Carbon Footprint of Common Quay Structures

Extended Abstract

Master Thesis Civil Engineering

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1. Introduction

1.1 Background

Climate change is a reality that is significantly affecting the wellbeing of the planet and all of its inhabitants. Climate Change is caused by anthropogenic greenhouse gas (GHG) emissions (WRI and WBCSD, 2011). The main GHG's are carbon dioxide (CO_2) methane (CH_4) and nitrous oxide (N_2O). In 2017 the building and construction sector were responsible for approximately 11% of global CO_2 emissions (IEA and UNEP, 2018) which includes the production of construction materials such as steel and cement. In the 2015 Paris climate agreement most of the countries in the world signed an agreement to limit global warming to 1.5 to 2 degrees Celsius above pre-industrial levels (UNFCCC, 2020). In order to achieve this goal, the European Union has committed to reduce GHG emissions by 40% by 2030 compared with 1990 (Eurostat, 2019). However, not only in Europe, but globally, the civil engineering and construction industry clearly has an important role to play in the effort to reduce carbon emissions. This will require innovation in designing and planning in order to achieve the goals of carbon reduction. On a project level Life Cycle Assessment (LCA) is a very useful tool that needs to be used in order to identify carbon reduction opportunities.

This thesis is a study of the carbon footprint of various alternative designs and construction methods for a quay wall to be used as a container terminal. The designs that were considered for the quay wall are concrete caissons, sheet piled combi-walls and open piled suspended decks as these are the most commonly used structures for the design and construction of container terminals.

1.2 Structure

This extended abstract has been divided into six sections. The first section is an introduction and provides a background on the significance of civil engineering and construction on climate change as well as LCA. The second section is a state of the art and literature review and summarises the main international standards, tools and databases used for carbon footprint calculations and LCA. A review of existing port infrastructure carbon footprint studies is also presented. The third section goes over the assumptions and calculation that were done in order to develop outline designs for each of the quay wall structure types. In the fourth section the LCA steps of goal and scope definition, life cycle inventory and the LCA results are presented. The fifth section is a discussion and interpretation of the results and the final section the conclusions are summarised.

2. State of the Art and Literature Review

2.1 LCA Standards

Various LCA and carbon footprint standards were reviewed as part of this study. These are discussed in this section.

ISO14040 describes the principles for doing a Life Cycle Assessment, which is based on the following four main phases:

1) Goal and scope definition phase. The goal of the LCA as well as the system boundary are defined in this phase.
2) Life Cycle Inventory analysis phase (LCI). This phase involves compiling all the required input and output data for a system or product being investigated.
3) The Life Cycle Impact Assessment phase (LCIA). In the LCIA phase the potential environmental impacts for the various processes of a study are quantified. In this study only one impact category was investigated, namely climate change.
4) The Interpretation phase. Here the results of the LCI and the LCIA phases are discussed and interpreted in order to identify significant issues and draw conclusions and recommendations.

ISO 14044 describes in greater detail the requirements for doing an LCA in line with the above four stages. It also provides detailed guidelines on the reporting of an LCA study and the critical review.

ISO 14040 and 14044 are generic standards that guide a user for performing an LCA whereas ISO 14067 is specifically focussed on calculation the carbon footprint and is based on ISO 14040 and ISO 14044. The seven principles used to quantify the carbon footprint as per ISO 14067 (ISO, 2018) are summarised in Table 1.

Table 1 - Principles for performing a carbon footprint study according to ISO 14067

Principle	Meaning
1) Relevance	Use of data and methods that are applicable to the system being studied.
2) Completeness	All GHG emissions that provide a significant contribution should be included.
3) Consistency	Assumptions, methods and data should be applied in the same way throughout the various stages of the LCA study.
4) Coherence	Use of methodologies, standards and guidance documents internationally recognized.
5) Accuracy	Quantification of the carbon footprint in an accurate way and biases and uncertainties reduced as far as possible.
6) Transparency	Methodologies, assumptions and data documented and referenced in an open manner.
7) Double Counting	Prevention of double counting of GHG emissions.

PAS 2050 (Published by the British Standards Institute) and the Greenhouse Gas (GHG) Protocol (developed by the World Resource Institute and the World Business Council for Sustainable Development) are carbon footprint standards also built around the LCA approach with the four main phases as described above. The standards are more detailed than the ISO standards and may provide an LCA practitioner with more guidance on specific issues than the ISO standards.

Euronorm EN 15978:2011 is a standard that is used to evaluate the environmental performance of a building according to an LCA approach. It defines various life cycle stages of a building which is useful to adopt for infrastructure projects such as quay walls. These life cycle stages are summarised in Table 2. In this study only the production (A1-A3), transport (A4) and construction (A5) life cycle stages were considered.

