Quantifying Life Cycle Environmental Benefits of Circular Steel Building Designs

development of an environmental assessment tool for reuse of steel members in building designs for the Netherlands

by

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Abstract

The re-use of building components and structural elements is an underdeveloped practice which could be an important strategy in the global paradigm shift towards a circular economy. Steel is one of the most important structural building materials which combines incredible strength, favourable mechanical properties and excellent durability characteristics. It is practically infinitely recyclable and raw materials required for the production of steel are abundantly available in the Earth's crust. This makes steel one of the most interesting sustainable engineering materials. However, the production process requires vast energy investments and produces considerate environmental pollution. To make steel an increasingly sustainable material and a frontrunner in the global transition towards a circular economy, significant investments and process improvements are necessary. The global environmental challenges of the 21st century demand rapid and far-reaching changes from the steel industry but it also poses opportunities for creative thinking and development of alternative strategies.

The re-use of structural steel elements could offer great potential in reducing both the embodied environmental impact of construction works as well as the vast waste streams that result from demolition. There is general consensus on the technical feasibility of this circular alternative across academic literature and the idea enjoys widespread scientific support. Actual implementation is however limited, presumably due to the existence of several multi-level barriers. A diversity of actors along the value chain have indicated that various *attitudinal*, *financial*, *structural*, *operational*, *technological* and *legislative* barriers are preventing widespread adoption. Although some of the identified issues are of a practical nature, various perceived barriers have been identified which were found to be rather subjective. It is to be expected that providing additional information on the risks and opportunities, and by quantitative demonstration of the potential benefits of re-use, several of these perceived barriers could be alleviated.

This thesis aims to integrate the potential use of circular steel elements in the structural design process for steelworks as a sustainable alternative to the use of new steel. The developed method allows structural design & engineering professionals to assess the environmental impact of structural steel frameworks with increasing accuracy. Furthermore, it improves the current practice by making the design process reuse-inclusive. It thereby provides design professionals with a tool to assess and communicate the possibilities of improving a design with regard to their inherent sustainability.

It was found that the currently prescribed 'fast-track' LCA method, aimed at quantifying the embodied environmental impact of building structures, is highly sensitive and the current method could be leading to large inaccuracies and spread of misinformation. Two dominant national LCIA methodologies have been extensively compared and a sensitivity analysis has been performed for a variety of data resources. It could be concluded that the prescribed national data for steel products contained in the NMD is unverifiable and inconsistent with other resources. This raises serious concerns with regard to the accuracy and reliability of currently used 'fast-track' LCA methods for the Netherlands. It was calculated that the specific LCIA method used and the selection of modules included in the assessment can cause deviations of the estimated shadowprice up to approximately 424%.

Subsequently, a tool was developed based on the CML methodology to validate the potential deviations that could arise from selecting a specific data resource. The application analyses and evaluates structural steel frameworks with regard to their inherent environmental impact. Furthermore it allows the engineer to select and substitute new steel elements with remanufactured counterparts found in a circular steel database. A case study was performed for four different scenarios. Both the LCIA method as well as the considered modules were consistent for all scenarios. From the results it could be concluded that the estimated shadowprice is also highly sensitive to the specific data considered. It was indicated that the input data can lead to deviations of the shadowprice of up to approximately 281%. Furthermore, it was calculated what the potential benefits of reuse would be. It was calculated that substituting 25% of the required steel could lead to reductions of approximately the same magnitude by eliminating the required process for production and cutting the transportation requirements.

From the results of this thesis it could be concluded that there is serious inconsistency and limited transparency among the various data resources used for quantifying the environmental impact of steelworks. It is to be expected that the actual shadowcosts deviate significantly from the estimations provided by current assessment methods used in the Netherlands. Failure to accurately quantify the impact of primary building products could lead to significant errors as these materials have a relatively large contribution to the total impact of a building structure. Subsequently, this could lead to misinterpretation of LCA results thereby providing a misleading message for policy- and decision makers. However, it was also illustrated that the remanufacturing and reuse of structural steel profiles could offer significant environmental benefits and has the potential to significantly cut the environmental impact of structural steel framework constructions.

Nomenclature

AP	Acidification Potential
BF	Blast Furnace
BIM	Building Information Modelling
BOF	Basic Oxygen Furnace
C&D	Construction and Demolition
CAD	Computer Aided Design
CE	Circular Economy
DfD	Design for Disassembly
EAF	Electric Arc Furnace
EMF	Ellen MacArthur Foundation
EP	Eutrophication Potential
EPD	Environmental Product Declaration
GDP	Gross Domestic Product
GFA	Gross Floor Area
GHG	Greenhouse Gasses
GWP	Global Warming Potential
HTP	Human Toxicity Potential
IFC	Netherlands Organisation for Applied Scientific Research
LCA	Lifecycle Assessment
LCI	Lifecycle Inventory
MRPI	Environmental Relevant Product Information
NIBE	Dutch Institute for Biology and Ecology of the Building Industry
NMD	National Environmental Database
PCR	Product Category Rules
RIVM	National Institute for Public Health and the Environment
RL	Reverse Logistics
SBK	Dutch Association for Quality of the Building Industry
SDG	Sustainable Development Goal
TNO	Netherlands Organisation for Applied Scientific Research
UNFCCC	United Nations Framework Convention on Climate Change

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1 Introduction

Chapter 1 will provide a brief introduction into the subject and addresses the relevance of this research. It discusses the motivation for writing this thesis as well as its academic relevance. A scientific gap in literature is identified and accordingly a main research question and accompanying key questions are formulated. Lastly a description of the research methodology and its limitations are provided.

