installation costs under different allowance prices can be found in appendix E.

Total realisation costs

Figure 8-3 displays the relation between the EU allowance price and total realisation costs per design for all three scenarios. This figure shows that the total realisation costs remain the most expensive for the timber office and welfare design up to the displayed allowance price of 250 euros under all three scenarios.

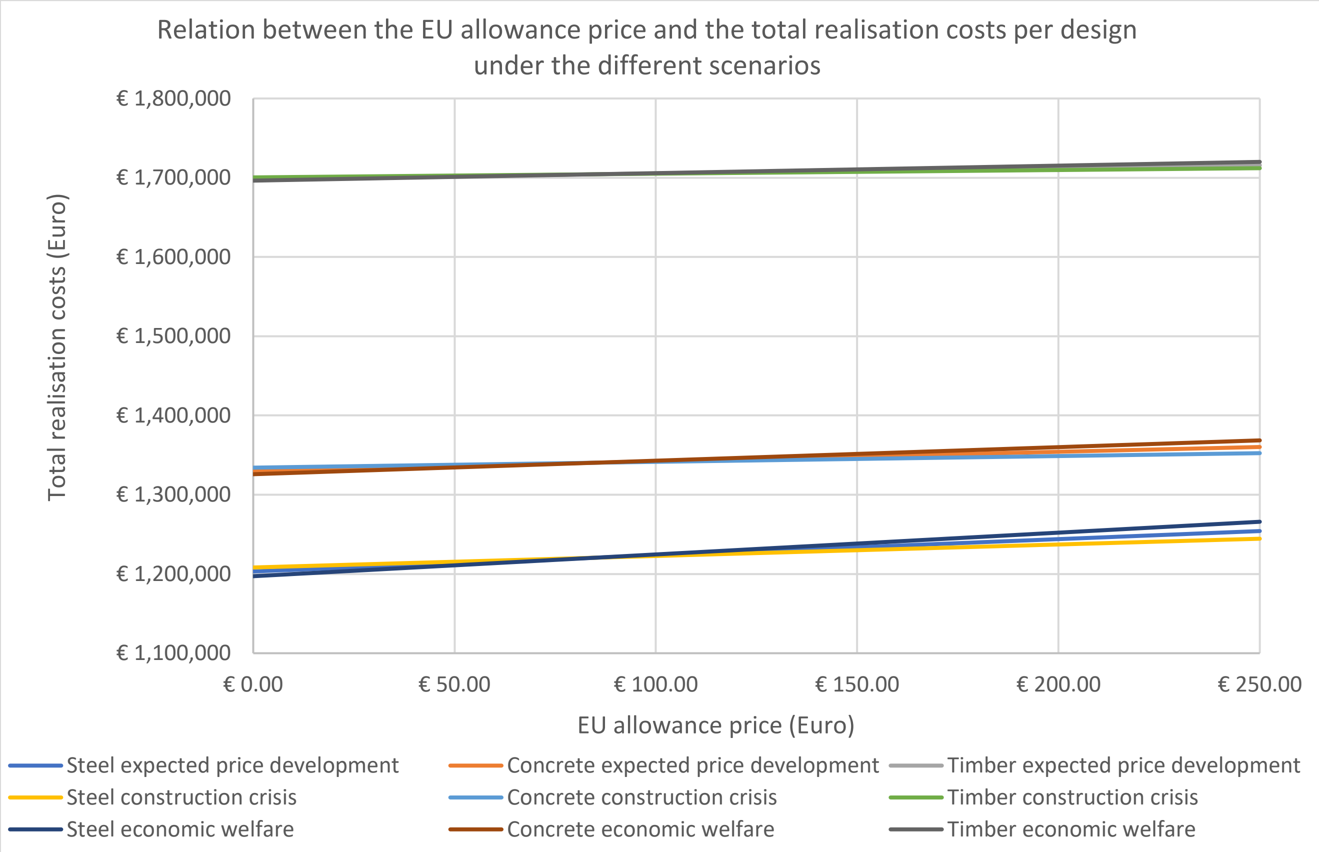

Figure 8-3: The relation between the EU allowance price and the total realisation costs per design under all three scenarios up to an allowance price of €250

The assumption of Shell that an allowance price of around 200 euros would deliver and sustain emission cuts does not apply to the office and welfare case because the environmental friendly timber design remains the most expensive to realise up to the displayed allowance price of €250 (Hatherick, 2020). However, the total realisation costs of the steel and concrete designs do increase more quickly for every increase in the allowance price compared to the timber design. This means that the timber design becomes financially favourable at some allowance price over the steel and concrete designs. This allowance price is known as the allowance price tipping point. The allowance price tipping point is found by solving the tipping point equation, which is presented in section 8.1.3. The tipping point results are presented in table 8-3.

Table 8-3: The allowance price tipping point results for the total realisation costs under the three scenarios

Scenario	**Allowance price tipping point**	**Total realisation costs**
Expected price development	€ 7,174.54	€ 2,192,470.85
Economic welfare	€ 4,864.43	€ 2,156,927.69
Construction crisis	€ 13,746.36	€ 2,338,036.53

To display the tipping point results of table 8-3, both axis from figure 8-3 have to be extended. This is done for all three designs under all three scenarios in figure 8-4.

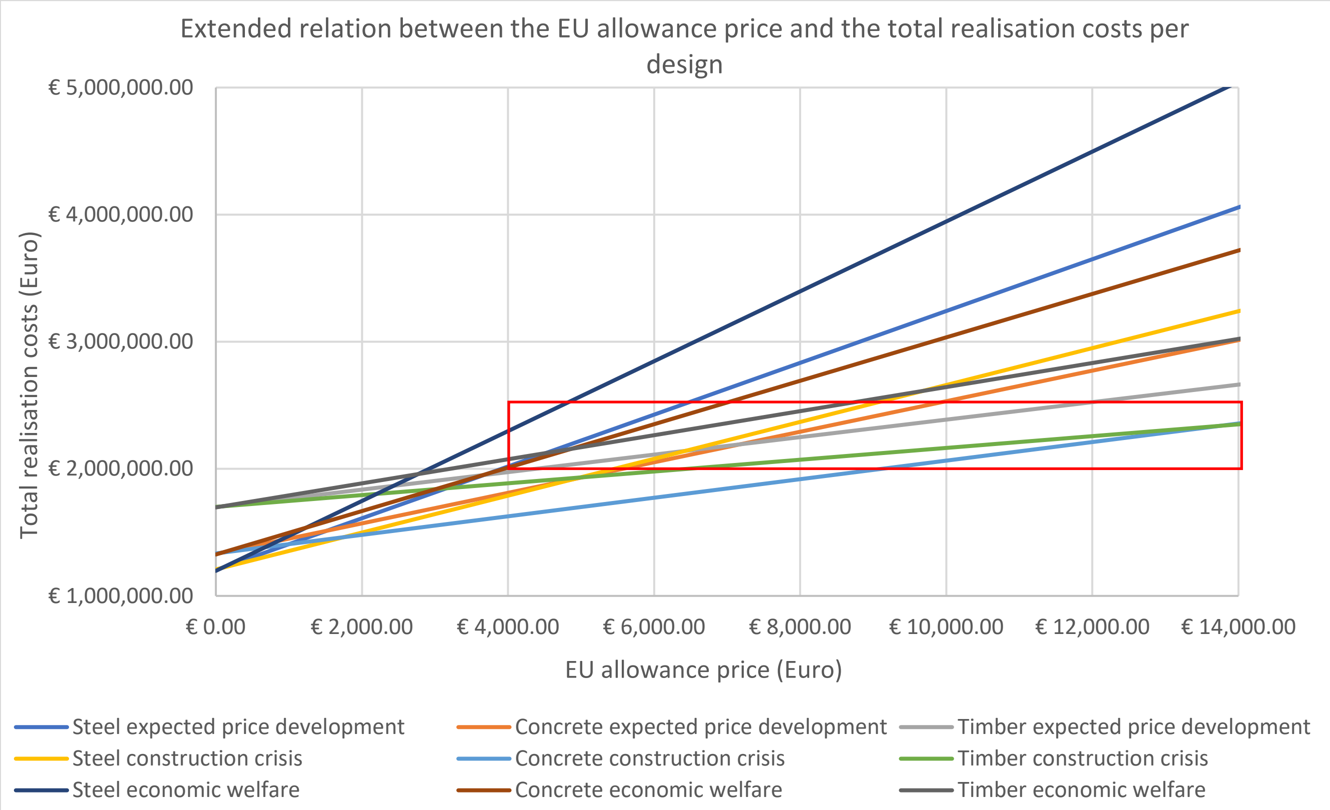

Figure 8-4: Extended relation between the EU allowance price and the total realisation costs per design under the different scenarios

The actual tipping points for the realisation costs are hard to indicate due to the high density of relations in figure 8-4. Therefore, figure 8-5 is made to zoom in on the tipping points and display them more clearly. Figure 8-5 is a zoomed-in version of figure 8-4 and displays the relations in the marked red box in figure 8-4.

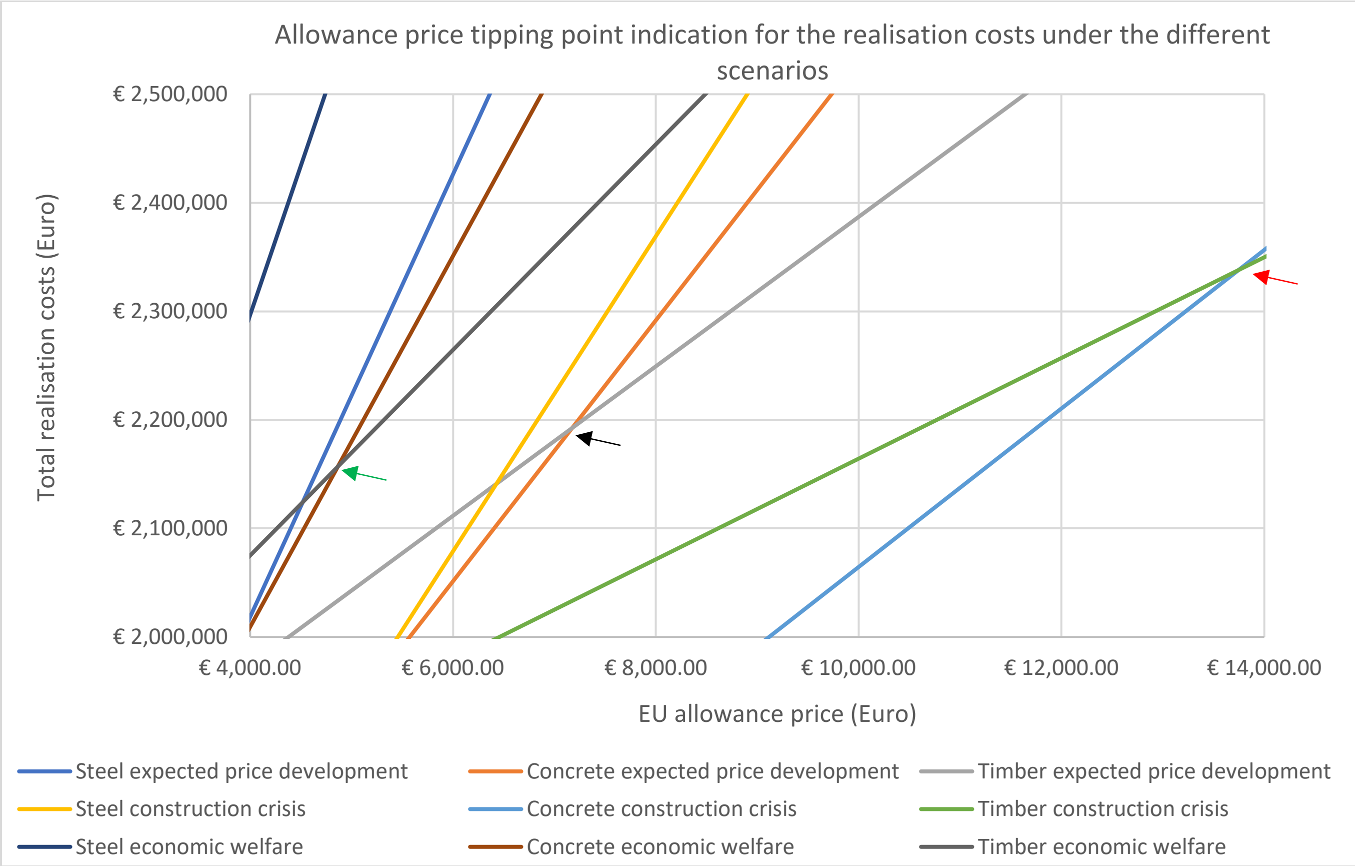

Figure 8-5: Zoomed-in relation between the EU allowance price and realisation costs with marked tipping points

In figure 8-5, the tipping points are marked by three arrows, one for each scenario. These points present the minimum allowance price that results in the lowest total realisation costs for the timber design compared to the steel or concrete design under the same scenario. The green arrow presents the tipping point for the economic welfare scenario. An allowance price equal to or higher than € 4,864 makes the timber design financially the most attractive design under the economic welfare scenario. The black arrow presents the tipping point for the expected development scenario, which is at €7,175. The red arrow presents the tipping point for the construction crisis scenario, which is at € 13,746.