Table 2 - Building Life Cycle Stages, adapted from Figure 6 in EN 15978 (CEN/TC 350, 2011)

Life Cycle Stage	Stage No.	Description	Example for Quay Wall
Production Stage	A1	Raw Material Extraction	Mining of Iron Ore
	A2	Transport of raw Materials	Transporting Ore from mine to steel Smelter
	A3	Manufacturing Constr. Materials	Producing Steel Piles
Construction Stage	A4	Transport	Transport Steel Piles to constr. Site
	A5	Construction	Installation of Steel Piles
Use Stage	B1	Use	Use of pier, e.g. vessels offloading/loading cargo
	B2	Maintenance	Replacing anodes on piles
	B3	Repair	Repairing damaged concrete sections
	B4 - B7	…	…
End-of life	C1	Demolition / De-construction	Demolish pile caps / Extract piles
	C2 - C4	…	…
R / R / R	D	Reuse / Recovery / Recycling	Recycle steel

2.2 LCA Databases and Tools

Databases

Ecoinvent is one of the most used and largest LCA database libraries. It has datasets that cover construction materials, metals, minerals and various transport processes (Ecoinvent, 2020). Depending on the specific dataset it has geographical coverage which is applicable to a specific country (mostly European and North American countries), continents or global averages. In a database review by Martinez-Rocamora et al., (2016) Ecoinvent was considered to be a library with a high level of consistency and transparency. EcoInvent is included in the SimaPro software which was available to the authour (faculty license).

The European reference Life Cycle Database (ELCD) was developed by the European commission and the JRC (Joint Research Centre). It is applicable specifically to Europe and contains datasets on multiple construction materials, transport and construction processes.

The Inventory of Carbon and Energy (ICE) is a free construction materials database developed by Hammond and Jones (2008). The latest version was from 2019 (Circular Ecology, 2020) and was available in an excel format. Most of the datasets are representative for the United Kingdom.

LCA Tools

SimaPro is one of the most widely used LCA software packages. Amongst others, it has the following significant features:

- An intuitive user interface,
- Use of parameters – useful for a sensitivity analysis,
- Transparent unit data allowing traceability,
- Process trees that enable one to identify significant contributors,
- Grouping of results
- It includes the Ecoinvent database and the World Steel Association LCA data on steel production as well as other industry.

OpenLCA, the European Federation of Foundation Contractors (EFFC) and the Deep Foundations Institute (DFI) Carbon Calculator and the Embodied Carbon in Construction (EC3) tool were also investigated. However, these tools did not provide the same advantages as SimaPro and were therefore not used.

Summary

In this study SimaPro was used with data from the Ecoinvent, ELCD and ICE libraries. In certain instances, data was used from Environmental Product Declarations (EPD´s).

2.3 LCA and CO_2 Footprint Studies

Port of Gothenburg

Stripple et al. (2016) performed an LCA study of port infrastructure and its operation for the Port of Gothenburg in Sweden. Various terminals, including the container terminal, were investigated.

The functional unit was kilograms of carbon dioxide equivalent per metric ton of cargo handled (kg CO_2e/t). For the container terminal an average load of 8112kg per twenty-foot equivalent unit (TEU) was estimated and a lifetime of 60 years was considered.

The life cycle stages considered in the study by Stripple et al. (2016) were construction, operation and maintenance of the port facilities. The construction phase included raw materials extraction and production (A1-A3, refer to Table 2), transport (A4) and operation of construction machinery (A5). The results for the container terminal are presented in Figure 1.

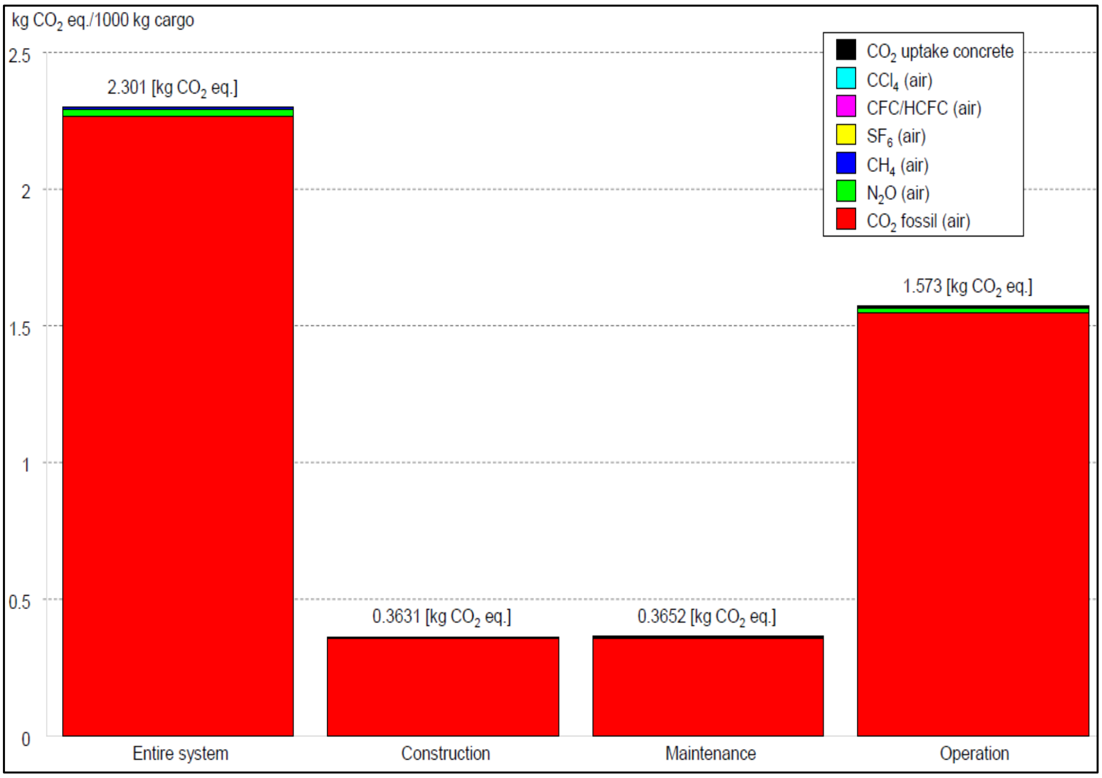


Figure 1 - GWP (kg CO2e/1000kg of cargo) for container terminal in the Port of Gothenburg, adopted from Figure 67 (Stripple et al.,2016, p.114)

Port of Rotterdam

Maas et al. (2011) performed an LCA study of quay wall designs made of concrete, steel, wood and fibre reinforced concrete. The case study was the Euromax Container Terminal in the Port of Rotterdam with a terminal length of 1900 m and a retaining wall height of 27 m.