1.1. Relevance

1.1.1. Sustainability and waste in the building industry

Over the last couple decades it has become increasingly evident that our planet's climate patterns are rapidly changing due to soaring levels of greenhouse gasses (GHG) being produced by human activity. Society's increasing demand for infrastructure and services has created complex environmental problems facing the world in the next decades such as global warming, environmental degradation and eco-system collapse. It will be a global challenge to resolve these issues and it is of utmost importance that the industry addresses these problems without delay and reinvents itself in order to slow down and reverse these detrimental changes to our climate and to restore balance to our planet before it will be too late. (Allen et al., 2018a)

The continuous growth of the world population, global spreading of industrialization and Western consumption patterns keep increasing the demand for resources and the emission of greenhouse gasses. Since material reserves are finite this will inevitably lead to a global depletion of natural capital. More than half of all non-renewable natural resources (Mulders, 2013; Willmott Dixon et al., 2010) that are used globally are consumed by the construction industry making it the most resource intensive sector in the world. Through the consecutive industrial processes of mining, extraction, refining, building and ultimately disposal, it has a detrimental impact on our environment. The industry is characterized by enormous voluminous waste streams and is causing global resource depletion, massive carbon emissions and immense energy consumption (Iacovidou & Purnell, 2016; Iacovidou, Purnell, & Lim, 2018). It is estimated that 35% of all solid waste deposited to landfills in Europe is comprised of C&D waste (Eurostat, 2018b). Steel, cement and timber account for 80% of this voluminous waste stream and the production of these materials also accounts for the largest share of emissions (Iacovidou et al., 2018; Mulders, 2013).

In recent years efforts by the European Commission to make waste management more sustainable have led to big improvements with regard to waste management and recycling throughout the European Union. There is now a multitude of national and European rules and regulations (European Commission, 2016a, 2016b; Eurostat & Deloitte, 2015; Planbureau voor de Leefomgeving, 2017; Spijker & van der Grinten, 2014) that address these problems.

However, in contrast to earlier estimations in which the Netherlands was praised as one of the leading member states with regard to waste management (Mulders, 2013; Spijker & van der Grinten, 2014; Willmott Dixon et al., 2010), more recent research by Eurostat (Eunomia, 2017; Eurostat, 2014) has indicated that the Netherlands has a recycling rate of merely 50% and is only just amongst the top 10. These numbers are in sharp contrast with previous estimations in which recycling rates in the Netherlands have been claimed to be as high as 95% (Mulders, 2013; Rijkswaterstaat, 2013; Spijker & van der Grinten, 2014).

This differentiation can be explained due to the fact that in earlier estimation methods incineration with energy recovery has been regarded as a proper recycling process. As clearly illustrated in the famous ‘waste hierarchy ladder’ by politician Ad Lansink in 1979 (Kemp & Van Lente, 2011); recycling, the reprocessing of products to create materials or components of a similar quality and functionality as the original product, is a way more preferred waste management strategy than incineration with energy recovery. This brings to light that in our pursuit of diminishing GHG emissions and resource depletion, it is of utmost importance to use a clear and robust terminology with regard to waste management.

Eurostat, the statistical information providing directorate-general of the European Commission, has estimated that the yearly amount of construction and demolition waste (C&D) generated in the Netherlands accounts for over 50%, around 68 Mton of a total of 133Mton in 2014, of the total amount of waste generated in the Netherlands (Eurostat, 2018b). Moreover, a multitude of C&D waste products that actually are recycled can generally only be re-used as low-grade materials and are thus down-cycled rather than recycled. According to Mulders merely 11% is suitable for recycling within the construction industry itself (Mulders, 2013). Moreover, recycling is also a process which often requires certain extraction methods, additional resources, production techniques, energy investment and therefore additional costs in order to convert waste materials into usable products.

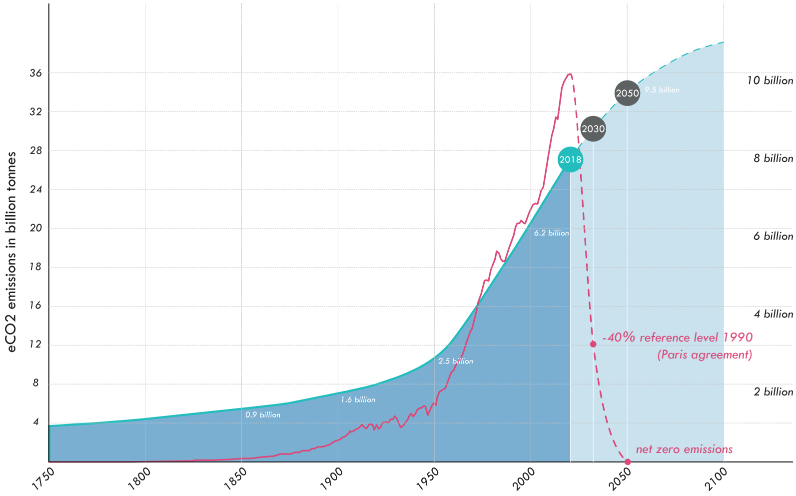


Figure 1: Expected growth of the world population & anthropogenic eCO2 emissions according to the Paris Agreement

The targets laid down in the 2015 Paris Agreement (UNFCCC, 2015) imply that all developed countries need to be carbon-neutral by 2050. As illustrated in **Figure 1**, in order to achieve these targets radical cuts to global anthropogenic carbon emissions will be necessary and an aggressive shift to renewable resources as a primary source of energy will need to be made. Failure to do so will lead to irrevocable damage to natural, managed and human systems as illustrated in **Figure 2**. However, a recent report by the Dutch environmental assessment agency (van Vuuren et al., 2017) has indicated that the Netherlands will not accomplish these goals with current policy. These insights have led to the Netherlands translating these goals into various rules, regulations and guidelines with regard to reducing GHG emissions, energy production from renewable sources and diminishing waste streams (Ministry of infrastructure and the environment & Ministry of economic affairs, 2016; Planbureau voor de Leefomgeving, 2017) and has even led to one of the world's most ambitious climate laws (Klaver et al., 2018). If passed, a 49 percent reduction in GHG by 2030 (compared to 1990 levels) and 95 percent decrease by 2050 will be put in statute (David Roberts, 2018). Therefore it is important for the Dutch building industry to take immediate action to reduce its carbon footprint and reinvent itself. It will become increasingly important to take the post service-life of products into account so components and materials can be effectively and efficiently re-used and recycled instead of down-cycled as low-grade materials or incinerated with energy recovery.