The allowance price tipping point results in the lowest total realisation costs for the timber design, However, there is also a point where the timber design stops having the least affordable realisation costs. This first realisation costs intersection happens with the steel design at an allowance price of € 3,670 under the expected price development scenario. This intersection could also happen at an allowance price that varies between € 2,770 (economic welfare scenario) and € 4,985 (construction crisis scenario). These points can be found in the figure that is presented in appendix F.

The other intersections that are not being discussed are intersections where designs of different scenarios intersect with each other. The different scenarios cannot be compared equally, so these intersections will not be discussed in this report.

Total material costs

Figure 8-6 displays the relation between the allowance price and the total material costs per design for the three scenarios. This relation is also displayed because chapter 7 has shown that there is a higher degree of uncertainty about the calculations of the total installation costs due to the absence of a standardised formula. This figure only includes the material costs component to see how the impact of the allowance price changes if only the material costs are included.

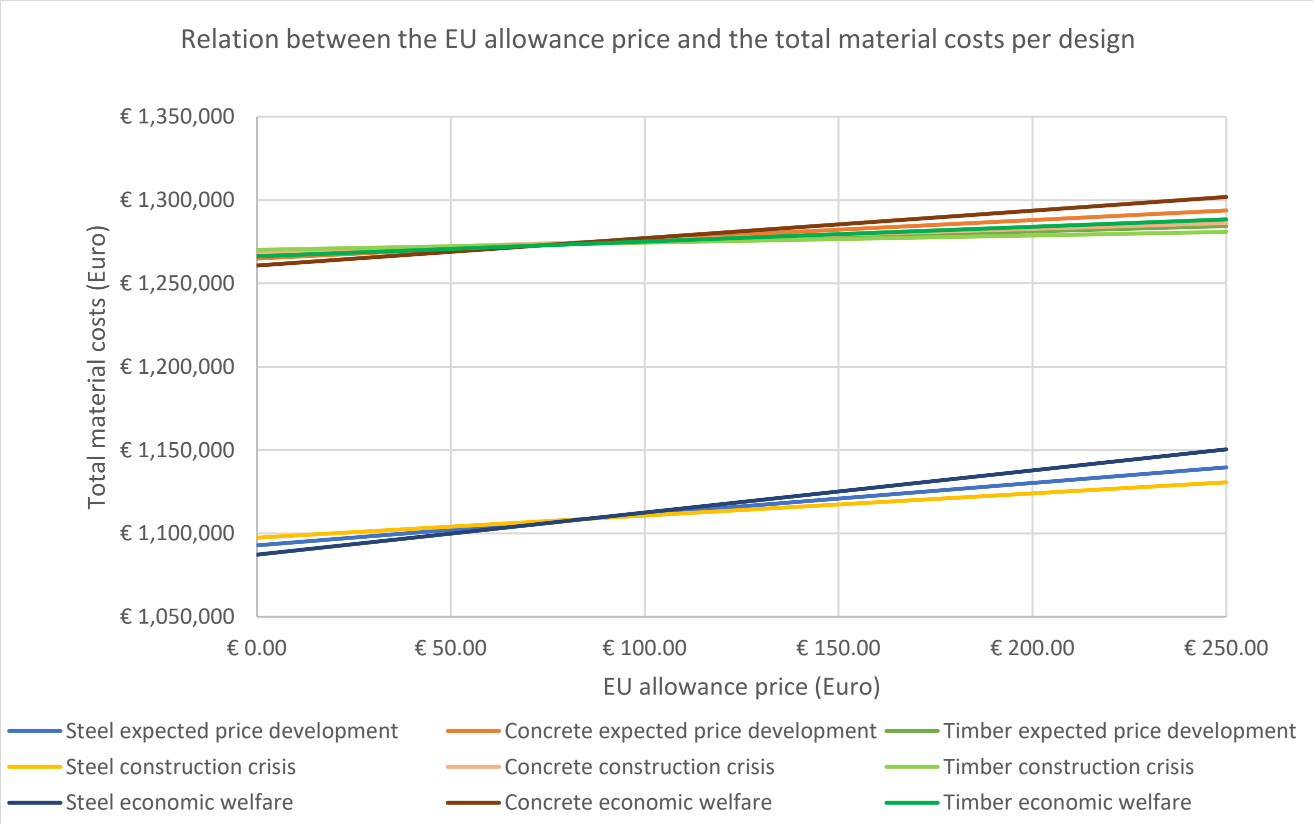

Figure 8-6: The relation between the EU allowance price and the total material costs per design under all three scenarios

Figure 8-6 shows that the total material costs of the timber and concrete design are almost the same. The material costs of the steel design are approximately 150 thousand euros lower. However, the material costs of the steel design do increase more quickly for every increase in the allowance price, so there will be a tipping point. The allowance price tipping point is the point where the allowance price results in lower material costs for the timber design compared to the material costs of the steel and concrete designs. The tipping points are found by solving the tipping point equation from section 8.1.3 for the total material costs. The allowance price tipping results are presented in table 8-4.

Table 8-4 The allowance price tipping point results for the total material costs under the three scenarios

Scenario	**Allowance price tipping point**	**Total material costs**
Expected price development	€ 1,428.35	€ 1,360,151.52
Economic welfare	€ 1,091.13	€ 1,362,941.49
Construction crisis	€ 1,922.09	€ 1,356,121.85

To display the tipping point results of table 8-4, both axis from figure 8-6 have to be extended. This is done for all three designs under all three scenarios in figure 8-7.

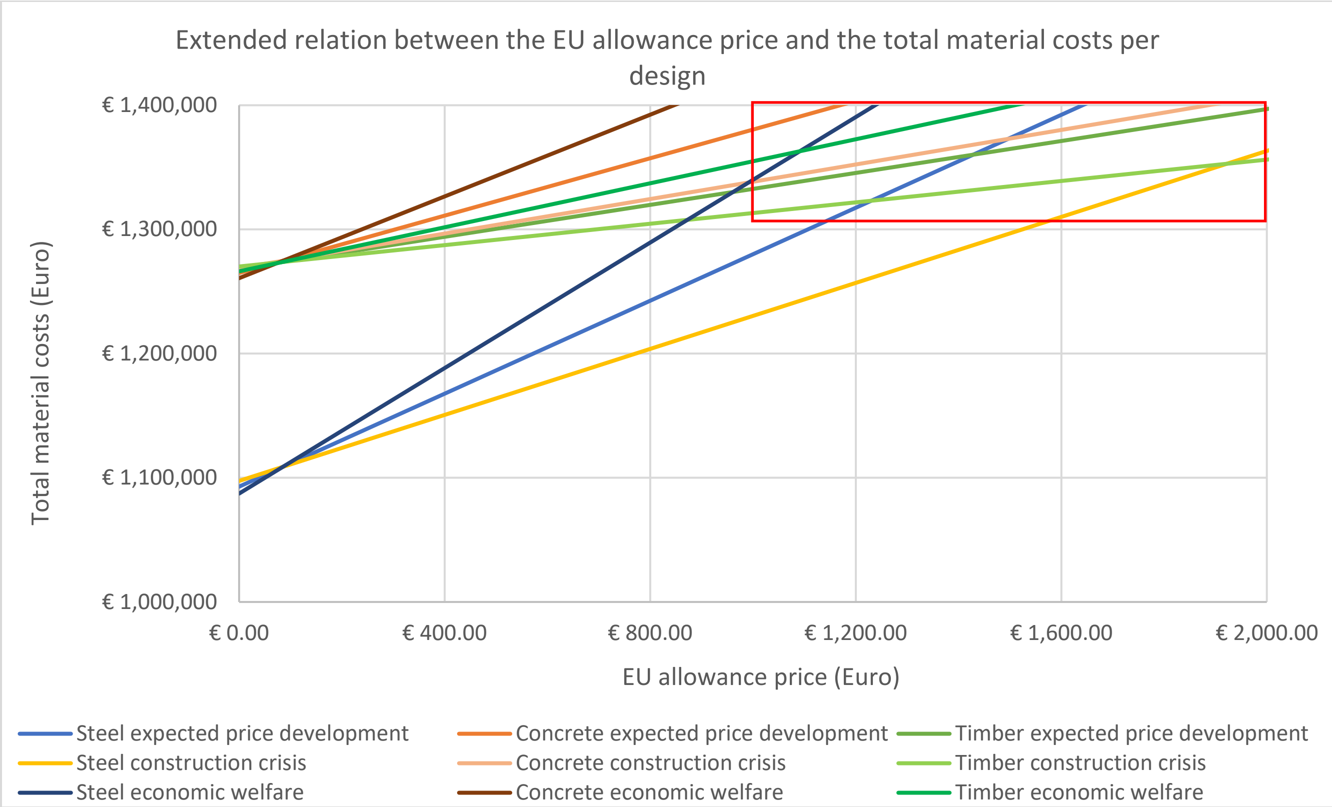

Figure 8-7: Extended relation between the EU allowance price and the total material costs per design under the three different scenarios

The actual tipping points for the material costs are hard to indicate due to the high density of relations in figure 8-7. Therefore, figure 8-8 is made to zoom in on the tipping points and display them more clearly. Figure 8-8 is a zoomed in version of figure 8-7 and displays the relations in the marked red box in figure 8-7.

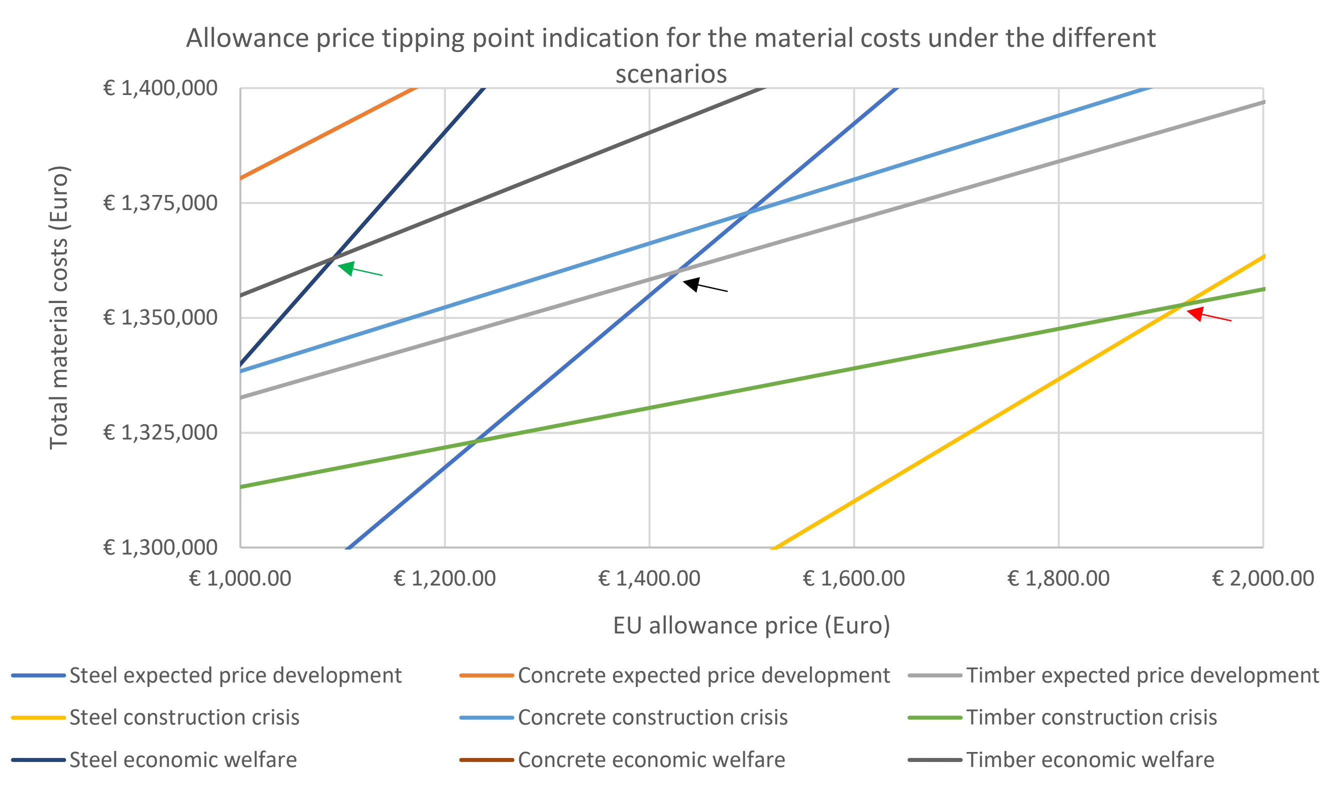

Figure 8-8: Allowance price tipping point indication for the material costs under the different scenarios

Figure 8-8 shows the tipping points for the material costs with the three coloured arrows. These tipping points indicate the minimum allowance price that results in the lowest total material costs for the timber design compared to the material costs of the steel and concrete design under the same scenarios. The green arrow presents the tipping point for the economic welfare scenario. An allowance price equal to or higher than € 1,091 results in the lowest material costs for the timber design under the economic welfare scenario. The black arrow presents the tipping point for the expected development scenario, and the red arrow presents the tipping point for the construction crisis scenario. These exact tipping point values can be found in table 8-4.

The allowance price tipping points are still very high compared to the current allowance price of 85 euros, but the tipping points are already much lower compared to the tipping points for the realisation costs. This has two reasons. The first reason is that the difference between the timber and steel realisation costs is much bigger than the difference between the timber and steel material costs. This results in a bigger cost difference for the realisation costs at the start, which takes longer to make up for. The second reason is the difference in the impact of the allowance price on the steepness of the relation between the realisation costs or the material costs. The allowance price has a direct effect on the material costs of steel and concrete, while the impact on the realisation costs is damped due to the presence of the installation costs component which is almost unaffected by the allowance price. This results in a relatively stronger increase in the material costs compared to the realisation costs per increase in the allowance price. The steeper the angle of the relation, the earlier an intersection with the timber design is found, and the lower the allowance price tipping point will be.