The main dimension for the various designs were as follows:

- concrete diaphragm wall: length = 32 m & thickness = 1,2 m;
- Steel combi wall: tubular piles length = 35 m & sheet pile length = 32 m;
- Timber wall (Azobe Hardwood): wall thickness = 1,4 m;
- Fibre reinforced polymer panels (FRP): wall thickness = 2,08 m.

The functional unit was kilograms of carbon dioxide equivalent per meter length of quay wall (kg CO_2e/m) for a structure with a design life of 50 years. The results of the study are presented in Figure 2.

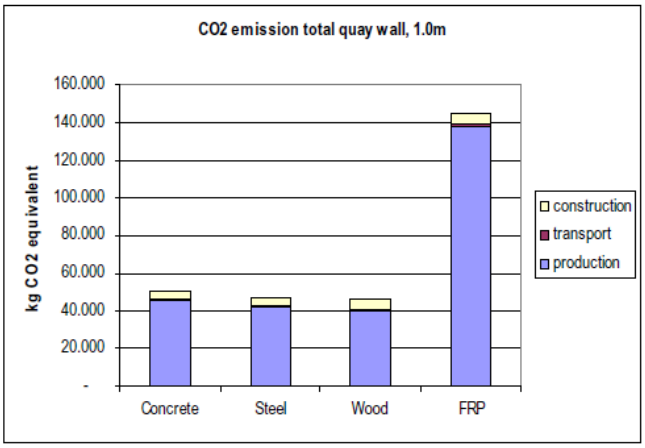


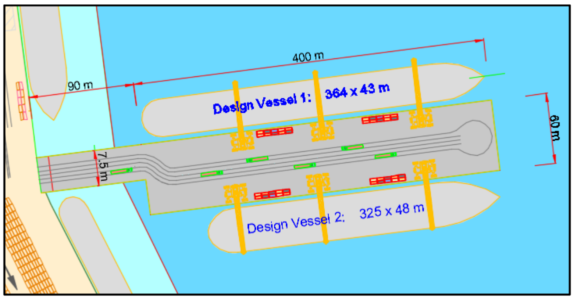
Figure 2 - Carbon footprint of alternative designs in kg CO_2e/m for a container terminal (Maas et al., 2011)

3. Design

3.1 Introduction

As part of this study outline designs for caisson, sheet pile combi-wall and open piled suspended deck type structures were developed. The purpose of developing the outline designs was to be able to determine material quantities and construction methodologies which could be used as a basis to calculate the carbon footprint of the alternative options.

The required dimensions of the pier as well as the specifications of the design vessels are indicated Figure 3.



	Design Vessel 1	Design Vessel 2
Max. Displacement	164 200 tons	180 500 tons
Overall Length	367 m	325 m
Breadth	43 m	48 m
Draught	15 m	16,5 m

Figure 3 - Layout dimensions of pier with design vessel specifications indicated

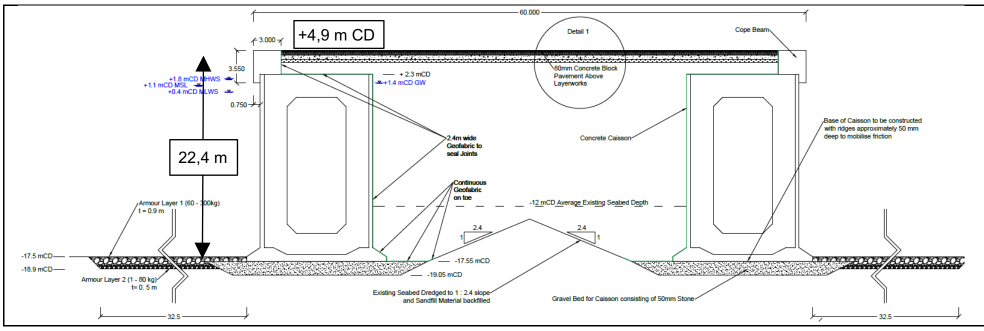
An existing geotechnical ground investigation of the area was used as a basis for calculating the various designs. This investigation consisted of boreholes with SPT tests.

3.2 Design Summary

A design life of 50 years was used as per BS 6349-1-1 (BSI, 2013a). The ultimate limit state (ULS) verifications as per the guidelines of Eurocode (EC) 7 for design approach 2 were performed for all the structures. The caisson structure was adapted from an existing design as detailed by Brueton et al. (2013) whereas the open piled deck design is based on an existing design from a project by Inros Lackner. The sheet pile combi wall outline design was carried out by the author using the GGU Retain software package. All self-weights of the structures and materials were considered. The live loads from a Liebherr LMH 600-2 mobile harbour crane and a uniformly distributed load (UDL) of 50 kN/m^2 were also used in all calculations.