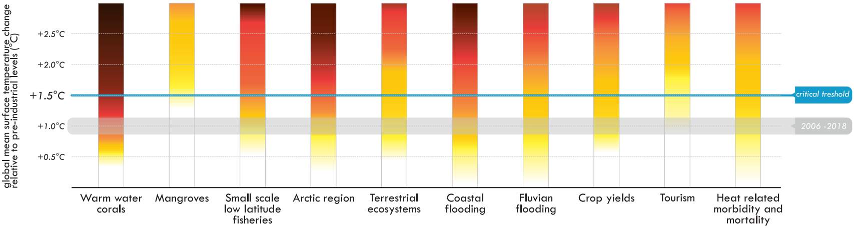


Figure 2: Impact for natural, managed and human systems,adapted from: IPCC 2018 (Allen et al., 2018a)

1.1.2. Circular economy

It is to be expected that a further depletion of natural resources will lead to an increased pressure on the production flow for building materials and will cause costs for 'raw' materials to rise significantly (International Council for Research and Innovation in Building and Construction, 2014). We are currently witnessing an ideological shift across the EU (European Commission, 2018c, 2018a, 2018b) from our stubborn notion of short-term economical thinking and linear industrial activity towards an increasingly restorative and regenerative economic system. Various models have been developed over the years aimed at decoupling economic growth and development from the consumption of finite resources (Boulding, 1966; Daly, 2008; Meadows, Donela H. Meadows, Randers, & Behrens, 1972; W. R. Stahel & Reday-Mulvey, 1981; Walter R. Stahel, 2010). Although these earlier models have failed to see large-scale adoption, the increasing public consciousness of the negative environmental effects of human activity over the years seems to have generated enough momentum for a paradigm shift causing the concept of a circular economy (Ellen MacArthur Foundation, 2015b) to flourish. Strategic implementation of this framework for thinking by government entities such as the European Commission, the Dutch Government and the municipality of Amsterdam (European Commission, 2018c; Gemeente

Amsterdam, Circle Economy, TNO, & Fabric, 2017; Ministry of infrastructure and the environment & Ministry of economic affairs, 2016) has generated multi-level support and encouragement for widespread adoption by both the industry and the public.

Although CE is often mistakenly referred to simply as a more effective approach to recycling or waste-management (Kalmykova, Sadagopan, & Rosado, 2017; Prieto-Sandoval, Jaca, & Ormazabal, 2018); it's definition goes far beyond these principles and should be seen as a framework for thinking on how the economy operates. As Raworth (Raworth, 2017) mentions in her critically acclaimed book the Donut Economy; over the past 70 years economics has been fixated on GDP, or national output as a primary measure of progress. Our priority has thusfar been to achieve 'the highest sustainable economic growth' – aiming to sustain not the environment but output growth. Raworth argues that in order to combat inequality and pollution we should change our economic language by merging the issues of economy and environment. By coupling these, Circular Economy provides us with the <u>means</u> to achieve our sustainability development goals. Although, critics would deem Raworth's view slightly overoptimistic there is general consensus that the Circular Economy can indeed be seen as a manifestation of a paradigm shift. According to the Ellen MacArthur Foundation the four key principles of the CE are; "to optimize the use of resources and energy throughout lifecycles, to maintain products and components in use for longer, to cycle materials through the system as many times as possible and to utilize pure materials for improving quality of post-life use." (Ellen MacArthur Foundation, 2013). This 21st century economic ideology hence requires producers and consumers alike to rethink current product life cycles and close the loop of technical and biological cycles in order to reduce environmental impact.

As mentioned earlier, the building industry is the most resource intensive sector in the world and in order for the industry to become increasingly 'circular' we need to revise current building material & product loops and improve product life cycles. In order to adhere to the key principles laid out by the Ellen MacArthur Foundation we have to prioritize our waste management strategies and strive for the highest possible reuse value at a minimum of environmental costs. Moreover, we need to disclose the financials behind reuse and demonstrate the economic feasibility of reuse in a circular economy.

Recent technological advances in the building industry such as computer aided design (CAD), Building Information Modelling (BIM), machine learning and the analysis of big data allow us to increase our understanding of complex systems. As laid out by Ness et al. (Ness, Swift, Ranasinghe, Xing, & Soebarto, 2015) these digital technologies look promising for improving resource efficiency and could help facilitate disassembly, take back and re-use.

1.1.3. Structural steel and re-use

Steel has exceptional strength and durability properties which make it much less prone to aging in comparison with other materials. When maintained properly steel elements can have a remarkable service-life of up to 200 years or more (Worldsteel Association, 2018b). The major problems affecting the service life of structural steel elements are overloading, corrosion and fatigue, e.g. due to seismic motion (So, Cheung, & Zhang, 2012). With proper routine inspections, repair and maintenance deterioration processes can be minimized or prevented altogether significantly extending the potential service life of structural steel components. Steel can also be easily recovered and is infinitely recyclable without loss of quality. Older products can actually even be ‘up-cycled’ due to the possibility of producing higher steel strengths through new production methods that have become possible over recent years (Worldsteel Association, 2018d). With global recycling nearing 650 Mt in 2017 it is currently the most recycled material in the world (Worldsteel Association, 2018b). Moreover, structural steel elements are among some of the few structural building components that allow for relative easy dismantling and reprocessing. Even without special jointing techniques, that allow for easy dismantling, steel elements can simply be cut from existing structures, trimmed to a specific length and refabricated. Through the consecutive processes of cutting, drilling, abrasive blasting, coating and painting used steel components can hence be reprocessed and reused in another project (Fujita & Masuda, 2014).

However, the production process of steel is a rather energy and resource intensive process which has detrimental effects on our environment due to the resulting greenhouse gas (GHG) emissions. In order to meet the GHG emissions target for 2050 set by the European Commission (European Commission, 2011) the steel industry will have to introduce significant changes in their extraction, refining and production processes in order to achieve the required carbon reductions. The current virgin steel production process, dominated by the use of blast furnaces, has an average carbon intensity of 1.78 – 1.83 kg CO_2/ kg steel due to energy input and by-product gasses (Dunant et al., 2017; European Commission, 2016c; Worldsteel Association, 2017b). However, there are significant differences between the various steel plants and production processes causing embodied carbon dioxide emissions to vary significantly depending on their origin. It is estimated that the embodied carbon footprint of EAF steel varies between 0,7-1,2 kg CO_2/kg steel and the footprint of BF-BOF steel between 1.8 - 3.0kg CO_2/kg steel (Dorota Burchart-Korol, 2013; Carbon Trust, 2011).With a global steel production of 1.691 million tons (Mt) in 2017 alone (Worldsteel Association, 2018b) it is evident that the steel industry has to introduce substantial changes. The GHG emissions associated with recycled steel products are roughly 20-25% of the average GHG emissions associated with virgin steel (Dunant et al., 2017), making steel recycling significantly less carbon intensive. This is mainly due to the fact that the steel recycling process uses an electric arc furnace (EAF) rather than blast furnaces which requires significantly less energy. Moreover, materials in an EAF are heated by means of an electric arc (graphite electrodes). Since the energy input for this process is purely electric, the EAF production process has the potential to become increasingly sustainable as the input share of renewable energy is increasing. However, as the current EAF process still requires massive amounts of energy input it does not seem likely to become fully dependent on renewable energy in the near future. Hence, it would seem beneficial, with regard to environmental savings, to try and extend the product life-time of steel elements that are currently circulating by reusing used components in new projects before considering recycling these elements.