Figure 8-6 already contains the intersections between the timber and concrete designs. These intersections are the points where the material costs of the timber design stop being the least affordable. The material costs intersection occurs at an allowance price of € 67.00 under the expected price development scenario. The other intersections occur at an allowance price of € 50.27 (construction crisis scenario) and € 72.87 (economic welfare scenario). These intersections can be found in detail in the figure that is presented in appendix G.

9. Conclusion

This research focuses on how the European Union emissions trading system can contribute to a more sustainable construction sector. This research studied whether using a timber structure can become financially favourable over a conventional steel or concrete structure because of the impact of the European Union emissions trading system.

The main research question that has been answered in this report is:

What is the European Union Emissions Trading System allowance price tipping point for a profitable business case for a timber constructed structure over a steel or concrete constructed structure in the Dutch built environment?

In order to answer this question, a few smaller research questions had to be answered. First, these research questions will shortly be answered, after which the answer to the main research question will be presented as the conclusion of this research.

Sub-question 1: What are the main barriers to sustainable construction and how does the European emissions trading system affect sustainable construction?

In chapter 3, a literature review was performed and found that the biggest barrier towards sustainable construction is the barrier of affordability. This barrier could be lowered by policy measures that result in more competitive prices for sustainable construction However, the introduction of the EU emissions trading system policy tool did not lower the barrier of affordability so far.

Sub-question 2: What theoretical framework supports the determination of the relation between the European Union allowance price and material prices of steel and cement?

In chapter 4, two theoretical frameworks were created to identify the relation between the EU allowance price and the market price for steel and cement. The ‘reduced opportunity costs' framework assumes that the freely allocated allowances are directly used to compensate for the emissions coming from the production of the product. The ‘profit maximisation framework' assumes that the number of free allowances does not influence the final market price change because the emission costs are completely used as opportunity costs to maximize profits.

Sub-question 3 : What is the relation between the European Union allowance price and the material prices for steel and cement as structural building materials in the Dutch construction market?

In chapter 5, a scenario analysis was performed on two frameworks. The profit maximisation framework found that the steel market price increases on average € 0,729 per tonne of steel for every euro that the allowance price increases. The cement market price increased on average € 0,088 per tonne of cement for every euro that the allowance price increased. The actual increase in the market price for every euro that the allowance price increases depends on the applied pass-through ratio on carbon costs by the product producer. The scenario analysis results from the reduced opportunity costs framework are in contrast with the historical data and did not support the profit-seeking goal of private companies. Therefore, only the results from the profit maximisation framework were used in the continuation of the report.

Sub-question 4: What is the level of embodied carbon for the steel, concrete, and timber structural designs of the selected project?

In chapter 6, a life cycle analysis was performed on the steel, concrete, and timber structural designs of the office and welfare building and found that the use of timber results in the lowest level of embodied carbon. The timber design had a global warming potential of 503 tonnes CO_2eq. The global warming potential of the steel design was found to be 1,045 tonnes CO_2eq, which is 108 percent higher, while the global warming potential of the concrete design was found to be 1,288 tonnes CO_2eq, which is 156 percent higher.

Sub-question 5: What are the realisation costs for the steel, concrete, and timber structural designs of the selected project?

In chapter 7, a costs analysis was performed to calculate the total realisation costs per design. The analysis found that the total realisation costs of the timber design are the most expensive, with a value of € 1.704.391. The total realisation costs of the steel design are € 1.220.525, which is 40 percent less expensive, while the total realisation costs of the concrete design are € 1.340.389, which is 27 percent less expensive.

Based on the information obtained from the sub-questions and the tipping point analysis in chapter 8, an answer to the main research question can be formulated.

What is the European Union Emissions Trading System allowance price tipping point for a profitable business case for a timber constructed structure over a steel or concrete constructed structure in the Dutch built environment?

The average allowance price tipping point for a profitable timber design over a steel and concrete structure is found at an allowance price of € 7,175 compared to the current allowance price of € 85. This is the allowance price in 2022, where the timber office and welfare design becomes financially favourable over the steel and concrete office and welfare design. The actual price tipping point could vary between an allowance price of € 4,864 and € 13,746 because it depends on the applied pass-through ratio of carbon costs by the steel and cement producers. The steel and cement producers adjust their pass-through ratio based on the actual market conditions. A higher pass-through ratio of carbon costs increases steel and cement market prices, which lowers the allowance price tipping point for the timber design. The timber design stops being the least affordable design at an average allowance price of € 3,670. This allowance price varies between € 2,770 and € 4,985 based on the applied PTR by the steel and cement producers.

By only looking at the material costs component, a much lower average allowance price tipping point is found at an allowance price of € 1,428. The allowance price tipping point that results in the lowest material costs for the timber design could vary between € 1,091 and € 1,922 based on the applied pass-through ratio by the steel and cement producers.

10. Discussion

Chapter 10 will discuss the interpretation of the research results. Section 10.1 presents the research validation. In section 10.2, the researcher will reflect on the research results. Section 10.3 explains the applicability of the research. Section 10.4 presents the research limitations, and section 10.5 presents recommendations for future research.

10.1. Research validation

The research validation checks whether the research analysis measured what it was supposed to measure. The validation of this research can be assured because of multiple validation methods.

This research has only made use of reliable sources. Reliable sources are considered sources in the form of acknowledged scientific research published on Google scholar or reports published by acknowledged institutions like the European Commission and well-known independent consultancy reports. This improves the validity of the found literature, which is used to identify the barriers towards sustainable construction and to create the theoretical frameworks.

This research has used the knowledge of multiple experts in sustainability, construction, and finance to check whether the executed research steps covered the full problem and whether the steps were performed correctly. The theoretical framework that is used to research the relation between the EU allowance price and the change in the price of cement and steel has been constructed after consultation with an ETS expert. This consultation validated that all the crucial elements were included in the framework. This improves the validity of the results on the relation between the allowance price and the steel and cement price change. An LCA expert has checked the performed LCAs on the correct material translations from the model towards the LCA tool. This check resulted in an adjustment of one of the materials in the LCA tool. This expert consultation improved the validity of the LCA results. The realisation costs formulas and the values of the constant variables have been formulated after consultation of a construction costs expert. A second construction costs expert has checked the results of the cost analysis. The expert verified the cost analysis results after an adjustment in the material costs and installation costs of timber. The double expert consultation improved the validity of the realisation costs results. The last expert consultation took place with an engineering expert who is concrete specialist. This consultation helped to define the shares of cement in the different strength types of concrete. This expert consultation increased the validity of the right translation from the allowance price impact on cement towards the allowance price impact on the different types of concrete. All the expert consultations combined helped improve the total research's validity.

The scope of the research has defined the boundaries of the research. By only including the Dutch production market of steel and cement only 2 construction material producers could be included. This research also only included values for variables applicable for the year 2022. This reduced the number of assumptions to almost none for the values of variables that are used within the theoretical framework.

10.2. Results reflection

The research results have shown that the allowance price impacts the market prices of carbon-intensive goods like cement and steel. A price increase helps to lower the biggest barrier towards implementing sustainable construction, which is the affordability of projects. A higher allowance price will therefore stimulate the implementation of sustainable construction. However, the research results also showed that the allowance price needs to increase to a price of € 7,175 to make the timber design the most environmentally friendly and the most affordable option. This allowance price seems very unrealistic to occur based on the current allowance price of € 80 in March 2022. Therefore, the ETS allowance price can be considered helpful towards lowering the barrier of affordability. However, it is highly unlikely that the allowance price will be the key factor to overcome the barrier of affordability. Other factors that do influence the price of construction materials like new policy measures, energy prices, raw material prices and technological development are expected to have a more significant impact in lowering the barrier of affordability and contribute to a more sustainable construction sector.

Multiple possible explanations can be given for the high allowance price tipping point. The first explanation could be the big difference in the installation costs for the timber design compared to the steel and concrete design. The timber installation costs have a value of € 430,588, approximately 3.9 times higher than the steel design and 6.5 times higher than the concrete design. The formulas to calculate the installation costs for timber and concrete elements are constant over time, so the difference in the installation costs of the different designs mainly must be compensated by a change in the total material costs. The small differences in the slope of the relation between the material costs and the allowance price for concrete and timber designs make it very hard to compensate for the difference in the installation costs. This results in a very high allowance price tipping point for the total realisation costs of the timber design. Section 8.2 has also presented the results for the price tipping point for just the material costs component. This already reduces the allowance price tipping point by more than 80 percent.

Another possible explanation for the high allowance price tipping point could be the low pass-through ratio of carbon costs within the cement production chain. The PTR of cement has been tested between 0.20 and 0.58 which means that for every one euro increase in the carbon costs the cement price only increases by € 0.20-0.58. This is a lot lower than the PTR of steel which is between 0.55 and 1.00. A low PTR results in a lower slope degree in the relation between a cost component and the allowance price. The less steep the slope of the relation is, the higher the allowance price needs to be to find an intersection with the price of the timber design. This results in a higher allowance price tipping point. The difference in the PTRs of steel and cement could be supported by differences in the demand for the product.

The results of this study help to create new insights into the effectiveness of the European ETS policy measure. This system was introduced to lower the emissions of European GHGs by increasing the costs of carbon-intensive products, but because of the allocation of free allowances, production costs do not increase for all ETS participants. The calculations on the number of freely received allowances by Tata Steel found that as the biggest Dutch emitter of GHGs, they receive more emission allowances for free than it needs to compensate for their emissions. This full compensation of carbon costs results in higher market prices for steel due to the use of opportunity costs, while the polluter does not have increased production costs. This assumes that the introduction of the ETS only helped Tata Steel to justify price increases. This assumption is in line with the study of CE Delft (2016) which was discussed in section 3.6. CE Delft showed that the overallocation of free allowances also resulted in extra profits for polluting industries between 2008 and 2014. Tata's high number of received free allowances can be explained by the set benchmark value to produce hot iron in the EU. Tata steel is in the top 5 percent of most efficient steel producers. This results in a situation where Tata steel can produce steel more efficient than the European benchmark value which results in a received surplus of allowances. Different opinions can be formulated about this situation. On one hand, Tata steel must be rewarded because they can relative reduce the European GHG emissions with their steel compared to steel produced in other European countries. On the other hand, it is ridiculous that the biggest Dutch emitter of GHGs can make a profit out of a policy measure that is intended to lower GHG emissions. This is a dangerous situation because as long as other European steel producers set a benchmark value that is higher than Tata's production efficiency there will be no urge for Tata to change their production processes to for example hydrogen.

10.3. Applicability of the research

For the application of the results from the selected case, two things have to be considered.

Application of results to different structural designs

The research results have been obtained by using one case study. This case study covered a structural part of a pan-European template of a large distribution centre. The obtained allowance price tipping point is the result for this specific case. Researching a complete building instead of just the structure or researching a different type of building instead of a distribution centre could result in different tipping point results. Applying the used method to one case reduces the applicability of the results to the entire Dutch construction sector.

Application of results to different points in time

The values of the variables that have been used as input in the theoretical framework and the cost calculations have been based on the values that were applicable at the start of 2022. These values are likely to change in the future due to the high volatility of material prices, and this would also change the outcome of the results. How these values will change in the future is very uncertain because the exact change depends on multiple factors. Using the variable values applicable at the start of 2022 reduces the applicability of the results once significant changes in the values have taken place. This is more likely to happen further in the future.

10.4. Research limitations

Some research limitations should be considered when reading this report. Section 10.3 already presented the first research limitations by using one case and using the variable values of 2022. Next to this, results on the allowance price tipping point are very sensitive towards a change in the PTR because the PTR has a direct influence on the change in the material price. The uncertainty around the exact PTR for steel and cement has led to 3 scenarios to test between the maximum and minimum values. The scenario analysis covers all potential outcomes. This increases the validity of the research but covering all the potential outcomes also resulted in a wide range of potential answers between € 4,864 and € 13,746. This range of potential answers reduces the reliability of the results.

This research only considered steel and cement as construction materials subject to the impact of the allowance price. Although the timber production process does not have to compensate for its emissions by handing in allowances, there is still the opportunity that the price is indirectly impacted by any change in the allowance price. This potential relation between the timber price and the allowance price is not included in this research.

This research did not cover a potential relation between the PTR of carbon costs and the actual allowance price. The PTR has been kept constant within the different scenarios. This limits the opportunity that there exists a relation between the PTR and the allowance price.
This research also assumed that the imported clinker within the cement production chain is subject to the same ETS impact as the rest of the cement production chain, while the origin of the clinker is unknown.

10.5. Future research recommendations

There is still a lot of room for subject-related research in the future. Recommendations for potential future research will be shared.

To improve the reliability and validity of the conclusion which have been found within this report, more cases must be researched by the same method in the future. These cases could contain the same kind of structural buildings which would improve the reliability, but the cases could also contain fully finished buildings or different types of buildings which would contribute to the validity.

The scope of this research has focused on the Dutch construction market, but the ETS is active in all of Europe. Therefore, it would be interesting to research how the ETS allowance price has a different impact on the prices of construction materials produced in other European countries and how this changes the tipping point results. The used case study is a pan-European template, so the same three designs could be used to find the allowance price tipping point in another European country.