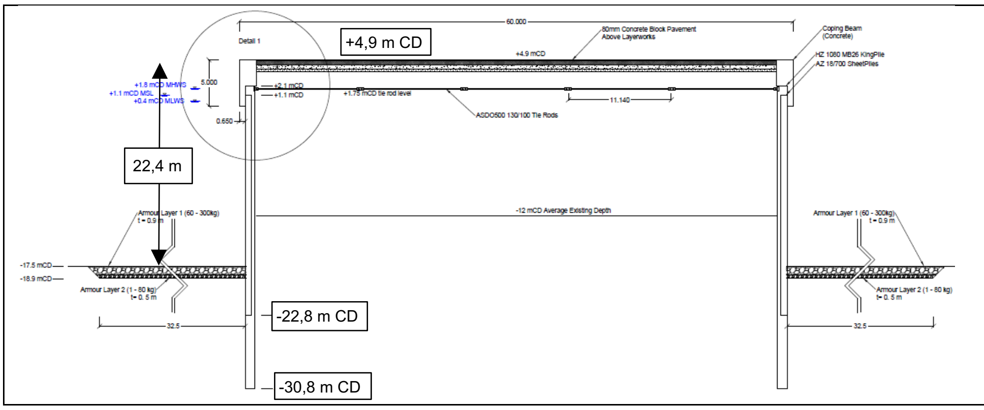
A typical cross section for each design with the main total material quantities is displayed in Figure 4, Figure 5 and Figure 6.

A concrete mix design corresponding to a concrete grade of C35/45 was used for all concrete elements in each of the designs. This mix design was adopted from an existing project from Inros-Lackner. The concrete mix design is detailed in Table 3. The steel reinforcement content that was used for the main components of the various designs is detailed in Table 4.



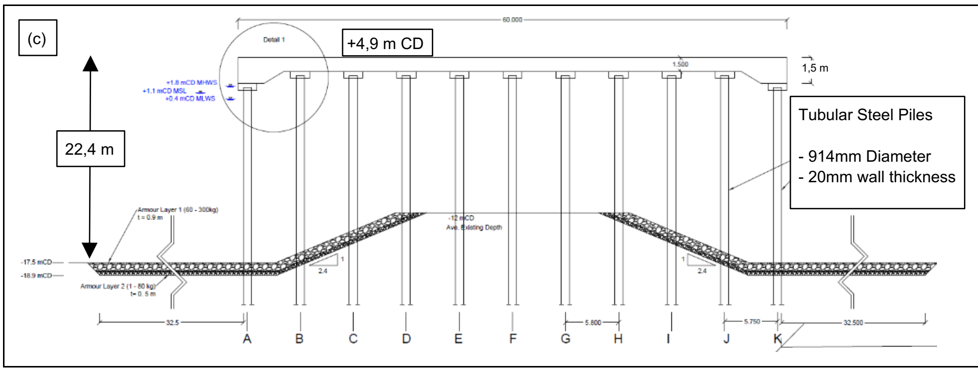
Concrete = 49 951 m^3
Steel Rebar = 9 547 t
Dredging = 736 000 m^3
Backfill = 377 984 m^3
Gravel = 37 688 m^3
Scour = 45 546 m^3
Layerworks & Pavement = 28 959 m^3

Figure 4 - Cross section of concrete caisson design with main material quantities



Concrete = 8 140 m^3
Steel rebar = 1 197 t
Sheet Piles and King Piles = 24 402 t
Tie Rods = 1 679 t
Dredging = 549 240 m^3
Backfill = 317 757 m^3
Scour = 45 546 m^3
Layerworks & Pavement = 70 624 m^3

Figure 5 - Cross section of sheet piled combi wall with main material quantities



Concrete = 33 004 m^3
Steel Rebar = 5 941 t
Tubular Piles = 12 396 t
Dredging = 623 760 m^3
Scour = 164 088 m^3

Figure 6 - Typical cross sections of open pile suspended deck with main material quantities

Table 3 - Baseline Concrete Mix Design

Component	Quantity	Comment
Water	152 Litres	Water cement ratio: 0,33
Cement (CEM I 42,5 N)	391 kg	Total Binder content (Cement and Fly Ash) = 460 kg. Therefore, cement content = 85% and Fly Ash content = 15%
Fly Ash	69 kg	
Sand (4,75mm)	615 kg	
Stone (5-10mm)	358 kg	
Stone (10 -20 mm)	835 kg	
Plasticizer	5 kg	Sika ViscoCrete 3088

Table 4 - Steel Reinforcement content used in various designs

Component	Reinforcement	Comment
Concrete Caisson	210 kg/m^3	Based on an existing project (Transnet, 2019).
Concrete Cope Beam	147 kg/m^3	Based on an existing project (PMI Ltd. , 2016). This reinforcing content was used for the cope beam for the caisson design and for the sheet pile combi wall design.
Precast Beam, Plank, Pile Cap, In situ slab and plugs	180 kg/m^3	Based on an existing project by Inros Lackner. All these components were used in the open-piled suspended Deck structure.

4. LCA

The four stages of an LCA are Goal and Scope Definition, LCI, LCIA and the Interpretation phase as described above in section 2.1. The first three phases are discussed in this section while the Interpretation phase is presented in the next section, number five, of this extended abstract.

4.1 Goal and Scope Definition

Goal

The Goal of this study was to estimate the carbon footprint of the different quay wall structure types in order to determine any differences between the various designs and construction methods.