Durmisevic states, that in the current design and construction phase there is little emphasis on the post-service life of materials. Disassembly is normally not considered and there is a lack of deconstruction guidelines making the reuse of materials generally impossible (Durmisevic & Binnemars, 2014). Moreover EU protocols (European Commission, 2016b; Spijker & van der Grinten, 2014) also focus on post-service life measures. Regulations dictate that extensive research should be conducted before demolition in order to effectively deconstruct buildings and to subdivide materials into different waste streams for recycling purposes. Therefore every deconstruction process has to start from scratch with an extensive analysis of the building typology, location conditions, construction method, materials used and the possibility of hazardous substances (Dorsthorst & Kowalczyk, 2005). Since buildings are often of a unique nature and frequently consist of a variety of composite materials, deconstruction can be a rather complex, expensive and time consuming effort. There seems to be growing awareness in recent years that buildings should be increasingly designed with deconstruction in mind. Innovative technologies and products enabling increased ease of deconstruction at the end-of-life are making their way onto the market (Brambilla, Lavagna, Vasdravellis, & Castiglioni, 2019; Wind, 2018). There are also some interesting recent projects in the Netherlands which were specifically designed for disassembly such as the Greenhouse in Utrecht by Cepezed and the People's Pavilion by bureau SLA (de Architect, 2018). However, design strategies aimed at improving reuse are primarily focused on improving future reuse. But how should design professionals currently design buildings with previously used components? There seems to be relatively little studies on this topic and in order to increasingly facilitate the Dutch building industry CE transition additional research is crucial.

1.2. Domain and scope

Literature from various fields of study related to; circular economy, the structural steel industry, environmental impact and supply chain management have been referred to. Among other topics, the majority of papers used in the literature study are focused on Design for Dissassembly (DfD), Reverse Logistics (RL), Circular Economy (CE), Life Cycle Analysis (LCA) and Structural Steel Reuse (SSR). Literature indicates several distinct barriers with regard to the reuse of structural steel on cultural, technological and market levels. However, although there is general consensus between the different actors with regard to the most important barriers, it is stated that additional quantitative research is needed to gain insight into the linkage between deconstruction and project cost, the savings in greenhouse gas emissions, energy and resources conserved. Also, communication between the various actors in the building industry, as well as the linear, sequential relationship between the different phases are often mentioned as important barriers for effective disassembly of buildings. It is important to address these critical factors and to provide empirical demonstration of potential environmental benefits as well as the possible risks for industry stakeholders in order to create a solid decision-making basis (Akinade et al., 2017; Densley Tingley, Cooper, & Cullen, 2017; Dunant et al., 2017; Hosseini, Rameezdeen, Chileshe, & Lehmann, 2015; Kirchherr et al., 2018; Rios, Chong, & Grau, 2015). It is to be expected that by doing so re-use of structural steel components in newly designed buildings will be stimulated.

1.3. Research objective and questions

1.3.1. Problem statement

Studies agree that design professionals have the most critical role in addressing circularity challenges within the building industry since in the design phase they have a major influence on the final product (Iacovidou & Purnell, 2016; Iacovidou et al., 2018; Rijkswaterstaat, 2013; Tingley & Allwood, 2014). However, although architects and engineers know a great deal about how to build buildings they have limited knowledge of the service-life of buildings and their deconstruction (Dorsthorst & Kowalczyk, 2005). Buildings are, in general, not designed with deconstruction in mind from the outset (Durmisevic & Binnemars, 2014).Therefore in many cases reuse turns out to be difficult, expensive or even impossible. In order to increase the potential for re-use of construction materials industry wide changes are necessary and reuse strategies should become an integral part of a building design. ‘Re-use at the highest level is only possible if every actor in the building cycle is aware of the fact that the used materials are to be re-used after demolition. So at every building stage, from the initiative, design, building, use, maintenance to the demolition stage, measures must be taken to improve re-use at the highest possible level.’ (Dorsthorst & Kowalczyk, 2005). Moreover, in order for the industry to develop and implement new business models aimed at the re-use of structural (steel-) components it is crucial to demonstrate that there is an actual economic case for re-use.

Material experts from the Building Research Establishment Group (BRE) have done extensive research with regard to the barriers and potential for reuse for specific materials. These analyses mainly show the current state of deconstruction possibilities as well as the potential there is to solve some of the barriers with an adaptation in the design phase (International Council for Research and Innovation in Building and Construction, 2014). Especially steel offers great prospects with regard to recycling and re-use (Allwood, Cullen, & Carruth, 2012; Pongiglione & Calderini, 2014; Tingley & Allwood, 2014). It is a tensile material which exhibits great strength and uniformity. It is also relatively light-weight allowing for easy transportation. Due to standardization and mass fabrication it is widely available throughout Europe in standard lengths and sizes and components are often connected with nuts and bolts allowing for relative easy assembly and dismantling. According to Allwood and Cullen (Allwood et al., 2012; Tingley & Allwood, 2014) 42% of total steel produced is used in buildings and another 14% in infrastructure. The majority of this steel is 'temporarily stored in the building stock' for the lifespan of these structures. At the end of life-cycle of these structures, the bulk of these products are recovered and recycled. According to European surveys from 2000 and 2012 the amount of primary and secondary structural steel that is being recovered after demolition in Europe is estimated at around 98% (Sansom & Avery, 2014). The amount of heavy and light structural steel components that are currently being directly re-used without extensive reprocessing is very limited and accounts for roughly only 6% of the total amount of steel being recovered (Sansom & Avery, 2014). Recycling; collecting, sorting and reprocessing of these materials has several drawbacks in terms of cost, energy requirements, carbon emissions and other environmental impacts. There seems to be general consensus on the fact that steel reuse is an effective method to reduce the environmental impact of construction in terms of carbon and energy savings required for recycling or the procurement of new steel (Densley Tingley et al., 2017; Dunant et al., 2017; Iacovidou & Purnell, 2016; Tingley & Allwood, 2014). However, quantitative data supporting this claim seems to be missing across literature.