The performed LCA has shown that the use of timber significantly lowers the level of embodied carbon within the structure of a building. The costs analysis has shown that the timber design also had the highest total realisation costs. Although the realisation costs of the timber design are initially the least favourable financial option, there must exist some financial value in owning a building with a low level of embodied carbon compared to a conventional building with a high level of embodied carbon. Therefore, it would be interesting to research how the value of real estate increases due to a low level of embodied carbon. This could change the willingness of a project owner to have higher initial construction costs as long as a reduction in the level of embodied carbon within the building can be realised.

10.6. Recommendations for European and national climate policymakers

At last, this report will provide recommendations towards European climate policymakers who work to green up Europe.

The ETS was introduced to let the polluter pay, but this is currently not always the case. Therefore, the first recommendation is to increase the effectiveness of the ETS system. This can be done in multiple ways. The first one focuses on lowering the number of freely allocated allowances. This can be done by lowering the benchmark value or the carbon leakage exposure factor. The benchmark value can for example be set based on the efficiency of the most efficient producer. This makes it impossible to receive more allowances than needed, which is now still possible. The other way is to lower the carbon leakage exposure factor because literature has not found any evidence for a carbon leakage risk due to the ETS introduction (Branger,2016; Naegele and Zaklan, 2019). The second option is to increase the decrease in the annual allowance cap. Lowering the total allowance supply increases the price per allowance. A higher allowance price only helps if producers do not receive 100 percent of their allowances for free.

This research has shown that the use of timber within the structure is beneficial for the environment, but it also showed that the use of timber results in unfavourable costs compared to the use of steel or concrete. It is recommended for climate policymakers to look at the possibilities to subsidize the use of timber within the structure of a building and the possibilities to create more timber supply. This helps to lower the costs of timber and lower the affordability barrier. The height of the subsidy can depend on the saved level of carbon compared to an alternative conventional design.

Nationally, it is recommended for climate policymakers to look into the possibilities to stimulate the use of timber via the Dutch ‘bouwbesluit’. The ‘bouwbesluit’ is a collection of regulations that apply to the construction, the use and the condition of buildings that everyone must follow. Chapter five contains the regulations about sustainability and the environment. Introducing a maximum level of embodied carbon per square meter of surface area could help to create a constraint for project owners to use more low carbon materials. This potential new 'bouwbesluit' rule can incentivize the use of timber while also limiting the impact of volatile material prices because a minimum standard must be met.

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Appendix

Appendix A – Summary material lists

Steel design:

Location	Material in design	One-click material title	Material type	Country of origin	Volume (m3)	GWP (tonne CO2)
Floor	Concrete in situ	Ready-mix concrete, normal strength, generic, C28/35, 0% recycled binders	Ready-mix concrete for external walls and floors	NL	702,9076	217
Structural foundation	Piedestal concrete floor	Ready-mix concrete, normal strength, generic, C25/30, 0% recycled binders	Ready-mix concrete for foundations and internal walls	NL	132,8824	39
Structural column	HEBSteel 360	Structural steel profiles, generic, 0% recycled content, H section	Structural steel and steel profiles	NL	4,1904	107
Structural column	HEBSteel 300	Structural steel profiles, generic, 0% recycled content, H section	Structural steel and steel profiles	NL	3,5671	91
Structural framing	Angle steel: L80x8	Structural steel profiles, generic, 0% recycled content, L section	Structural steel and steel profiles	NL	0,514	13
Structural framing	Castellated diamond steel HEB 240	Structural steel profiles, generic, 0% recycled content, H section	Structural steel and steel profiles	NL	13,6845	351
Structural framing	Kingspan multibeam purlin: 350x90	Structural steel profiles, generic, 0% recycled content,I, H, U, L, T sections	Structural steel and steel profiles	NL	5,8595	150
Structural framing	HEAsteel 260	Structural steel profiles, generic, 0% recycled content, H section	Structural steel and steel profiles	NL	1,1326	29
Structural framing	SHSsteel: 120x10	Structural hollow steel sections (HSS), cold rolled, generic, 10 % recycled content	Structural steel and steel profiles	NL	0,7082	21
Structural framing	One sided rebate concrete	Ready-mix concrete, normal strength, generic, C28/35, 0% recycled binders	Ready-mix concrete for external walls and floors	NL	73,4171	23

Concrete design:

Location	Material in design	One-click material title	Material type	Country of origin	Volume (m3)	GWP (tonne CO2)
Floor	Concrete in situ	Ready-mix concrete, normal strength, generic, C28/35, 0% recycled binders	Ready-mix concrete for external walls and floors	NL	600,563 0	185
Structural foundation	Piedestal concrete floor	Ready-mix concrete, normal strength, generic, C25/30, 0% recycled binders	Ready-mix concrete for foundations and internal walls	NL	656,550 0	193

Structural column	Rectangular concrete	Ready-mix concrete, normal-strength, generic, C40/50, 0% recycled binders in cement	Ready-mix concrete for structures (beams, columns, piling)	NL	2,0990	1
Structural column	Rectangular concrete precast	Precast concrete structural elements (beams, columns and other), C20/25-C35/45	Structural concrete (beams, columns, piling)	GER	141,980 8	103
Structural framing	Angle steel: L80x8	Structural steel profiles, generic, 0% recycled content, L section	Structural steel and steel profiles	NL	0,5667	15
Structural framing	Kingspan multibeam purlin: 350x90	Structural steel profiles, generic, 0% recycled content,I, H, U, L, T sections	Structural steel and steel profiles	NL	4,5969	118
Structural framing	SHSsteel: 120x10	Structural hollow steel sections (HSS), cold rolled, generic, 10 % recycled content	Structural steel and steel profiles	NL	0,9610	28
Structural framing	One sided rebate concrete	Ready-mix concrete, normal strength, generic, C28/35, 0% recycled binders	Ready-mix concrete for external walls and floors	NL	59,1575	18
Structural framing	Rectangular concrete	Ready-mix concrete, normal-strength, generic, C40/50, 0% recycled binders	Ready-mix concrete for structures (beams, columns, piling)	NL	13,2319	6,4
Structural framing	Rectangular concrete precast	Precast concrete structural elements (beams, columns and other), C20/25-C35/45	Structural concrete (beams, columns, piling)	GER	30,1665	22
Structural framing	One sided rebate concrete precast	Precast concrete structural elements (beams, columns and other), C20/25-C35/45	Structural concrete (beams, columns, piling)	GER	49,7559	36
Structural framing	Two sided rebate concrete precast	Precast concrete structural elements (beams, columns and other), C20/25-C35/45	Structural concrete (beams, columns, piling)	GER	94,0222	68
Structural framing	Variable concrete precast	Precast concrete structural elements (beams, columns and other), C20/25-C35/45	Structural concrete (beams, columns, piling)	GER	123,314 2	89
Walls	Basic wall concrete in situ	Ready-mix concrete, normal strength, generic, C25/30, 0% recycled binders	Ready-mix concrete for foundations and internal walls	NL	5,8330	1,7
Walls	Basic wall precast concrete	Precast concrete wall elements, C30/37, 0%recycled binders in cement	Concrete wall elements	NL	427,195 9	170

Timber design:

Location	**Material in design**	**One-click material title**	**Material type**	**Country of origin**	**Volume (m3)**	**GWP (tonne CO2)**
Floor	Concrete in situ	Ready-mix concrete, normal strength, generic, C28/35, 0% recycled binders	Ready-mix concrete for external walls and floors	NL	702,9076	217
Structural foundation	Piedestal concrete floor	Ready-mix concrete, normal strength, generic, C25/30, 0% recycled binders	Ready-mix concrete for foundations and internal walls	NL	8,0000	2,3
Structural column	HEBSteel 360	Structural steel profiles, generic, 0% recycled content, H section	Structural steel and steel profiles	NL	0,537	14

Structural column	Pine plane wood	Planed and strength-graded timber, pine or spruce	Plain wood/timber	NL	21,824	1,9
Structural framing	One sided rebate concrete	Ready-mix concrete, normal strength, generic, C28/35, 0% recycled binders	Ready-mix concrete for external walls and floors	NL	113,4258	35
Structural framing	HEAsteel 260	Structural steel profiles, generic, 0% recycled content, H section	Structural steel and steel profiles	NL	1,1326	29
Structural column	Pine plane wood	Planed and strength-graded timber, pine or spruce	Plain wood/timber	NL	286,7101	25
Structural framing	Kingspan multibeam purlin: 350x90	Structural steel profiles, generic, 0% recycled content,I, H, U, L, T sections	Structural steel and steel profiles	NL	5,4004	138
Walls	Basic wall wood	Planed and strength-graded timber, pine or spruce	Plain wood/timber	NL	465,1459	41

Appendix B – Mass per linear meter for the steel parts

Steel type	mass (kg/m)
HEBSteel 360	144,8
HEBSteel 300	119,3
Angle steel L80x8	9,81
Castellated diamond steel HEB 240	72,08[1]
Kingspan multibeam purlin: 350x90	13,72
HEAsteel 260	69,5
SHSsteel: 120x10	33,66

Sources: (Smit staal, n.d.; Sölken, 2022; Hekim Profile, 2014)

[1]. Castellated diamond beams do save 15 percent in material compared to a solid beam (Pavlovic, 2018)

Appendix C – Realisation costs built up per design

Steel

Location	Material in design	Material type	Volume (m3)	Lenght (m)	Material costs (Euro)	Installation costs (euro)	Realisation costs (Euro)
Floor	Concrete in situ C28/35	Ready-mix concrete for external walls and floors	702,908	(-)	€ 60.801,51	€ 6.670,59	€ 67.472,1
Structural foundation	Piedestal concrete floor C25/30	Ready-mix concrete for foundations and internal walls	132,882	(-)	€ 10.431,27	€ 1.261,05	€ 11.692,3
Structural column	HEBSteel 360	Structural steel and steel profiles	4,190	240,31	€ 156.585,79	€ 15.658,58	€ 172.244,4
Structural column	HEBSteel 300	Structural steel and steel profiles	3,567	249,76	€ 134.084,53	€ 13.408,45	€ 147.493,0
Structural framing	Angle steel L80x8	Structural steel and steel profiles	0,514	422,70	€ 18.659,97	€ 1.866,00	€ 20.526,0
Structural framing	Castellated diamon steel HEB 240	Structural steel and steel profiles	13,685	1285,84	€ 417.074,09	€ 41.707,41	€ 458.781,5
Structural framing	Kingspan multibeam purlin: 350x90	Structural steel and steel profiles	5,860	3812,77	€ 235.400,29	€ 23.540,03	€ 258.940,3
Structural framing	HEAsteel 260	Structural steel and steel profiles	1,133	143,44	€ 44.860,03	€ 4.486,00	€ 49.346,0
Structural framing	SHSsteel: 120x10	Structural steel and steel profiles	0,708	161,94	€ 24.528,76	€ 2.452,88	€ 26.981,6
Structural framing	One sided rebate concrete C28/35	Ready-mix concrete for external walls and floors	73,417	(-)	€ 6.350,58	€ 696,73	€ 7.047,3
					€ 1.108.776,81	€ 111.747,72	€ 1.220.524,5

Concrete (not yet compensated)

Location	Material in design	Material type	Volume (m3)	Lenght (m)	Material costs (Euro)	Installation costs (euro)	Realisation costs (Euro)
Floor	Concrete in situ C28/35	Ready-mix concrete for external walls and floors	600,563	(-)	€ 51.948,70	€ 5.699,34	€ 57.648,04
Structural foundation	Piedestal concrete floor C25/30	Ready-mix concrete for foundations and internal walls	656,550	(-)	€ 51.539,18	€ 6.230,66	€ 57.769,83