Scope

The system under study was a pier that would function as a container terminal, provide berthing space for two vessels simultaneously and function as a platform for cargo handling equipment. The three types of quay wall structures that were considered are: 1. Concrete Caissons 2. Sheet Piled Combi-Wall and 3. Open Piled Suspended Decks.

The functional unit was metric tons of carbon dioxide equivalent per meter of berthing length provided (t CO_2e/m) for a structure with a design life of 50 years. The life cycle stages that were considered were production (A1-A3), transportation (A4) and the construction stage (A5), refer to Table 2.The System Boundary is summarised in Table 5.

Table 5 - System Boundary

Process	Comment	Include/Excl.
1. Mobilisation	Major equipment such as barges, cranes, piling hammers mobilised from overseas.	Included
2. Dredging and Reclamation	This includes dredging and dumping of dredged materials. Reclamation includes the dredging, transporting and placing of fill material to form the new pier.	Included
3. Quay Structure	This includes all the structural components for the various quay structure designs, for example, piles, caisson, precast concrete elements, corrosion protection and so on.	Included
4. Scour Protection	Rock scour protection as per the designs.	Included
5. Services & Quay Furniture	5.1 Services: Lighting, firefighting system, electricity supply, water supply and so on. 5.2 Furniture: Road furniture, signalisation, buildings. Since the services and the furniture will be approximately the same for all the different designs these have been excluded as they will not influence the conclusions of the CFP.	Excluded
6. Berth Equipment	Include fenders, bollards, safety ladders, hydrants, navigation aids. Will be approximately the same for the different designs and were therefore not included.	Excluded
7. Earthworks and Pavement	Includes the layer works and pavement.	Included
8. De-Mobilisation	De-mobilisation of major equipment to country of origin.	Included

4.2 Life Cycle Inventory

Material Quantities

The production of construction materials represents life cycle stages A1-A3. The material quantities were calculated from the designs. The main material quantities are summarised in Figure 4, Figure 5 and Figure 6.

Transport Distances

For the transport of materials from their sources, for example a quarry or factory, to the construction site certain assumptions were made. These are summarised in Table 6. The transport of materials represents the life cycle stage A4. The emission factors that were used for the transportation distances (ton-kilometre) stem from the Ecoinvent 3 Dataset included in SimaPro.

Table 6 - Transport Distances for LCI

Item	Distance	Comment
Quarry to site	50 km	Used for scour rock, gravels, layer works, aggregates, sands. Return trip = 100km
Cement factory to site	30 km	Transporting Portland Cement from factory to site. Return trip = 60 km.
Steel factory to site	25 km	Transporting reinforcing steel from factory to site. Return trip = 50 km.
International Shipping & Mobilisation	9825 km	Used as the shipping distance for materials shipped from overseas for example steel piles, fly ash, slag, geotextiles. Also used as the mobilisation distance for mobilisation of construction equipment from overseas.

Machines

The operation of construction machinery represents the construction life cycle stage (A5). In order to estimate the required operating hours for the various machines, an outline construction programme was developed by the author based on his previous experience of working on similar quay wall construction projects. Based on this construction programme machines were allocated to each activity corresponding to the required productivity in order to complete the activity on time. Based on this concept the total machine hours were estimated. A set of emission factors (from Ecoinvent 3) was used based on the machines rated power output and the load factor as recommended by United States Environmental Protection Agency (US EPA , 2010).

Fan (2017) notes that there are many aspects influencing the emissions from construction machinery, such as the equipment conditions, operating conditions and degree of equipment maintenance amongst several others. Therefore, it is noted that the actual emissions from the machinery may deviate significantly from the ones that were used.

4.3 Life Cycle Impact Assessment Results (LCIA)

As described previously the LCIA was done for only one impact category, namely global warming. This section details the carbon footprints from each type of quay wall structure and the contribution from each life cycle stage. First the baseline carbon footprints are described. In the second part of this section the results of the sensitivity analysis are presented which show how the carbon footprint is affected when certain parameters are changed.

Baseline Carbon Footprint

The baseline carbon footprint estimates are displayed in the first bar of Figure 7,Figure 8 and Figure 9 for the caisson, sheet pile wall and open piled structure design options respectively. The results in the graph are presented in metric tons of carbon dioxide equivalent per meter of berthing length provided (t CO_2e/m). The relative contribution from each life cycle stage is also displayed. For comparison purposes when referring to the results in Figure 7 to Figure 9, the carbon footprint for one return flight between London and New York is approximately 986 kg CO_2 per person (Kommenda, 2019). This implies that the CO_2e emissions of constructing one meter of a concrete caisson quay wall, for example, would be equivalent to over 60 return flights between London and New York for one person. The assumptions on which the baseline carbon footprint calculations are based on are summarised in Table 7.

Table 7 - Assumptions for Baseline Carbon Footprint Calculation

Steel Elements:	For all steel elements the global average emission factors as per the world steel association were used.
Caisson Steel Reinforcement:	For the concrete caissons a steel reinforcement content of 210 kg/m^3 was used as per the design based on an existing project.
Concrete:	All concrete components were made as per the mix design detailed in Table 3.

Sensitivity Analysis

The parameters that were investigated in the sensitivity analysis are summarised in Table 8.