According to Ness and Swift (Ness et al., 2015) emerging new tracking and modelling technologies such as Building Information Modelling (BIM) and Radio Frequency Identification (RFID) could prove to be useful in the search for such tools that could promote disassembly and reuse of structural components (Ness et al., 2015). These technologies could enable components to be tracked and imported into virtual models for new buildings at the design stage. Currently there are several organizations in the Netherlands that aim to provide increased insight into the current building stock and the materials and components that are ‘temporarily’ stored in building structures during their lifetime. Initiatives such as Madaster, BAMB and Excess Material Exchange are providing material passports for buildings and generating extensive databases with building products which are part of the current building stock. They intend to facilitate a potential future marketplace for used building materials and thereby improve material re-use and recycling. Although these technologies are still at an early stage of development, the initial results look promising and can be a good starting point in the development of a tool or system, for structural design professionals in the building industry, which promotes the re-use of structural steel components.

1.3.2. Aim and main research question

The aim of this thesis is to provide possible measures in the design process for steel constructions at structural design & engineering firms that will facilitate and promote the reuse of structural steel sections. This will be done by linking (hypothetical) used product data to structural modelling software in order to optimize a construction with regard to reuse by facilitating the possible incorporation of used components in future designs for building structures. Furthermore, potential savings in terms of emissions, energy and resources conserved will be quantified in order to build an environmental case for reuse. The result will hence be a BIM plugin which will optimize a structural steel design by incorporating used structural steel components that can be found in the beforementioned database. Consequently output data with regard to the model will be generated in terms of environmental savings and practical guidelines for manufacturers.

Hence, the meta-goal of this research will be:
To decrease the negative impact of the steel industry on the environment and to limit the depletion of natural capital.

In which the used definition of re-use is:
Taking steel components from an older building and using them in a new project with minimal reprocessing (Ness et al., 2015).

The accompanying main research question will be:
How can structural design & engineering firms accurately quantify the environmental benefits of using circular structural steel elements for primary load bearing building structures in the Netherlands?

The various aspects of this main question and the scope of this research will be explained in the following subsections.

1.3.3. Key questions

To answer the main research question, the following key questions have been developed:

1. What is Circular Economy? And what are the barriers for adoption by the construction industry?
2. How can circular strategies contribute to a more sustainable steel construction industry?
3. What are the most important parameters for measuring the environmental impact of the steel industry?
4. Under which conditions and to what extent can the re-use of structural steel sections contribute to a more circular economy? What are the enabling conditions and alternative strategies?
5. What are the current critical barriers and possibilities with regard to re-using structural steel sections (in the European market) according to literature? And what are the actor specific barriers for structural design professionals?
6. What are the most crucial bottlenecks preventing structural steel re-use in the

Netherlands and how can these bottlenecks most likely be overcome?

7. What are the dominant methods and databases currently used in the Netherlands for assessing environmental impact and what are the most important limitations?
8. How can structural engineers efficiently incorporate circular steel components into new structural steel building designs and to what extent should the subsequent potential environmental benefits be quantified?
9. In what way should the information on possible environmental impact savings and remanufacturing process be transferred to clients and fabricators?
10. How can the structural steel building industry be improved based on the outcomes of this study? What are the prospective positive effects with regard to sustainability?

Each chapter will discuss several key questions. This thesis will be divided into three parts. ***Part I*** consists of an extensive literature study. Key concepts such as Circular Economy, Design for Disassembly and structural steel reuse are discussed and an overview is provided of identified barriers and opportunities for CE is derived from literature (chapter 2). Furthermore, this section elaborates on the current state of the steel industry, the steel production process and the various actors along the supply chain. Potential success factors for reuse of structural steel are discussed as well as the critical bottlenecks (chapter 3). The next chapter addresses the general process for quantifying the environmental impact of building structures, the dominantly used assessment methods in the Netherlands as well as the commonly used environmental impact information databases for building products (chapter 4).

In ***Part II*** the current practice in the Netherlands with regard to environmental impact assessment is critically reviewed and limitations are discussed (chapter 5). Consequently, the final paragraph will discuss the conclusions that can be drawn from the analysis of the current practice and the possible implications for the accuracy of assessment methods that aim to quantify the environmental impact of steel structures. ***Part III*** will be dedicated to establishing a theoretical CE assessment model for the steel industry incorporating re-use strategies as a valid end-of-life scenario for structural steel members. This model will consist of a digital assessment tool which allows engineers to compare their designs with a specific circular steel database providing them with insight into possible substitutions that could be made. The application illustrates the specific environmental benefits which can aid policy and decision makers (chapter 6). Subsequently, in the following chapter a reference study will be performed for four distinct scenarios which are elaborated on in chapter 7 and the results will be presented in chapter 8. Lastly. The two final chapters will provide the conclusions and recommendations (chapter 9) and a discussion of the results (chapter 10).

1.3.4. Scope of the research and delimitations

This study will be focused on *various actors within the building process*, that could potentially influence the re-use potential of structural steel sections. The scope of this research will therefore be on the entire product loop and building life-cycle of steel structures; the consecutive *manufacturing, design, construction, use and demolition phases*. Although the government, NGO's and institutions also play an important role in stimulating re-use and recycling, through for example incentives and legislation, these actors are beyond the scope of this research since they can be regarded as an external influence.

The focus will primarily be on the *Dutch building Industry*. Since the scope of this research needs to be limited and this information will be easiest accessible for the author. However, results might be used for other countries within the European Union (EU) as member states generally adhere to the same regulations provided by the Eurocode. Furthermore, there is a universal European standard for structural steel sections within the European Union and hence a wide availability of standard profiles throughout the EU. Nevertheless, specific conditions will differ per country and other factors might thus play a role here.

This research will specifically address the role of *structural design & engineering firms*. However, in order to do so it is crucial to evaluate the production chain from a broad perspective. Actor specific barriers will be investigated as well as the collaboration between different parties in order to assess to which extent structural design & engineering firms can improve or extend their design services in aid of other parties (such as demolition firms) in order to promote the re-use of structural steel components.