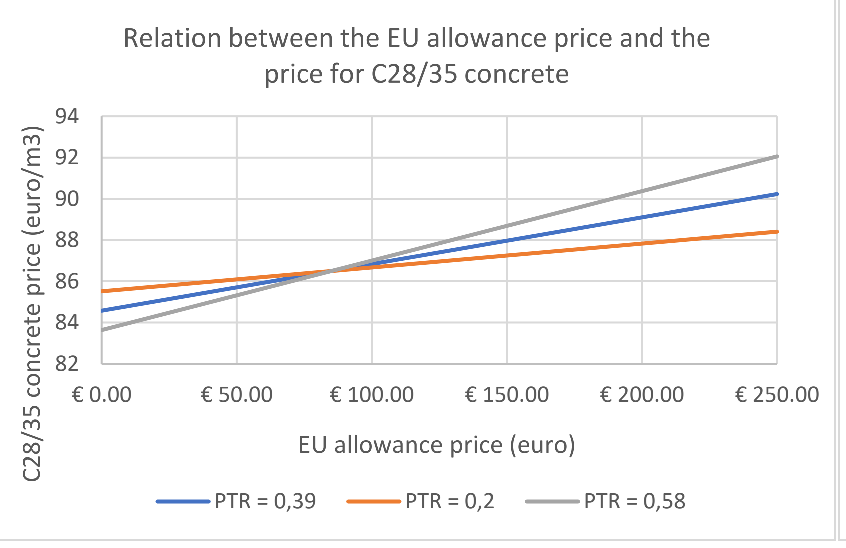
Structural column	Rectangular concrete C45/55	Ready-mix concrete for structures (beams, columns, piling)	2,099	(-)	€ 223,54	€ 19,92	€ 243,46
Structural column	Rectangular concrete precast (N=21)	Structural concrete (beams, columns, piling)	141,981	(-)	€ 113.584,64	€ 3.601,50	€ 117.186,14
Structural framing	Angle steel L80x8	Structural steel and steel profiles	0,567	466,04	€ 20.573,17	€ 2.057,32	€ 22.630,48
Structural framing	Kingspan multibeam purlin: 350x90	Structural steel and steel profiles	4,597	2991,20	€ 184.676,44	€ 18.467,64	€ 203.144,08
Structural framing	SHSsteel: 120x10	Structural steel and steel profiles	0,961	219,74	€ 33.284,58	€ 3.328,46	€ 36.613,04
Structural framing	One sided rebate concrete C28/35	Ready-mix concrete for external walls and floors	59,158	(-)	€ 5.117,12	€ 561,40	€ 5.678,53
Structural framing	Rectangular concrete C45/55	Ready-mix concrete for structures (beams, columns, piling)	13,232	(-)	€ 1.409,20	€ 125,57	€ 1.534,77
Structural framing	Rectangular concrete precast (N=9)	Structural concrete (beams, columns, piling)	30,167	(-)	€ 24.133,20	€ 1.543,50	€ 25.676,70
Structural framing	One sided rebate concrete precast (N=1)	Structural concrete (beams, columns, piling)	49,756	(-)	€ 39.804,72	€ 171,50	€ 39.976,22
Structural framing	Two sided rebate concrete precast (N=1)	Structural concrete (beams, columns, piling)	94,022	(-)	€ 75.217,76	€ 171,50	€ 75.389,26
Structural framing	Variable concrete precast (N=52)	Structural concrete (beams, columns, piling)	123,314	(-)	€ 98.651,36	€ 8.918,00	€ 107.569,36
Walls	Basic wall concrete in situ C25/30	Ready-mix concrete for foundations and internal walls	5,833	(-)	€ 457,89	€ 55,36	€ 513,25
Walls	Basic wall precast concrete (N=16)	Concrete wall elements	427,196	(-)	€ 341.756,72	€ 2.744,00	€ 344.500,72
					€ 1.042.378,21	€ 53.695,67	€ 1.096.073,88

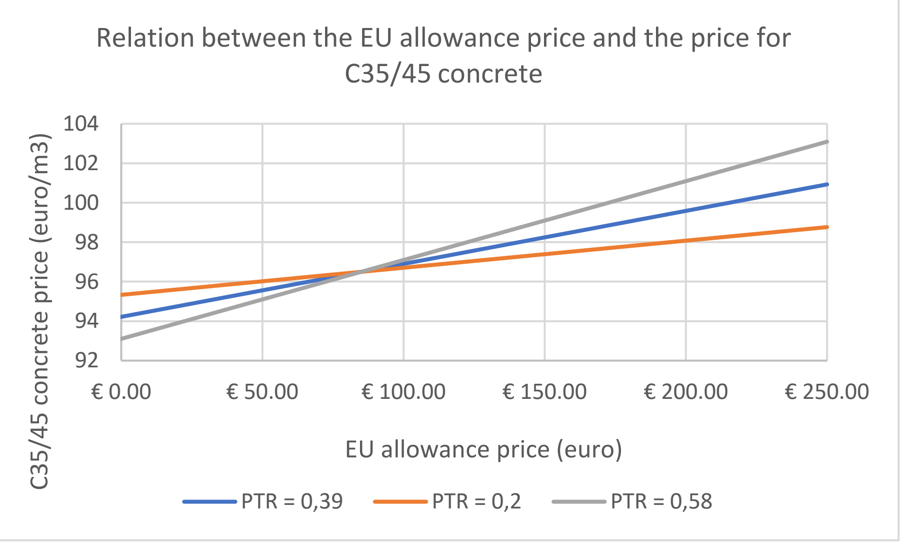
Timber

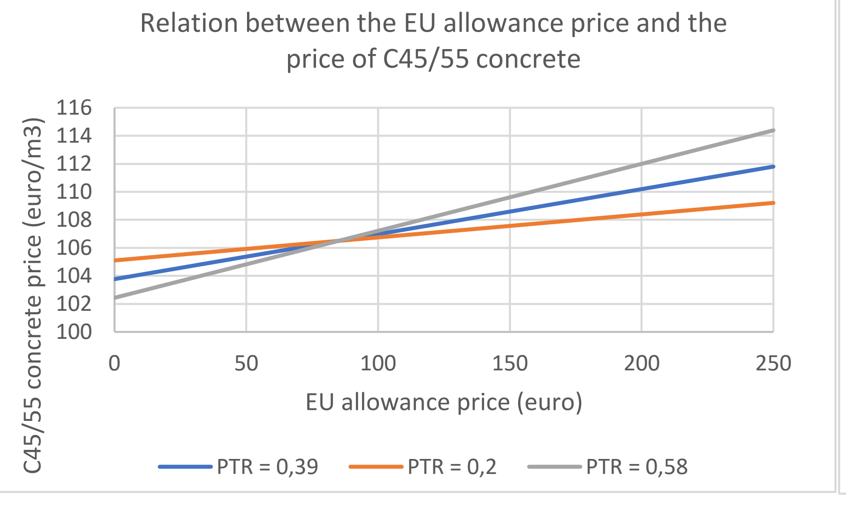
Location	Material in design	Material type	Volume (m3)	Lenght (m)	Material costs (Euro)	Installation costs (euro)	Realisation costs (Euro)
Floor	Concrete in situ C28/35	Ready-mix concrete for external walls and floors	702,908	(-)	€ 60.801,51	€ 6.670,59	€ 67.472,10
Structural foundation	Piedestal concrete floor C25/30	Ready-mix concrete for foundations and internal walls	8,000	(-)	€ 628,00	€ 75,92	€ 703,92

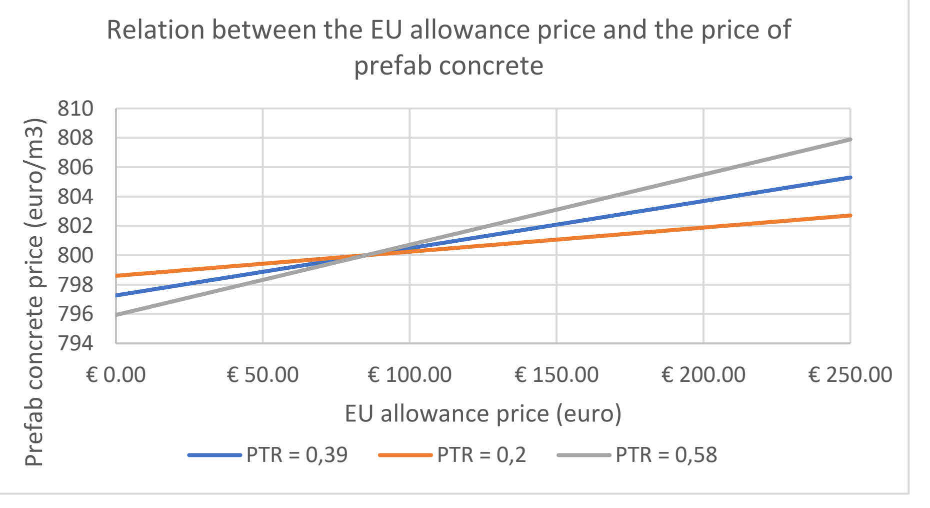
Structural column	HEBSteel 360	Structural steel and steel profiles	0,537	30,80	€ 20.066,48	€ 2.006,65	€ 22.073,13
Structural column	Pine plane wood	Plain wood/timber	21,824	(-)	€ 25.970,56	€ 11.130,24	€ 37.100,80
Structural framing	One sided rebate concrete C28/35	Ready-mix concrete for external walls and floors	113,426	(-)	€ 9.811,33	€ 1.076,41	€ 10.887,74
Structural framing	HEAsteel 260	Structural steel and steel profiles	1,133	143,44	€ 44.860,03	€ 4.486,00	€ 49.346,03
Structural framing	Pine plane wood	Plain wood/timber	286,710	(-)	€ 341.185,02	€ 146.222,15	€ 487.407,17
Structural framing	Kingspan multibeam purlin: 350x90	Structural steel and steel profiles	5,400	3514,03	€ 216.956,35	€ 21.695,63	€ 238.651,98
Walls	Basic wall wood	Plain wood/timber	465,146	(-)	€ 553.523,62	€ 237.224,41	€ 790.748,03
					€ 1.273.802,89	€ 430.588,01	€ 1.704.390,90

Appendix D – Relation between the EU allowance price and the price for sorts of concrete