Table 8 - Summary of Parameters Investigated in the Sensitivity Analysis

Parameter	Comment
Steel (Reinforcing and Piles)	Use of emission factors corresponding to a recycled steel content of approximately 85%
Caisson steel reinforcement	For the caissons investigate what the effects are of changing the reinforcement content to baseline (210 kg/m^3) +-40 kg/m^3
Binder composition	Investigate the effects of changing the binder composition to a) 65% Portland cement with 35% Fly Ash and b) 35 % Portland cement with 65% Ground Granulated Blast furnace slag (GGBS) as per the limits of British Standards BS 6349-1-4:2013 (BSI, 2013b)
Tubular Pile Length	For the open piled suspended deck structure investigate the effects of decreasing the pile length from 37 m to 34 m.

In Figure 7, Figure 8 and Figure 9 the results of the sensitivity analysis for each of the quay wall structure types is also displayed. The last bar in each figure represents the "total optimisations" which are a combination of various parameters as indicated in Table 9.

Table 9 - Parameters Considered for Total Optimisations for each Design Option

Design	85% Recycled Rebar	85 % Recycled Piles	65 % GGBS in Binder	34m tubular piles	Caisson Steel reinforcement
Caisson	✓	✓	✓	Not Applicable	210 kg/m^3
Sheet Pile Wall	✓	✓	✓	Not Applicable	Not Applicable
Open Piled Deck	✓	✓	✓	✓	Not Applicable