In addition this study will primarily focus on the use of *standard European steel sections (Euronorm)* that are most commonly used in the Netherlands for the design of primary load bearing steel constructions such as hot rolled stainless steel profiles as plates, beams and tubes. Standardized I-profiles and H-profiles have a long history of use in the Dutch building industry and it can be assumed that increasing numbers will become available through deconstruction in the coming years. Cold rolled stainless steel profiles are beyond the scope of this research.

Finally, the focus will be limited to *buildings* (*soil-bound structures)* with a primary steel load-bearing construction. Specifically buildings that are designed with a high degree of repetitiveness and are modular in nature. Furthermore buildings with a relative short lifespan (less than 20 years) are of particular interest such as industrial halls, storage facilities and data centers. Buildings can however have various functions, like industrial, healthcare, residential, offices or leisure. This is due to the fact that the consideration of re-use as an end-of-life strategy is likely to become less environmentally feasible on the long run as increasingly sustainable steel recycling practices will develop. Although results might also apply to civil structures such as roads or bridges, these projects are often of a 'custom-design' and the amount of standardized structural steel sections used in these projects is thereby limited. This implicates that reuse on a component level is less relevant for these structures and therefore beyond the scope of this research.

1.4. Methodology

In this thesis quantitative data was acquired from (inter-) national databases on the environmental impact of structural steel products and evaluated by means of mainly qualitative methods (literature review, semi-structured interviews and expert opinions) which have been used to answer the key questions and, ultimately, the main research question.

1.4.1. Phase 1: Literature review

The theoretical part of this thesis provides insight into the status quo with regard to the principle of Circular Economy. An overview of definitions and critical indicators will be provided, based on publications from Resources & Recycling, Environmental Economics and Environmental Management. Also, insight in the lifecycle of structural steel components and constructions will be provided by mapping the entire production cycle from mining and extraction up until demolition, reuse and recycling. Various actors and stakeholders in the product loop will be approached in order to acquire quantitative data on key processes such as production, construction and transportation. This will provide an initial framework for measuring energy and resource consumption, emissions and waste streams within the structural steel lifecycle.

To gain insight into the current building industry practice and the European market with regard to the re-use of structural steel sections, literature from various relevant fields of study such as Design for Disassembly, Reverse Logistics, Environmental Economy and Structural Steel Reuse will be studied with regard to the opportunities and barriers for reuse. Also, interviews should be conducted with demolition contractors, structural engineers and other building industry experts in order to provide a first check on suitability and to validate the listed barriers and key success factors for the Dutch building industry. This will result in an overview of various technical, cultural and market specific factors influencing the potential for reuse of structural steel sections.

1.4.2. Phase 2: Assessment of Environmental Benefits

The second part of this thesis is focused on quantifying the possible environmental benefits of reuse strategies opposed to the still dominant recycling scenario for structural steel at the end-of-life of buildings. It critically reviews key metrics that can be used for measuring environmental impact, commonly used assessment methods, legislation and data resources. Currently dominant quantitative assessment methods used in the Netherlands as well as national data resources are critically reviewed and current shortcomings are discussed. Conclusions are drawn and potential barriers and opportunities are mapped.

1.4.3. Phase 3: Tool development, validation and possible improvements

The last part of this thesis will be the development of a theoretical CE framework for the re-use of structural steel and a CE tool that will allow structural engineers to incorporate reused and reconditioned steel members in their designs for steel load-bearing structures. The theoretical framework will be a flowchart which can aid policy- and decision makers in the steel industry in order for businesses to become more sustainable. Also, the digital CE tool will allow structural engineers to evaluate their BIM models with respect to the possibility for re-use, by comparing their structural models with a database of available circular steel elements. The application will provide feedback in terms of possible environmental benefits that would be incurred by substituting virgin steel elements with circular steel. This will indirectly provide an indication of the degree of circularity of the design of a certain construction model. Moreover, a financial indication for the application of specific reused components compared to virgin steel will be provided illustrating possible economic benefits for reuse. Hereby, the tool will allow for analysis and comparison of certain reuse and recycling strategies and provide insight into feasibility boundary conditions for reuse.

Concludingly an evaluation of new potential value chain business models for re-use will be provided as well as a formulation of a set of improvements or additional design guidelines which could aid structural engineers in their design for future CE projects with a steel load-bearing structure.

Part I: Literature Research

Definitions

This paragraph presents a brief overview of relevant terminology used in this thesis.

The used definition of circular economy (CE) in this paper will be:

‘an economic system that represents a change of paradigm in the way that human society is interrelated with nature and aims to prevent the depletion of resources, close energy and materials loops, and facilitate sustainable development through its implementation. Attaining this circular model requires cyclical and regenerative environmental innovations in the way society legislates, produces and consumes.’ (Prieto-Sandoval et al., 2018)

The definition of sustainability is:

‘The process of maintaining environmental balance by avoiding the depletion of natural resources and ensuring renewable resources harvest in order to meet the needs of the present as well as future generations.’

The definition of environmental impact is:

‘An indication of the direct adverse effects of human activity on the natural environment and resulting societal consequences.’

The definition of demolition is:

‘The process aimed at destroying a building completely disregarding any waste hierarchy which generally results in reduced conservation of resources.’

The definition of deconstruction is:

‘A process aimed at systematic disassembly of buildings upholding the waste hierarchy by giving top priority to waste prevention through material reuse and recycling. (Akinade et al., 2017)

The definition of disposal is:

‘The act of getting rid of used building materials or components by sending them to landfills or by incineration (with or without energy recovery).’

The definition of recycling is:

‘The reprocessing of materials or building products recovered at the end of service life of a building producing new materials or products of the same quality and without loss of functionality.’

The definition of down-cycling is:

‘*The reprocessing of materials or building products recovered at the end of service life of a building producing new materials of lesser quality and reduced functionality.’*

The definition of Design for Disassembly (DfD) is:

‘The process of designing buildings by taking dismantling into close consideration thereby ensuring cost- and time-efficient extraction of materials or building components at the end of a building’s life.’

The definition of reuse is:

‘Putting construction materials or building components to a new use after extraction from the obsolete building with no or trivial reprocessing.’ (Hosseini et al., 2015)

The definition of virgin steel is:

‘Steel free of any impurities or deformations of which structural properties can be highly controlled by means of finetuning of raw material quantities and the primary production processes’

The definition of recycled steel is:

‘Structural steel components which have been acquired through the reprocessing of steel materials or products which have been recovered at the end of their service life.’