Appendix E – Tipping point data results

Expected development scenario

	Steel			concrete			timber		
ETS	Material costs	Installation costs	Realisation costs	Material costs	Installation costs	Realisation costs	Material costs	Installation costs	Realisation costs
€ 0,00	€ 1.092.871,20	€ 110.327,77	€ 1.203.198,97	€ 1.264.909,96	€ 65.262,76	€ 1.330.172,72	€ 1.268.339,21	€ 430.199,86	€ 1.698.539,07
€ 5,00	€ 1.093.806,83	€ 110.411,29	€ 1.204.218,12	€ 1.265.487,27	€ 65.286,39	€ 1.330.773,66	€ 1.268.660,60	€ 430.222,69	€ 1.698.883,29
€ 10,00	€ 1.094.742,45	€ 110.494,82	€ 1.205.237,27	€ 1.266.064,59	€ 65.310,02	€ 1.331.374,60	€ 1.268.982,00	€ 430.245,52	€ 1.699.227,52
€ 15,00	€ 1.095.678,07	€ 110.578,35	€ 1.206.256,42	€ 1.266.641,90	€ 65.333,64	€ 1.331.975,55	€ 1.269.303,39	€ 430.268,35	€ 1.699.571,74
€ 20,00	€ 1.096.613,70	€ 110.661,87	€ 1.207.275,57	€ 1.267.219,22	€ 65.357,27	€ 1.332.576,49	€ 1.269.624,78	€ 430.291,19	€ 1.699.915,97
€ 25,00	€ 1.097.549,32	€ 110.745,40	€ 1.208.294,72	€ 1.267.796,53	€ 65.380,90	€ 1.333.177,43	€ 1.269.946,17	€ 430.314,02	€ 1.700.260,19
€ 30,00	€ 1.098.484,95	€ 110.828,93	€ 1.209.313,87	€ 1.268.373,85	€ 65.404,53	€ 1.333.778,38	€ 1.270.267,57	€ 430.336,85	€ 1.700.604,42
€ 35,00	€ 1.099.420,57	€ 110.912,45	€ 1.210.333,03	€ 1.268.951,16	€ 65.428,16	€ 1.334.379,32	€ 1.270.588,96	€ 430.359,68	€ 1.700.948,64
€ 40,00	€ 1.100.356,19	€ 110.995,98	€ 1.211.352,18	€ 1.269.528,48	€ 65.451,78	€ 1.334.980,26	€ 1.270.910,35	€ 430.382,52	€ 1.701.292,87
€ 45,00	€ 1.101.291,82	€ 111.079,51	€ 1.212.371,33	€ 1.270.105,79	€ 65.475,41	€ 1.335.581,21	€ 1.271.231,75	€ 430.405,35	€ 1.701.637,10
€ 50,00	€ 1.102.227,44	€ 111.163,03	€ 1.213.390,48	€ 1.270.683,11	€ 65.499,04	€ 1.336.182,15	€ 1.271.553,14	€ 430.428,18	€ 1.701.981,32
€ 55,00	€ 1.103.163,07	€ 111.246,56	€ 1.214.409,63	€ 1.271.260,42	€ 65.522,67	€ 1.336.783,09	€ 1.271.874,53	€ 430.451,01	€ 1.702.325,55
€ 60,00	€ 1.104.098,69	€ 111.330,09	€ 1.215.428,78	€ 1.271.837,74	€ 65.546,30	€ 1.337.384,04	€ 1.272.195,93	€ 430.473,85	€ 1.702.669,77
€ 65,00	€ 1.105.034,32	€ 111.413,61	€ 1.216.447,93	€ 1.272.415,05	€ 65.569,92	€ 1.337.984,98	€ 1.272.517,32	€ 430.496,68	€ 1.703.014,00
€ 70,00	€ 1.105.969,94	€ 111.497,14	€ 1.217.467,08	€ 1.272.992,37	€ 65.593,55	€ 1.338.585,92	€ 1.272.838,71	€ 430.519,51	€ 1.703.358,22
€ 75,00	€ 1.106.905,56	€ 111.580,67	€ 1.218.486,23	€ 1.273.569,68	€ 65.617,18	€ 1.339.186,86	€ 1.273.160,10	€ 430.542,34	€ 1.703.702,45
€ 80,00	€ 1.107.841,19	€ 111.664,19	€ 1.219.505,38	€ 1.274.147,00	€ 65.640,81	€ 1.339.787,81	€ 1.273.481,50	€ 430.565,18	€ 1.704.046,67
€ 85,00	€ 1.108.776,81	€ 111.747,72	€ 1.220.524,53	€ 1.274.724,32	€ 65.664,44	€ 1.340.388,75	€ 1.273.802,89	€ 430.588,01	€ 1.704.390,90
€ 90,00	€ 1.109.712,44	€ 111.831,25	€ 1.221.543,68	€ 1.275.301,63	€ 65.688,06	€ 1.340.989,69	€ 1.274.124,28	€ 430.610,84	€ 1.704.735,12
€ 95,00	€ 1.110.648,06	€ 111.914,77	€ 1.222.562,84	€ 1.275.878,95	€ 65.711,69	€ 1.341.590,64	€ 1.274.445,68	€ 430.633,67	€ 1.705.079,35
€ 100,00	€ 1.111.583,69	€ 111.998,30	€ 1.223.581,99	€ 1.276.456,26	€ 65.735,32	€ 1.342.191,58	€ 1.274.767,07	€ 430.656,51	€ 1.705.423,57
€ 105,00	€ 1.112.519,31	€ 112.081,83	€ 1.224.601,14	€ 1.277.033,58	€ 65.758,95	€ 1.342.792,52	€ 1.275.088,46	€ 430.679,34	€ 1.705.767,80
€ 110,00	€ 1.113.454,93	€ 112.165,35	€ 1.225.620,29	€ 1.277.610,89	€ 65.782,58	€ 1.343.393,47	€ 1.275.409,85	€ 430.702,17	€ 1.706.112,03
€ 115,00	€ 1.114.390,56	€ 112.248,88	€ 1.226.639,44	€ 1.278.188,21	€ 65.806,20	€ 1.343.994,41	€ 1.275.731,25	€ 430.725,00	€ 1.706.456,25
€ 120,00	€ 1.115.326,18	€ 112.332,41	€ 1.227.658,59	€ 1.278.765,52	€ 65.829,83	€ 1.344.595,35	€ 1.276.052,64	€ 430.747,84	€ 1.706.800,48
€ 125,00	€ 1.116.261,81	€ 112.415,93	€ 1.228.677,74	€ 1.279.342,84	€ 65.853,46	€ 1.345.196,30	€ 1.276.374,03	€ 430.770,67	€ 1.707.144,70
€ 130,00	€ 1.117.197,43	€ 112.499,46	€ 1.229.696,89	€ 1.279.920,15	€ 65.877,09	€ 1.345.797,24	€ 1.276.695,43	€ 430.793,50	€ 1.707.488,93
€ 135,00	€ 1.118.133,05	€ 112.582,99	€ 1.230.716,04	€ 1.280.497,47	€ 65.900,72	€ 1.346.398,18	€ 1.277.016,82	€ 430.816,33	€ 1.707.833,15
€ 140,00	€ 1.119.068,68	€ 112.666,51	€ 1.231.735,19	€ 1.281.074,78	€ 65.924,34	€ 1.346.999,13	€ 1.277.338,21	€ 430.839,17	€ 1.708.177,38
€ 145,00	€ 1.120.004,30	€ 112.750,04	€ 1.232.754,34	€ 1.281.652,10	€ 65.947,97	€ 1.347.600,07	€ 1.277.659,60	€ 430.862,00	€ 1.708.521,60
€ 150,00	€ 1.120.939,93	€ 112.833,57	€ 1.233.773,49	€ 1.282.229,41	€ 65.971,60	€ 1.348.201,01	€ 1.277.981,00	€ 430.884,83	€ 1.708.865,83
€ 155,00	€ 1.121.875,55	€ 112.917,09	€ 1.234.792,65	€ 1.282.806,73	€ 65.995,23	€ 1.348.801,96	€ 1.278.302,39	€ 430.907,66	€ 1.709.210,05
€ 160,00	€ 1.122.811,18	€ 113.000,62	€ 1.235.811,80	€ 1.283.384,04	€ 66.018,86	€ 1.349.402,90	€ 1.278.623,78	€ 430.930,50	€ 1.709.554,28
€ 165,00	€ 1.123.746,80	€ 113.084,15	€ 1.236.830,95	€ 1.283.961,36	€ 66.042,48	€ 1.350.003,84	€ 1.278.945,18	€ 430.953,33	€ 1.709.898,50
€ 170,00	€ 1.124.682,42	€ 113.167,67	€ 1.237.850,10	€ 1.284.538,67	€ 66.066,11	€ 1.350.604,78	€ 1.279.266,57	€ 430.976,16	€ 1.710.242,73
€ 175,00	€ 1.125.618,05	€ 113.251,20	€ 1.238.869,25	€ 1.285.115,99	€ 66.089,74	€ 1.351.205,73	€ 1.279.587,96	€ 430.998,99	€ 1.710.586,96
€ 180,00	€ 1.126.553,67	€ 113.334,73	€ 1.239.888,40	€ 1.285.693,30	€ 66.113,37	€ 1.351.806,67	€ 1.279.909,35	€ 431.021,83	€ 1.710.931,18
€ 185,00	€ 1.127.489,30	€ 113.418,25	€ 1.240.907,55	€ 1.286.270,62	€ 66.137,00	€ 1.352.407,61	€ 1.280.230,75	€ 431.044,66	€ 1.711.275,41
€ 190,00	€ 1.128.424,92	€ 113.501,78	€ 1.241.926,70	€ 1.286.847,93	€ 66.160,62	€ 1.353.008,56	€ 1.280.552,14	€ 431.067,49	€ 1.711.619,63
€ 195,00	€ 1.129.360,54	€ 113.585,31	€ 1.242.945,85	€ 1.287.425,25	€ 66.184,25	€ 1.353.609,50	€ 1.280.873,53	€ 431.090,32	€ 1.711.963,86
€ 200,00	€ 1.130.296,17	€ 113.668,83	€ 1.243.965,00	€ 1.288.002,56	€ 66.207,88	€ 1.354.210,44	€ 1.281.194,93	€ 431.113,16	€ 1.712.308,08

€ 205,00	€ 1.131.231,79	€ 113.752,36	€ 1.244.984,15	€ 1.288.579,88	€ 66.231,51	€ 1.354.811,39	€ 1.281.516,32	€ 431.135,99	€ 1.712.652,31
€ 210,00	€ 1.132.167,42	€ 113.835,89	€ 1.246.003,30	€ 1.289.157,20	€ 66.255,14	€ 1.355.412,33	€ 1.281.837,71	€ 431.158,82	€ 1.712.996,53
€ 215,00	€ 1.133.103,04	€ 113.919,41	€ 1.247.022,46	€ 1.289.734,51	€ 66.278,76	€ 1.356.013,27	€ 1.282.159,10	€ 431.181,65	€ 1.713.340,76
€ 220,00	€ 1.134.038,67	€ 114.002,94	€ 1.248.041,61	€ 1.290.311,83	€ 66.302,39	€ 1.356.614,22	€ 1.282.480,50	€ 431.204,49	€ 1.713.684,98
€ 225,00	€ 1.134.974,29	€ 114.086,47	€ 1.249.060,76	€ 1.290.889,14	€ 66.326,02	€ 1.357.215,16	€ 1.282.801,89	€ 431.227,32	€ 1.714.029,21
€ 230,00	€ 1.135.909,91	€ 114.169,99	€ 1.250.079,91	€ 1.291.466,46	€ 66.349,65	€ 1.357.816,10	€ 1.283.123,28	€ 431.250,15	€ 1.714.373,44
€ 235,00	€ 1.136.845,54	€ 114.253,52	€ 1.251.099,06	€ 1.292.043,77	€ 66.373,28	€ 1.358.417,05	€ 1.283.444,68	€ 431.272,98	€ 1.714.717,66
€ 240,00	€ 1.137.781,16	€ 114.337,05	€ 1.252.118,21	€ 1.292.621,09	€ 66.396,90	€ 1.359.017,99	€ 1.283.766,07	€ 431.295,82	€ 1.715.061,89
€ 245,00	€ 1.138.716,79	€ 114.420,57	€ 1.253.137,36	€ 1.293.198,40	€ 66.420,53	€ 1.359.618,93	€ 1.284.087,46	€ 431.318,65	€ 1.715.406,11
€ 250,00	€ 1.139.652,41	€ 114.504,10	€ 1.254.156,51	€ 1.293.775,72	€ 66.444,16	€ 1.360.219,88	€ 1.284.408,85	€ 431.341,48	€ 1.715.750,34

Economic growth scenario

	Steel			Concrete			Timber		
allowance price	material costs	Installation costs	Realisation costs	material costs	Installation costs	Realisation costs	material costs	Installation costs	Realisation costs
€ 0,00	€ 1.087.304,37	€ 109.854,45	€ 1.197.158,82	€ 1.260.738,12	€ 65.128,87	€ 1.325.866,99	€ 1.266.272,27	€ 430.070,47	€ 1.696.342,74
€ 5,00	€ 1.088.567,46	€ 109.965,82	€ 1.198.533,28	€ 1.261.560,84	€ 65.160,37	€ 1.326.721,21	€ 1.266.715,25	€ 430.100,92	€ 1.696.816,16
€ 10,00	€ 1.089.830,54	€ 110.077,19	€ 1.199.907,73	€ 1.262.383,55	€ 65.191,88	€ 1.327.575,43	€ 1.267.158,23	€ 430.131,36	€ 1.697.289,58
€ 15,00	€ 1.091.093,63	€ 110.188,56	€ 1.201.282,18	€ 1.263.206,27	€ 65.223,38	€ 1.328.429,65	€ 1.267.601,20	€ 430.161,80	€ 1.697.763,01
€ 20,00	€ 1.092.356,71	€ 110.299,93	€ 1.202.656,64	€ 1.264.028,99	€ 65.254,88	€ 1.329.283,87	€ 1.268.044,18	€ 430.192,25	€ 1.698.236,43
€ 25,00	€ 1.093.619,80	€ 110.411,29	€ 1.204.031,09	€ 1.264.851,71	€ 65.286,39	€ 1.330.138,09	€ 1.268.487,16	€ 430.222,69	€ 1.698.709,85
€ 30,00	€ 1.094.882,88	€ 110.522,66	€ 1.205.405,54	€ 1.265.674,42	€ 65.317,89	€ 1.330.992,32	€ 1.268.930,14	€ 430.253,13	€ 1.699.183,27
€ 35,00	€ 1.096.145,97	€ 110.634,03	€ 1.206.780,00	€ 1.266.497,14	€ 65.349,40	€ 1.331.846,54	€ 1.269.373,11	€ 430.283,58	€ 1.699.656,69
€ 40,00	€ 1.097.409,05	€ 110.745,40	€ 1.208.154,45	€ 1.267.319,86	€ 65.380,90	€ 1.332.700,76	€ 1.269.816,09	€ 430.314,02	€ 1.700.130,11
€ 45,00	€ 1.098.672,13	€ 110.856,77	€ 1.209.528,90	€ 1.268.142,58	€ 65.412,40	€ 1.333.554,98	€ 1.270.259,07	€ 430.344,46	€ 1.700.603,53
€ 50,00	€ 1.099.935,22	€ 110.968,14	€ 1.210.903,36	€ 1.268.965,29	€ 65.443,91	€ 1.334.409,20	€ 1.270.702,05	€ 430.374,91	€ 1.701.076,95
€ 55,00	€ 1.101.198,30	€ 111.079,51	€ 1.212.277,81	€ 1.269.788,01	€ 65.475,41	€ 1.335.263,42	€ 1.271.145,02	€ 430.405,35	€ 1.701.550,37
€ 60,00	€ 1.102.461,39	€ 111.190,88	€ 1.213.652,27	€ 1.270.610,73	€ 65.506,92	€ 1.336.117,64	€ 1.271.588,00	€ 430.435,79	€ 1.702.023,79
€ 65,00	€ 1.103.724,47	€ 111.302,25	€ 1.215.026,72	€ 1.271.433,45	€ 65.538,42	€ 1.336.971,87	€ 1.272.030,98	€ 430.466,24	€ 1.702.497,21
€ 70,00	€ 1.104.987,56	€ 111.413,61	€ 1.216.401,17	€ 1.272.256,16	€ 65.569,92	€ 1.337.826,09	€ 1.272.473,96	€ 430.496,68	€ 1.702.970,64
€ 75,00	€ 1.106.250,64	€ 111.524,98	€ 1.217.775,63	€ 1.273.078,88	€ 65.601,43	€ 1.338.680,31	€ 1.272.916,93	€ 430.527,12	€ 1.703.444,06
€ 80,00	€ 1.107.513,73	€ 111.636,35	€ 1.219.150,08	€ 1.273.901,60	€ 65.632,93	€ 1.339.534,53	€ 1.273.359,91	€ 430.557,57	€ 1.703.917,48
€ 85,00	€ 1.108.776,81	€ 111.747,72	€ 1.220.524,53	€ 1.274.724,32	€ 65.664,44	€ 1.340.388,75	€ 1.273.802,89	€ 430.588,01	€ 1.704.390,90
€ 90,00	€ 1.110.039,90	€ 111.859,09	€ 1.221.898,99	€ 1.275.547,03	€ 65.695,94	€ 1.341.242,97	€ 1.274.245,87	€ 430.618,45	€ 1.704.864,32
€ 95,00	€ 1.111.302,98	€ 111.970,46	€ 1.223.273,44	€ 1.276.369,75	€ 65.727,44	€ 1.342.097,19	€ 1.274.688,84	€ 430.648,90	€ 1.705.337,74
€ 100,00	€ 1.112.566,07	€ 112.081,83	€ 1.224.647,89	€ 1.277.192,47	€ 65.758,95	€ 1.342.951,42	€ 1.275.131,82	€ 430.679,34	€ 1.705.811,16
€ 105,00	€ 1.113.829,15	€ 112.193,20	€ 1.226.022,35	€ 1.278.015,18	€ 65.790,45	€ 1.343.805,64	€ 1.275.574,80	€ 430.709,78	€ 1.706.284,58
€ 110,00	€ 1.115.092,24	€ 112.304,57	€ 1.227.396,80	€ 1.278.837,90	€ 65.821,96	€ 1.344.659,86	€ 1.276.017,78	€ 430.740,23	€ 1.706.758,00
€ 115,00	€ 1.116.355,32	€ 112.415,93	€ 1.228.771,26	€ 1.279.660,62	€ 65.853,46	€ 1.345.514,08	€ 1.276.460,75	€ 430.770,67	€ 1.707.231,42
€ 120,00	€ 1.117.618,41	€ 112.527,30	€ 1.230.145,71	€ 1.280.483,34	€ 65.884,96	€ 1.346.368,30	€ 1.276.903,73	€ 430.801,11	€ 1.707.704,84
€ 125,00	€ 1.118.881,49	€ 112.638,67	€ 1.231.520,16	€ 1.281.306,05	€ 65.916,47	€ 1.347.222,52	€ 1.277.346,71	€ 430.831,56	€ 1.708.178,27
€ 130,00	€ 1.120.144,58	€ 112.750,04	€ 1.232.894,62	€ 1.282.128,77	€ 65.947,97	€ 1.348.076,74	€ 1.277.789,69	€ 430.862,00	€ 1.708.651,69
€ 135,00	€ 1.121.407,66	€ 112.861,41	€ 1.234.269,07	€ 1.282.951,49	€ 65.979,48	€ 1.348.930,96	€ 1.278.232,67	€ 430.892,44	€ 1.709.125,11
€ 140,00	€ 1.122.670,74	€ 112.972,78	€ 1.235.643,52	€ 1.283.774,21	€ 66.010,98	€ 1.349.785,19	€ 1.278.675,64	€ 430.922,89	€ 1.709.598,53
€ 145,00	€ 1.123.933,83	€ 113.084,15	€ 1.237.017,98	€ 1.284.596,92	€ 66.042,48	€ 1.350.639,41	€ 1.279.118,62	€ 430.953,33	€ 1.710.071,95