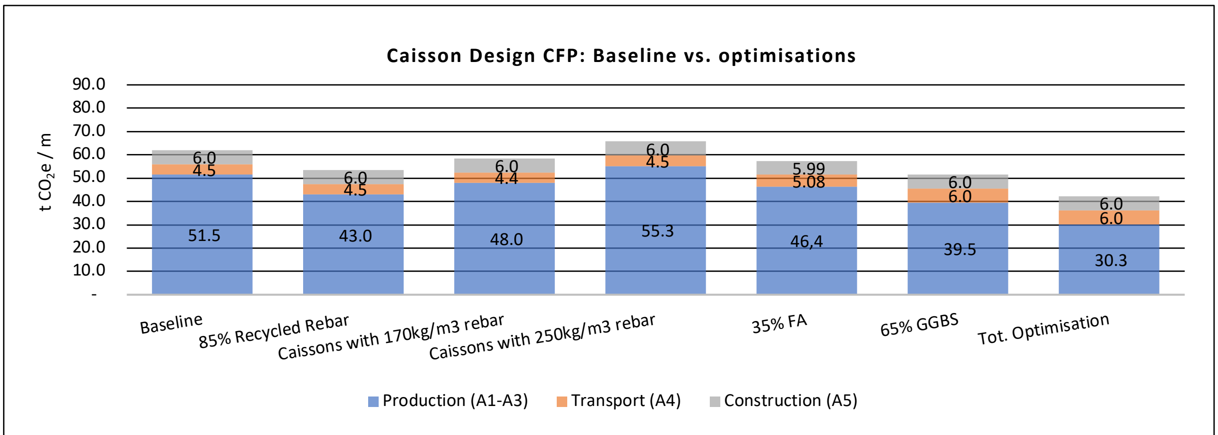


Figure 7 – Concrete Caisson Carbon Footprint Results

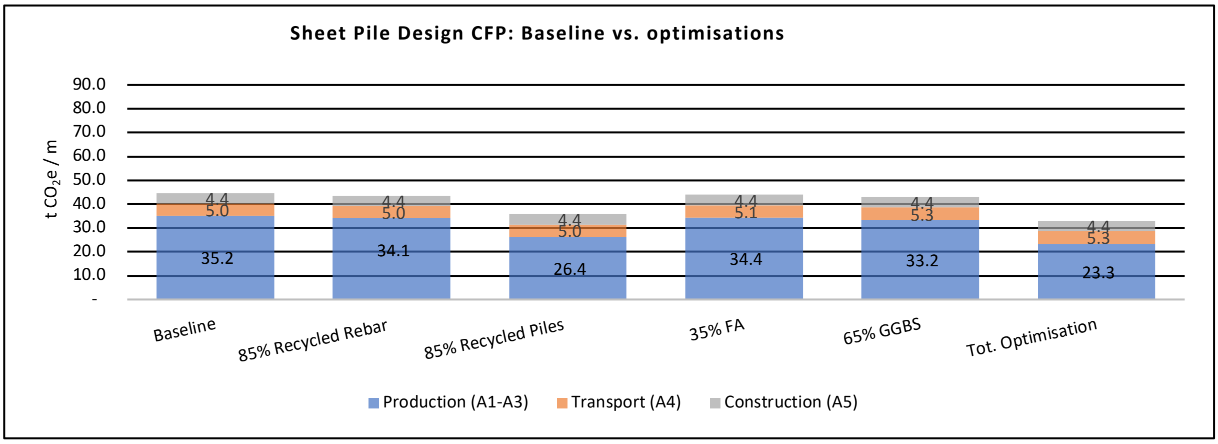


Figure 8 - Sheet Piled Combi-Wall Design Carbon Footprint

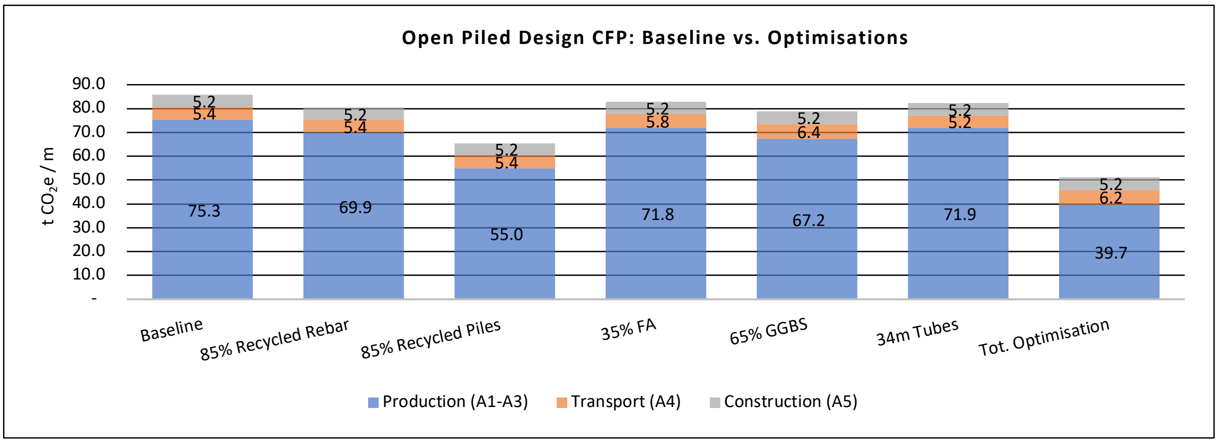


Figure 9 - Open Piled Suspended Deck Design Carbon Footprints

5. Discussion and Interpretation

5.1 Baseline Carbon Footprint Discussion

For the baseline carbon footprint estimate it can be seen that the has the sheet pile combi-wall has the lowest carbon footprint, followed by the caisson type structure and the open piled deck has the highest. It is also clear that the life cycle stages for production (A1-A3) are the most significant contributors to the total carbon footprint, namely over 79% in each case. This is because the production of steel and cement have a very high carbon footprint since the production of these materials involve energy intensive processes. The open piled suspended deck option had the highest carbon footprint, despite being the lightest of the three designs by mass. With reference to the material quantities displayed in Figure 4,Figure 5and Figure 6, it can be seen that the open piled deck structure has about four times more concrete than the sheet pile option and 1,7 times more steel than the caisson option. The combination of these two factors is the main reason for the high carbon footprint.

5.2 Sensitivity Analysis Results Discussion

For the caissons (see Figure 7) it can be seen that significant reductions can be achieved when the recycled steel reinforcement content is increased and when a large proportion of GGBS is used in the binder content. The adjustment of the steel rebar content by +- 40 kg /m^3 changed the carbon footprint by +-6 %, respectively. The combination of various parameters, as described in Table 9, results in a 32 % reduction from the baseline carbon footprint for the caisson option.

For the sheet piled combi-wall the greatest opportunity to reduce the carbon footprint came from the use of a high percentage of recycled steel for the piles. Since this design has relatively low concrete volumes, compared to the other two, the savings from adjusting the recycled steel reinforcement percentage and the binder content are relatively small. The combination of the various parameters, as described in Table 9, results in a 29 % reduction from the baseline carbon footprint for the sheet pile wall option.

For the open piled suspended deck, the use of recycled steel in the piles had the greatest effect on reducing the carbon footprint. The combination of the various parameters, as described in Table 9, results in a 40 % reduction from the baseline carbon footprint for the open piled deck option.

From Figure 7, Figure 8 and Figure 9 one can see that with the total optimisations, as described in Table 9, the sheet pile combi-wall option still has the lowest carbon footprint, followed by the caissons and with the open piled deck.

5.3 Cost Estimate

A very rough cost estimate was done in order to get a ballpark idea of the relative costs per meter for each of the quay wall structure types. The cost estimate was based on unit values used on a previous project by Inros Lackner. The relative costs for the quay walls are displayed in Table 10. The costs appear to be unrealistically high, however, the purpose of this cost estimate was only to get an impression of the relative costs between the various solutions.

Table 10 - Cost Estimate for Various Quay Wall Options

Quay Wall Type	Cost (in United States Dollar per meter)
Concrete Caissons	242 301 US$ / m
Sheet Pile Combi Wall	212 348 US$ / m
Open Piled Suspended Deck	269 532 US$ / m

5.4 Points of Discussion

Scrap Steel Supply for Recycling

Arcelor Mittal (2019) stated that currently the supply of scrap steel can only satisfy about 22 % of global demand and that this will rise to about 40 % to 50 % by the year 2050. In the sensitivity analysis of this study, recycled steel contents of about 85 % were used. However, considering the limited supply of scrap steel it may not be realistic to use such a high value. For project managers, designers and contractors it is therefore important to understand the steel supply chain as the recycled content has a large influence on the carbon footprint of steel. Since this thesis only investigated the life cycle stages from production to construction (A1-A5) it could be interesting to investigate potential benefits from recovering steel from a project so that it can be recycled, corresponding to life cycle stage D (see Table 2).

Binder Composition

The effects of changing the cementitious binder composition was investigated by increasing the Fly Ash and GGBS content of the binder to 35% and 65%, respectively. Typically concrete with higher amounts of GGBS or Fly Ash will have lower early strength than concretes containing only Portland cement (The Concrete Centre, 2020). This may influence the construction programme as it may increase the time required to remove formwork. However, the use of water reducing, and accelerating admixtures may also increase the early strength of concrete and thereby enable a higher usage of GGBS or Fly Ash. Again, it is important for designers to engage with suppliers and contractors from an early stage on a project to assess opportunities and limitations associated with carbon reduction of the concrete.