The definition of direct reuse is:

‘The reuse of structural steel components that have been extracted from an obsolete building by means of disassembly and which can be directly reused without any modifications.’

The definition of indirect reuse is:

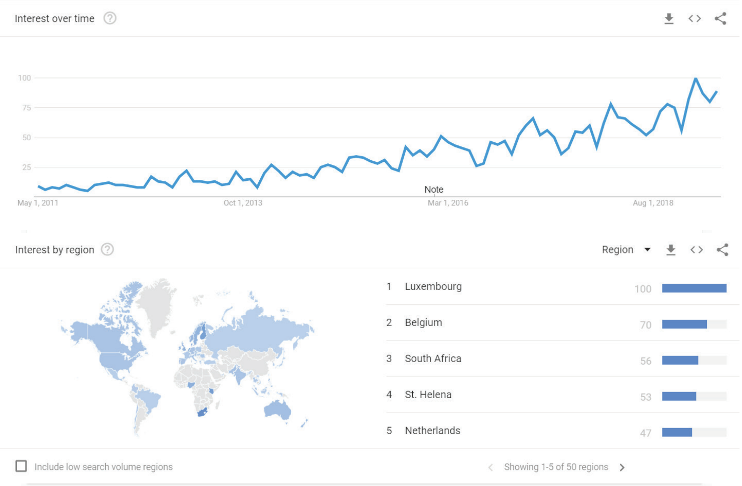
‘The reuse of structural steel components that have been extracted from an obsolete building by means of disassembly which need to be remanufactured in order to prepare the elements for reuse.’

2 Towards an increasingly circular economy

This paragraph will elaborate on the concept of circular economy and its historical development. It explains how the circular economy should operate and its importance in realizing a more sustainable society. Furthermore, it will be discussed how circularity can be quantified and how to measure underlying metrics.

2.1.1. Recent increase in popularity

As mentioned in paragraph 1.1.2 over the past years we have been witnessing a paradigm shift across the EU from short-term economical thinking towards an increasingly regenerative economical system causing the concept of **CE** to flourish. Governmental bodies, NGO's, research institutes, consultancy firms and the industry alike are adopting this concept and strategically implementing the framework on European, national and regional levels (European Commission, 2018b; Gemeente Amsterdam et al., 2017; Ministry of infrastructure and the environment & Ministry of economic affairs, 2016). An indication of the rise in popularity is represented below in **Figure 3** which indicates the rise in Google search trends for 'circular economy'. It can be observed that the concept is specifically experiencing a rise in popularity in Europe and especially within the Benelux.



1	Luxembourg	100
2	Belgium	70
3	South Africa	56
4	St. Helena	53
5	Netherlands	47

Figure 3: Indication of the popularity of the concept of circularity - derived from Google Trends

This increase in popularity is also reflected in the annual increase in academic publications on the subject of CE as illustrated by Prieto-Sandoval et al. in **Figure 4** below (Prieto-Sandoval et al., 2018). They performed an extensive literature review for a large amount of academic publications on the subject of CE pointing out the increasing popularity of the topic as an academic research field in the last decade.

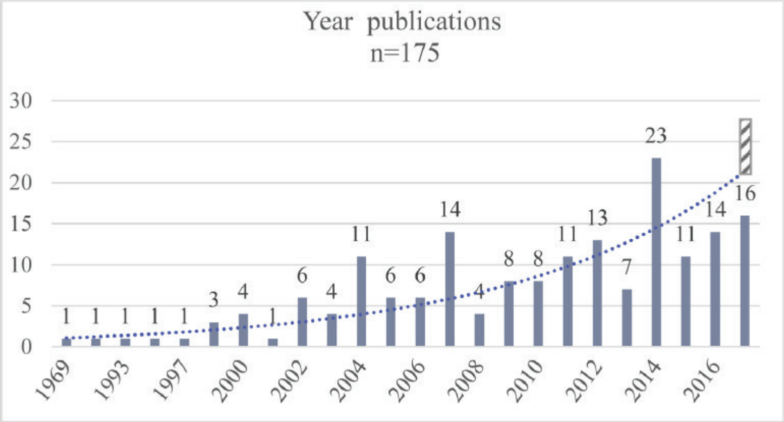


Figure 4: Academic publications on the subject of CE (Prieto-Sandoval et al., 2018)

The CE is high on the European political agenda and the framework is currently seeing increased incorporation on multi-level governmental policies and legislation. In order to achieve European and national sustainability goals, that have been laid out to limit global warming, the Dutch government is trying to accelerate the CE transition by increasingly calling for circular tenders on both national and regional levels (European Commission, 2018c; Gemeente Amsterdam et al., 2017; Ministry of infrastructure and the environment & Ministry of economic affairs, 2016). It is therefore becoming increasingly important for the building industry to understand how the circular economy should operate. However, there seems to be no general consensus on the exact definition of circular procurement or on how we should measure circularity of products, buildings or processes yet. Therefore the following paragraphs will elaborate on the origin and importance of the concept of CE as well as methods for quantification and important underlying parameters.

2.1.2. Historical overview

According to various sources the concept of CE first surfaced in China where policy makers coined the concept in the '*Circular Economy Promotion Law of the People's Republic of China*' in 2009 (Kalmykova et al., 2017; Kirchherr et al., 2018; Prieto-Sandoval et al., 2018). (National People's Congress Standing Committee, 2008). As illustrated in **Figure 3** the term 'circular economy' has been increasing in popularity since this publication.

However with his paper, 'The Economics of the Coming Spaceship Earth' Kenneth Edward Boulding already opted as early as 1966 for a radical change in thinking by suggesting to replace the conventional economic system with a cyclical system. Boulding, who was a professor of economics, argues in this poetic plea that the economy of the future would be a "spaceman" economy in which he depicts earth as a single space ship with limited resources in which "man must find his place in a cyclical ecological system which is capable of continuous reproduction of material form even though it cannot escape having inputs of energy". This in contradiction to the traditional industrial notion of the economy denoted as the "cowboy economy" as a symbolic representation "of the illimitable plains and also associated with reckless, exploitative, romantic, and violent behavior, which is characteristic of open societies" (Boulding, 1966).