€ 150,00	€ 1.125.196,91	€ 113.195,52	€ 1.238.392,43	€ 1.285.419,64	€ 66.073,99	€ 1.351.493,63	€ 1.279.561,60	€ 430.983,77	€ 1.710.545,37
€ 155,00	€ 1.126.460,00	€ 113.306,89	€ 1.239.766,88	€ 1.286.242,36	€ 66.105,49	€ 1.352.347,85	€ 1.280.004,58	€ 431.014,22	€ 1.711.018,79
€ 160,00	€ 1.127.723,08	€ 113.418,25	€ 1.241.141,34	€ 1.287.065,08	€ 66.137,00	€ 1.353.202,07	€ 1.280.447,55	€ 431.044,66	€ 1.711.492,21
€ 165,00	€ 1.128.986,17	€ 113.529,62	€ 1.242.515,79	€ 1.287.887,79	€ 66.168,50	€ 1.354.056,29	€ 1.280.890,53	€ 431.075,10	€ 1.711.965,63
€ 170,00	€ 1.130.249,25	€ 113.640,99	€ 1.243.890,25	€ 1.288.710,51	€ 66.200,00	€ 1.354.910,51	€ 1.281.333,51	€ 431.105,55	€ 1.712.439,05
€ 175,00	€ 1.131.512,34	€ 113.752,36	€ 1.245.264,70	€ 1.289.533,23	€ 66.231,51	€ 1.355.764,74	€ 1.281.776,49	€ 431.135,99	€ 1.712.912,47
€ 180,00	€ 1.132.775,42	€ 113.863,73	€ 1.246.639,15	€ 1.290.355,95	€ 66.263,01	€ 1.356.618,96	€ 1.282.219,46	€ 431.166,43	€ 1.713.385,90
€ 185,00	€ 1.134.038,51	€ 113.975,10	€ 1.248.013,61	€ 1.291.178,66	€ 66.294,52	€ 1.357.473,18	€ 1.282.662,44	€ 431.196,88	€ 1.713.859,32
€ 190,00	€ 1.135.301,59	€ 114.086,47	€ 1.249.388,06	€ 1.292.001,38	€ 66.326,02	€ 1.358.327,40	€ 1.283.105,42	€ 431.227,32	€ 1.714.332,74
€ 195,00	€ 1.136.564,68	€ 114.197,84	€ 1.250.762,51	€ 1.292.824,10	€ 66.357,52	€ 1.359.181,62	€ 1.283.548,40	€ 431.257,76	€ 1.714.806,16
€ 200,00	€ 1.137.827,76	€ 114.309,21	€ 1.252.136,97	€ 1.293.646,82	€ 66.389,03	€ 1.360.035,84	€ 1.283.991,37	€ 431.288,21	€ 1.715.279,58
€ 205,00	€ 1.139.090,85	€ 114.420,57	€ 1.253.511,42	€ 1.294.469,53	€ 66.420,53	€ 1.360.890,06	€ 1.284.434,35	€ 431.318,65	€ 1.715.753,00
€ 210,00	€ 1.140.353,93	€ 114.531,94	€ 1.254.885,87	€ 1.295.292,25	€ 66.452,04	€ 1.361.744,29	€ 1.284.877,33	€ 431.349,09	€ 1.716.226,42
€ 215,00	€ 1.141.617,02	€ 114.643,31	€ 1.256.260,33	€ 1.296.114,97	€ 66.483,54	€ 1.362.598,51	€ 1.285.320,31	€ 431.379,54	€ 1.716.699,84
€ 220,00	€ 1.142.880,10	€ 114.754,68	€ 1.257.634,78	€ 1.296.937,69	€ 66.515,04	€ 1.363.452,73	€ 1.285.763,28	€ 431.409,98	€ 1.717.173,26
€ 225,00	€ 1.144.143,18	€ 114.866,05	€ 1.259.009,23	€ 1.297.760,40	€ 66.546,55	€ 1.364.306,95	€ 1.286.206,26	€ 431.440,42	€ 1.717.646,68
€ 230,00	€ 1.145.406,27	€ 114.977,42	€ 1.260.383,69	€ 1.298.583,12	€ 66.578,05	€ 1.365.161,17	€ 1.286.649,24	€ 431.470,87	€ 1.718.120,10
€ 235,00	€ 1.146.669,35	€ 115.088,79	€ 1.261.758,14	€ 1.299.405,84	€ 66.609,55	€ 1.366.015,39	€ 1.287.092,22	€ 431.501,31	€ 1.718.593,53
€ 240,00	€ 1.147.932,44	€ 115.200,16	€ 1.263.132,60	€ 1.300.228,56	€ 66.641,06	€ 1.366.869,61	€ 1.287.535,19	€ 431.531,75	€ 1.719.066,95
€ 245,00	€ 1.149.195,52	€ 115.311,53	€ 1.264.507,05	€ 1.301.051,27	€ 66.672,56	€ 1.367.723,84	€ 1.287.978,17	€ 431.562,20	€ 1.719.540,37
€ 250,00	€ 1.150.458,61	€ 115.422,89	€ 1.265.881,50	€ 1.301.873,99	€ 66.704,07	€ 1.368.578,06	€ 1.288.421,15	€ 431.592,64	€ 1.720.013,79

Construction crisis scenario

	Steel			Concrete			Timber		
allowance price	Material costs	Installation costs	Realisation costs	Material costs	Installation costs	Realisation costs	Material costs	Installation costs	Realisation costs
€ 0,00	€ 1.097.483,60	€ 110.705,64	€ 1.208.189,25	€ 1.268.811,81	€ 65.369,65	€ 1.334.181,46	€ 1.270.145,25	€ 430.303,15	€ 1.700.448,40
€ 5,00	€ 1.098.147,91	€ 110.766,94	€ 1.208.914,85	€ 1.269.159,60	€ 65.386,99	€ 1.334.546,60	€ 1.270.360,41	€ 430.319,91	€ 1.700.680,31
€ 10,00	€ 1.098.812,22	€ 110.828,24	€ 1.209.640,46	€ 1.269.507,40	€ 65.404,33	€ 1.334.911,73	€ 1.270.575,56	€ 430.336,66	€ 1.700.912,23
€ 15,00	€ 1.099.476,52	€ 110.889,54	€ 1.210.366,06	€ 1.269.855,19	€ 65.421,67	€ 1.335.276,86	€ 1.270.790,72	€ 430.353,42	€ 1.701.144,14
€ 20,00	€ 1.100.140,83	€ 110.950,84	€ 1.211.091,67	€ 1.270.202,99	€ 65.439,01	€ 1.335.642,00	€ 1.271.005,87	€ 430.370,18	€ 1.701.376,05
€ 25,00	€ 1.100.805,14	€ 111.012,14	€ 1.211.817,27	€ 1.270.550,78	€ 65.456,35	€ 1.336.007,13	€ 1.271.221,03	€ 430.386,93	€ 1.701.607,96
€ 30,00	€ 1.101.469,44	€ 111.073,44	€ 1.212.542,88	€ 1.270.898,57	€ 65.473,69	€ 1.336.372,27	€ 1.271.436,18	€ 430.403,69	€ 1.701.839,87
€ 35,00	€ 1.102.133,75	€ 111.134,73	€ 1.213.268,48	€ 1.271.246,37	€ 65.491,03	€ 1.336.737,40	€ 1.271.651,34	€ 430.420,45	€ 1.702.071,78
€ 40,00	€ 1.102.798,06	€ 111.196,03	€ 1.213.994,09	€ 1.271.594,16	€ 65.508,37	€ 1.337.102,54	€ 1.271.866,49	€ 430.437,20	€ 1.702.303,69
€ 45,00	€ 1.103.462,36	€ 111.257,33	€ 1.214.719,69	€ 1.271.941,96	€ 65.525,71	€ 1.337.467,67	€ 1.272.081,65	€ 430.453,96	€ 1.702.535,61
€ 50,00	€ 1.104.126,67	€ 111.318,63	€ 1.215.445,30	€ 1.272.289,75	€ 65.543,05	€ 1.337.832,81	€ 1.272.296,80	€ 430.470,71	€ 1.702.767,52
€ 55,00	€ 1.104.790,97	€ 111.379,93	€ 1.216.170,90	€ 1.272.637,55	€ 65.560,39	€ 1.338.197,94	€ 1.272.511,96	€ 430.487,47	€ 1.702.999,43
€ 60,00	€ 1.105.455,28	€ 111.441,23	€ 1.216.896,51	€ 1.272.985,34	€ 65.577,73	€ 1.338.563,08	€ 1.272.727,11	€ 430.504,23	€ 1.703.231,34
€ 65,00	€ 1.106.119,59	€ 111.502,53	€ 1.217.622,11	€ 1.273.333,14	€ 65.595,08	€ 1.338.928,21	€ 1.272.942,27	€ 430.520,98	€ 1.703.463,25
€ 70,00	€ 1.106.783,89	€ 111.563,82	€ 1.218.347,72	€ 1.273.680,93	€ 65.612,42	€ 1.339.293,35	€ 1.273.157,42	€ 430.537,74	€ 1.703.695,16
€ 75,00	€ 1.107.448,20	€ 111.625,12	€ 1.219.073,32	€ 1.274.028,73	€ 65.629,76	€ 1.339.658,48	€ 1.273.372,58	€ 430.554,50	€ 1.703.927,08
€ 80,00	€ 1.108.112,51	€ 111.686,42	€ 1.219.798,93	€ 1.274.376,52	€ 65.647,10	€ 1.340.023,62	€ 1.273.587,73	€ 430.571,25	€ 1.704.158,99
€ 85,00	€ 1.108.776,81	€ 111.747,72	€ 1.220.524,53	€ 1.274.724,32	€ 65.664,44	€ 1.340.388,75	€ 1.273.802,89	€ 430.588,01	€ 1.704.390,90
€ 90,00	€ 1.109.441,12	€ 111.809,02	€ 1.221.250,14	€ 1.275.072,11	€ 65.681,78	€ 1.340.753,89	€ 1.274.018,04	€ 430.604,77	€ 1.704.622,81