6. Conclusion

The carbon footprint for three different solutions for a container terminal quay wall was investigated in this study, namely, concrete caissons, sheet piled combi walls and open piled suspended decks. The carbon footprint estimate was done using a Life Cycle Assessment approach and analysing only the production (A1-A3), transport (A4) and the construction (A5) life cycle stages.

It was determined that the sheet pile combi wall has the lowest carbon footprint, followed by the concrete caissons and the open piled suspended deck with the highest carbon footprint. In all three cases the most significant contributing life cycle stage was production (A1-A3) which was between 79 and 88 % for the various options. The reason for this was the high carbon footprint associated with steel and cement production.

A sensitivity analysis was done to determine the effects of adjusting various parameters such as recycled steel content, cementitious binder composition, steel reinforcing content and pile length. The results from the sensitivity analysis showed that there was potential to reduce the carbon footprint for concrete caisson, sheet pile wall and open piled deck by about 32%, 26% and 40% respectively. After these reductions the sheet pile wall still has the lowest carbon footprint, followed by the concrete caissons and the open piled decks with the highest CO_2e footprint.

Future investigations could focus on more detail for the construction (A5) life cycle stage and the recovery and recycling life cycle stage (D).

Bibliography

Arcelor Mittal , 2019. Climate Action Report - 1 , Luxembourg : Arcelor Mittal.

Brueton, V., Henning,D., Chetty, M., Le Roux, R. & Naidoo, N. , 2013. Proposed Deepening, Lengthening and Widening of Berth 203 to 205, Pier 2, Container Terminal, Port of Durban – Draft EIA Report, Durban: Nemai Consulting.

BSI, 2013a. BS 6349-1-1: General - Code of practice for planning and design for operations. London: British Standards Institute.

BSI, 2013b. BS 6349-1-4: General - Code of practice for materials. London: British Standards Institute .

CEN/TC 350, 2011. EN 15978:2011 - Sustainability of Construction Works. Assessment of environmental performance of building. Calculation method.. Brussels: CEN European Comittee for Standardization.

Circular Ecology, 2020. Embodied Energy and Carbon - The ICE Database. [Online]
Available at: https://www.circularecology.com/embodied-energy-and-carbon-footprint-database.html#.XmZlJ0nsboo
[Accessed 9 March 2020].

Ecoinvent, 2020. Ecoinvent. [Online]
Available at: https://www.ecoinvent.org/database/ecoinvent-36/new-data-in-ecoinvent-36/new-data-in-ecoinvent-36.html
[Accessed 9 March 2020].

Eurostat, 2019. Eurostat. [Online]
Available at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Greenhouse_gas_emission_statistics_-_emission_inventories

Fan, H., 2017. A Critical Review and Analysis of Construction Equipment Emission Factors. Procedia Engineering, Volume 196, pp. 351-358.

Hammond , G. P. & Jones, C. I., 2008. Embodied energy and carbon in construction materials. Proceedings of the Institution of Civil Engineers - Energy, 161(2), pp. 87-98.

IEA and UNEP, 2018. 2018 Global Status Report: Towards a zero-emission, efficient and resilient buildings and construction sector, s.l.: International Energy Agency (IEA) and United Nations Environement Programme (UNEP).

ISO, 2018. ISO 14067:2018 Greenhouse gases - Carbon footrpint of products - Requirements and guidelines for quantification. Berlin: International Organisation for Standardization.

Kommenda, N., 2019. The Guardian. [Online]
Available at: https://www.theguardian.com/environment/ng-interactive/2019/jul/19/carbon-calculator-how-taking-one-flight-emits-as-much-as-many-people-do-in-a-year
[Accessed 2 July 2020].

Maas, T., de Gijt, J. & Dudok van Heel, D., 2011. Comparison of quay wall designs in concrete, steel, wood and composites with regard to the CO 2 -emission and the Life Cycle Analysis. Singapore, MTEC.

Martinez-Rocamora, A., Solis-Guzman, J. & Merrero, M., 2016. LCA databases focused on construction materials: A review. Renewable and Sustainable Energy Reviews, Volume 58, pp. 565-573.

PMI Ltd. , 2016. Luanda Fishing Port Project Presentation at 2016 Arcelor Mittal Sheet Piling Symposium in Durban. Durban : PMI Ltd. .

Stripple, H., Fridell, E. & Winnes, H., 2016. Port Infrastructures in a System Perspective, Stockholm: IVL Swedish Environmental Research Institute.

The Concrete Centre, 2020. Specifying Sustainable Concrete, London: MPA The Concrete Centre .

Transnet, 2019. Tender Bulletions. [Online]
Available at: https://tenderbulletins.co.za/tender-bulletin/dct-berths-203-to-205-reconstruction-deepening-and-lengthening/
[Accessed 15 June 2020].

UNFCCC, 2020. United Nations Framework Convention on Climate Change. [Online]
Available at: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement/nationally-determined-contributions-ndcs#eq-1
[Accessed 9 July 2020].

US EPA , 2010. Median Life, Annual Activity, and Load Factors for Nonroad Engine Emissions Modeling ND-005d, s.l.: United States Environmental Protection Agency .

WRI and WBCSD, 2011. Green House Gas Protocol: Product Life Cycle and Accounting Standard. s.l.:World Resources Institute and World Business Council for Sustainable Development.