€ 95,00	€ 1.110.105,43	€ 111.870,32	€ 1.221.975,74	€ 1.275.419,90	€ 65.699,12	€ 1.341.119,02	€ 1.274.233,20	€ 430.621,52	€ 1.704.854,72
€ 100,00	€ 1.110.769,73	€ 111.931,62	€ 1.222.701,35	€ 1.275.767,70	€ 65.716,46	€ 1.341.484,16	€ 1.274.448,35	€ 430.638,28	€ 1.705.086,63
€ 105,00	€ 1.111.434,04	€ 111.992,92	€ 1.223.426,95	€ 1.276.115,49	€ 65.733,80	€ 1.341.849,29	€ 1.274.663,51	€ 430.655,03	€ 1.705.318,54
€ 110,00	€ 1.112.098,34	€ 112.054,21	€ 1.224.152,56	€ 1.276.463,29	€ 65.751,14	€ 1.342.214,42	€ 1.274.878,67	€ 430.671,79	€ 1.705.550,46
€ 115,00	€ 1.112.762,65	€ 112.115,51	€ 1.224.878,16	€ 1.276.811,08	€ 65.768,48	€ 1.342.579,56	€ 1.275.093,82	€ 430.688,55	€ 1.705.782,37
€ 120,00	€ 1.113.426,96	€ 112.176,81	€ 1.225.603,77	€ 1.277.158,88	€ 65.785,82	€ 1.342.944,69	€ 1.275.308,98	€ 430.705,30	€ 1.706.014,28
€ 125,00	€ 1.114.091,26	€ 112.238,11	€ 1.226.329,37	€ 1.277.506,67	€ 65.803,16	€ 1.343.309,83	€ 1.275.524,13	€ 430.722,06	€ 1.706.246,19
€ 130,00	€ 1.114.755,57	€ 112.299,41	€ 1.227.054,98	€ 1.277.854,47	€ 65.820,50	€ 1.343.674,96	€ 1.275.739,29	€ 430.738,82	€ 1.706.478,10
€ 135,00	€ 1.115.419,88	€ 112.360,71	€ 1.227.780,58	€ 1.278.202,26	€ 65.837,84	€ 1.344.040,10	€ 1.275.954,44	€ 430.755,57	€ 1.706.710,01
€ 140,00	€ 1.116.084,18	€ 112.422,01	€ 1.228.506,19	€ 1.278.550,06	€ 65.855,18	€ 1.344.405,23	€ 1.276.169,60	€ 430.772,33	€ 1.706.941,93
€ 145,00	€ 1.116.748,49	€ 112.483,31	€ 1.229.231,79	€ 1.278.897,85	€ 65.872,52	€ 1.344.770,37	€ 1.276.384,75	€ 430.789,09	€ 1.707.173,84
€ 150,00	€ 1.117.412,80	€ 112.544,60	€ 1.229.957,40	€ 1.279.245,65	€ 65.889,86	€ 1.345.135,50	€ 1.276.599,91	€ 430.805,84	€ 1.707.405,75
€ 155,00	€ 1.118.077,10	€ 112.605,90	€ 1.230.683,01	€ 1.279.593,44	€ 65.907,20	€ 1.345.500,64	€ 1.276.815,06	€ 430.822,60	€ 1.707.637,66
€ 160,00	€ 1.118.741,41	€ 112.667,20	€ 1.231.408,61	€ 1.279.941,23	€ 65.924,54	€ 1.345.865,77	€ 1.277.030,22	€ 430.839,35	€ 1.707.869,57
€ 165,00	€ 1.119.405,71	€ 112.728,50	€ 1.232.134,22	€ 1.280.289,03	€ 65.941,88	€ 1.346.230,91	€ 1.277.245,37	€ 430.856,11	€ 1.708.101,48
€ 170,00	€ 1.120.070,02	€ 112.789,80	€ 1.232.859,82	€ 1.280.636,82	€ 65.959,22	€ 1.346.596,04	€ 1.277.460,53	€ 430.872,87	€ 1.708.333,39
€ 175,00	€ 1.120.734,33	€ 112.851,10	€ 1.233.585,43	€ 1.280.984,62	€ 65.976,56	€ 1.346.961,18	€ 1.277.675,68	€ 430.889,62	€ 1.708.565,31
€ 180,00	€ 1.121.398,63	€ 112.912,40	€ 1.234.311,03	€ 1.281.332,41	€ 65.993,90	€ 1.347.326,31	€ 1.277.890,84	€ 430.906,38	€ 1.708.797,22
€ 185,00	€ 1.122.062,94	€ 112.973,70	€ 1.235.036,64	€ 1.281.680,21	€ 66.011,24	€ 1.347.691,45	€ 1.278.105,99	€ 430.923,14	€ 1.709.029,13
€ 190,00	€ 1.122.727,25	€ 113.034,99	€ 1.235.762,24	€ 1.282.028,00	€ 66.028,58	€ 1.348.056,58	€ 1.278.321,15	€ 430.939,89	€ 1.709.261,04
€ 195,00	€ 1.123.391,55	€ 113.096,29	€ 1.236.487,85	€ 1.282.375,80	€ 66.045,92	€ 1.348.421,72	€ 1.278.536,30	€ 430.956,65	€ 1.709.492,95
€ 200,00	€ 1.124.055,86	€ 113.157,59	€ 1.237.213,45	€ 1.282.723,59	€ 66.063,26	€ 1.348.786,85	€ 1.278.751,46	€ 430.973,41	€ 1.709.724,86
€ 205,00	€ 1.124.720,17	€ 113.218,89	€ 1.237.939,06	€ 1.283.071,39	€ 66.080,60	€ 1.349.151,98	€ 1.278.966,61	€ 430.990,16	€ 1.709.956,78
€ 210,00	€ 1.125.384,47	€ 113.280,19	€ 1.238.664,66	€ 1.283.419,18	€ 66.097,94	€ 1.349.517,12	€ 1.279.181,77	€ 431.006,92	€ 1.710.188,69
€ 215,00	€ 1.126.048,78	€ 113.341,49	€ 1.239.390,27	€ 1.283.766,97	€ 66.115,28	€ 1.349.882,25	€ 1.279.396,92	€ 431.023,67	€ 1.710.420,60
€ 220,00	€ 1.126.713,08	€ 113.402,79	€ 1.240.115,87	€ 1.284.114,77	€ 66.132,62	€ 1.350.247,39	€ 1.279.612,08	€ 431.040,43	€ 1.710.652,51
€ 225,00	€ 1.127.377,39	€ 113.464,09	€ 1.240.841,48	€ 1.284.462,56	€ 66.149,96	€ 1.350.612,52	€ 1.279.827,23	€ 431.057,19	€ 1.710.884,42
€ 230,00	€ 1.128.041,70	€ 113.525,38	€ 1.241.567,08	€ 1.284.810,36	€ 66.167,30	€ 1.350.977,66	€ 1.280.042,39	€ 431.073,94	€ 1.711.116,33
€ 235,00	€ 1.128.706,00	€ 113.586,68	€ 1.242.292,69	€ 1.285.158,15	€ 66.184,64	€ 1.351.342,79	€ 1.280.257,54	€ 431.090,70	€ 1.711.348,24
€ 240,00	€ 1.129.370,31	€ 113.647,98	€ 1.243.018,29	€ 1.285.505,95	€ 66.201,98	€ 1.351.707,93	€ 1.280.472,70	€ 431.107,46	€ 1.711.580,16
€ 245,00	€ 1.130.034,62	€ 113.709,28	€ 1.243.743,90	€ 1.285.853,74	€ 66.219,32	€ 1.352.073,06	€ 1.280.687,85	€ 431.124,21	€ 1.711.812,07
€ 250,00	€ 1.130.698,92	€ 113.770,58	€ 1.244.469,50	€ 1.286.201,54	€ 66.236,66	€ 1.352.438,20	€ 1.280.903,01	€ 431.140,97	€ 1.712.043,98

Appendix F – Relation between the EU allowance price and the total realisation costs

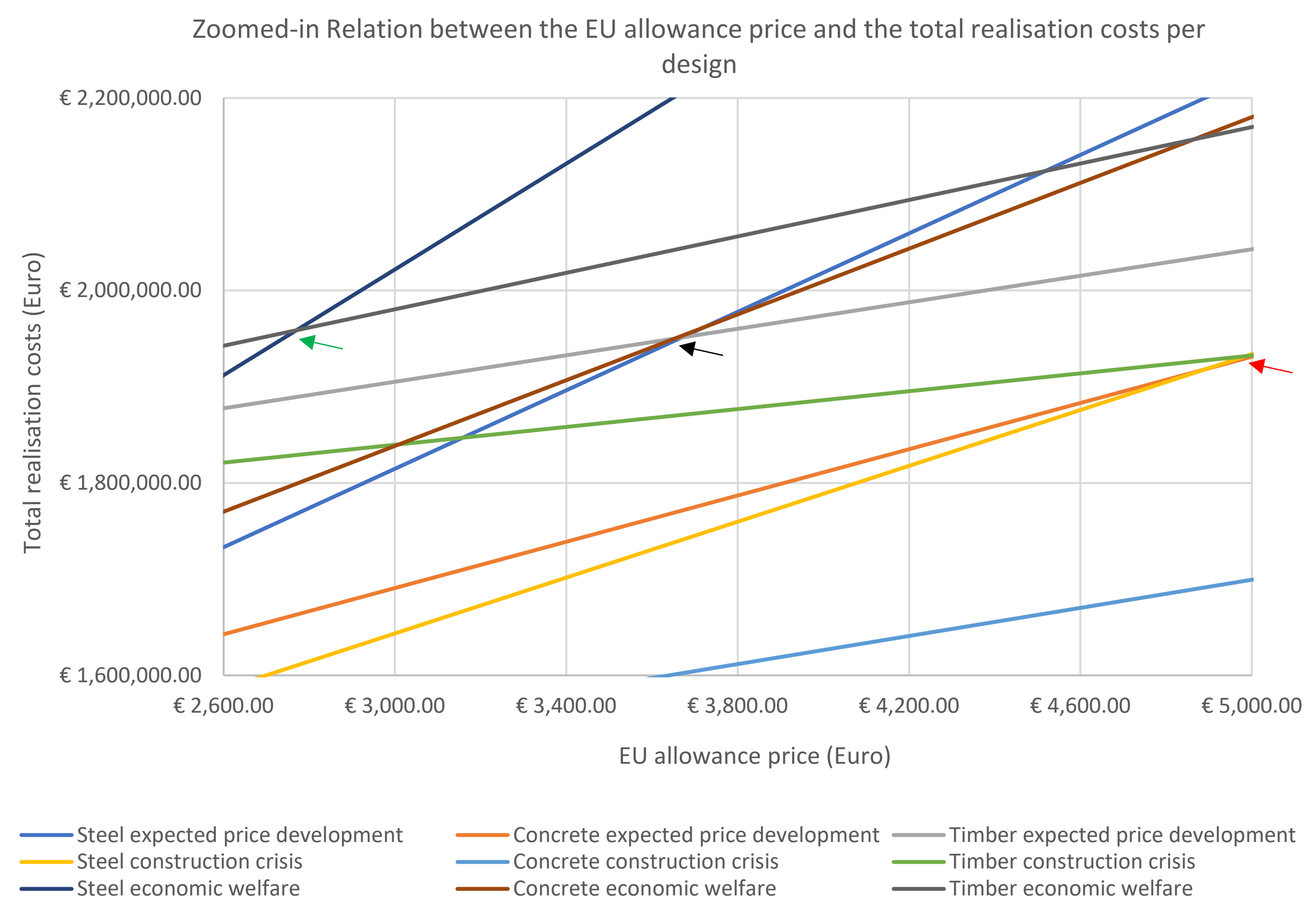


Figure F0-1: Tipping points for the timber design where it stops having the highest realisation costs

Appendix G – Relation between the EU allowance price and the material costs

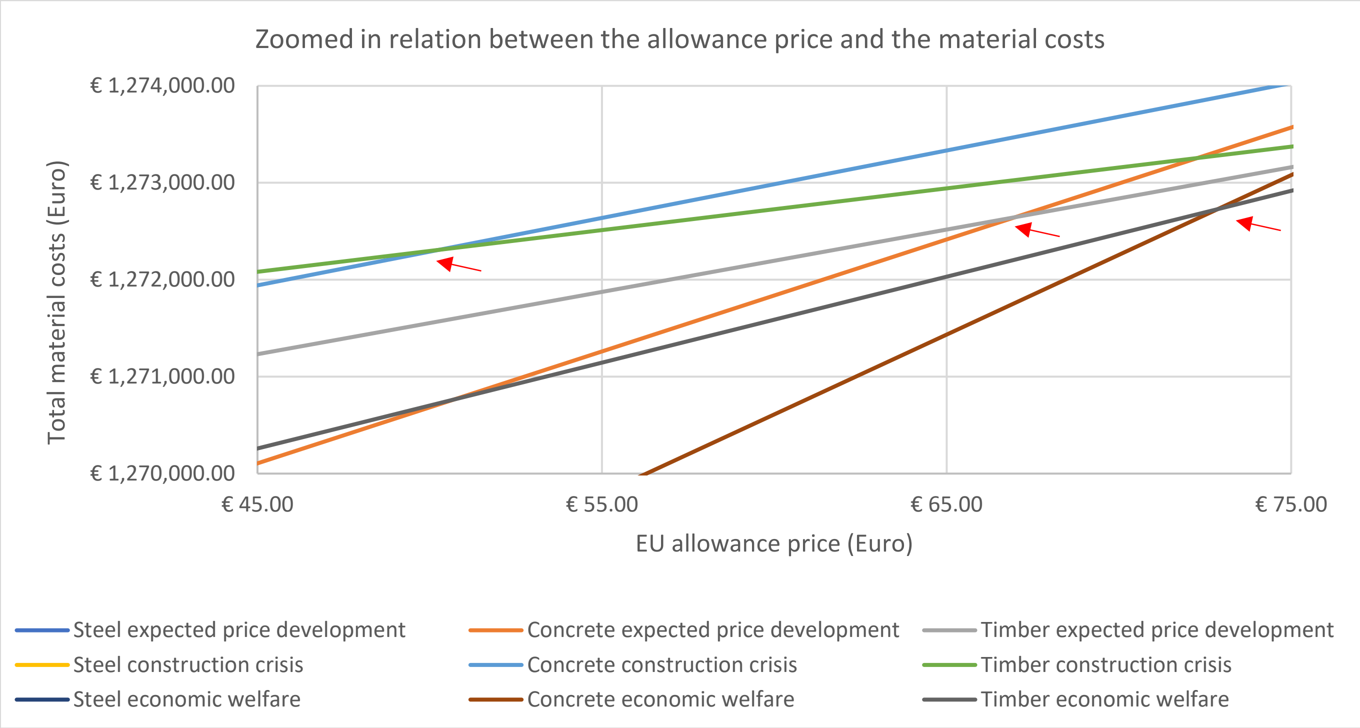


Figure G0-2: Tipping points for the timber design where it stops having the highest material costs

Master Thesis

R. J. de Jonge