Various other concepts have emerged since the second half of the 20th century which all contribute to the same line of thinking on how the future economy should operate such as cradle-to-cradle design (McDonough & Braungart, 2002), steady-state economy (Daly, 2008), loop-economy (W. R. Stahel & Reday-Mulvey, 1981) and the donut economy (Raworth, 2017). Although significant differences exist between these concepts, there seems to be general consensus that the traditional economic model, which prioritizes continuous growth and stimulates consumption patterns, is inherently flawed and unsustainable as earth's resources are finite. We need to rethink our priorities and move towards a cyclic environmental system which is regenerative by design.

Prieto-Sandoval et al. explained the historical development of the CE concept with a knowledge map. This visual representation indicates three distinct economical stages the first stage being the linear or 'cowboy' economy as defined by Boulding (Boulding, 1966). The second stage is depicted as the industrial ecology stage, an increasingly green economy which aims to improve human well-being and to reduce environmental impact. It is also characterized by little behavioral adaption of society and limited climate action. The third and final stage is the circular economy, here the economy is depicted as a closed loop system primarily aimed at sustaining environmental balance which as a result will increase human wellbeing. This depicts the concept of CE as a natural consequence to three consecutive stages of industrial, social and economic change (Prieto-Sandoval et al., 2018).

An important national influence that fueled sustainable thinking in the Netherlands was the ‘waste hierarchy’ framework or ‘Ladder of Lansink’ laid down by Ad Lansink in a parliamentary notion in 1979. He proposed to differentiate waste-streams in a hierarchical order prioritizing prevention followed by re-use, recycling, incineration (with heat recovery generation) and lastly landfilling. His ambitions were consolidated in several national waste sorting policies such as isolating waste-streams for paper and glass in order to improve recycling efforts and the introduction of a deposit system for beer bottles, plastic bottles and plastic crates (Kemp & Van Lente, 2011). These policies are still in effect today .

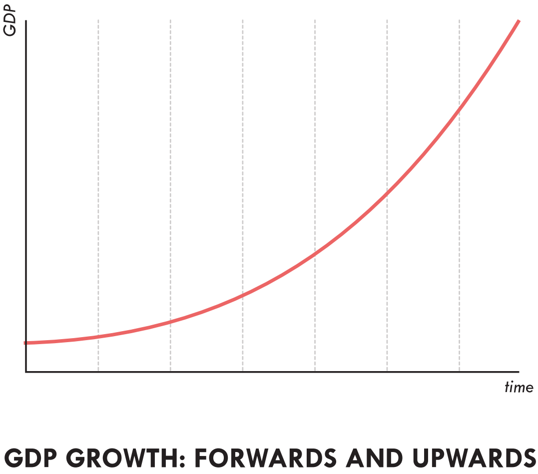


Figure 5: Ever increasing output growth, from Raworth (2017)

Lansink’s ambition to upgrade traditional waste practices is all the more relevant today. The growth of consumerism driven by our collective Western addiction to ever increasing GDP, depicted as a graph moving forwards and upwards indefinitely, as noted by Raworth (Raworth, 2017) has fueled the ‘Take-make-dispose’ economy. This linear economic model can be traced back to the 17th century industrial revolution where technological innovation produced a shift in both supply and demand ignoring the environmental limits of our planet. The waste-hierarchy by Lansink underpins an important core CE principle; that in order to achieve sustainable development we should strive to close energy and material loops. A more recent notion of this principle has been coined by the Ellen MacArthur Foundation (EMF) which has defined four fundamental characteristics of a CE as:

- Optimization of resources and energy use throughout lifecycles.
- Maintaining products and components in use for longer.
- Cycling materials through the system as many times as possible through cascaded uses.
- Utilizing pure materials for improving quality of post-life use.
  (Ellen MacArthur Foundation, 2013)

The EMF is a charity and thinktank which aims to inspire the future generation to rethink

the current global economic system and which has been a longtime advocate on the subject of CE. It was founded in 2009 in order to accelerate the transition to a circular economy. The EMF has published work on a variety of CE related subjects and their work is often referred to both by the scientific community as well as policy- and decision makers. Their specific interpretation of circular economy is focused on replacing the end-of-life concept with a restorative concept. As described by the Ellen MacArthur Foundation (2012) the CE is:
"… an industrial system that is restorative or regenerative by intention and design. It replaces the 'end of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models." (Ellen Macarthur Foundation, 2012, p. 9). Their work is frequently cited and referred to throughout this thesis.

2.1.3. Key principles of the Circular Economy concept

Literature studies have indicated that there seems to be little coherence with regard to the CE concept across literature and it seems that there is no collective consensus on its exact meaning (Kalmykova et al., 2017; Kirchherr, Reike, & Hekkert, 2017; Prieto-Sandoval et al., 2018). In order to prevent collapse of the concept due to vastly varying definitions, it is essential to provide a clear interpretation of the CE concept, it's key principles and determinants.

Several literature reviews have been conducted by academics in order to advance our understanding of CE and to identify the common ideas behind it. From the literature review by Prieto-Sandoval et al. it could be observed that the most common and frequently mentioned group of principles in academic publications on the subject was the 3Rs (Reduce, Reuse & Recycling) in relation to the CE concept and the use of sustainable design strategies (SDS) as the "official" CE principles. They concluded that the foundation of CE consists of four main components which can aid the scientific community and policy makers (Prieto-Sandoval et al., 2018);

- It is focused on recirculation of resources and energy by reuse and recycling,
- the approach is strongly multi-level,
- It is a means to achieve the ends of sustainable development,
- it is closely related to the society's view of innovation

Although there seems to be general consensus that recirculation of resources is at the core of CE, Kirchherr et al. noted that only a third of the definitions found in reviewed literature explicitly mention the importance of a waste hierarchy and especially the 'reduce' aspect is often not considered. Possibly this could be explained by the lack of focus in literature on the consumer perspective dimension (Kirchherr et al., 2017). Our current take-make-dispose Western consumption patterns are inherently unsustainable and a systematic shift towards a CE also requires a change in consumer consciousness and behavior. The first and foremost question with regard to resource use should be if consumption is actually necessary. We should ask ourselves what we truly want and what we genuinely need. This line of thinking is clearly illustrated by the 'tiny house' social movement in which people embrace Hippocrates' philosophy that "everything in excess is opposed by nature” and that getting rid of materialistic possession offers flexibility and freedom. Raworth also stresses the importance of a collective attitude change; to stop prioritizing the economical goal of endless GDP growth and to put humanity back at the heart of economics (Raworth, 2017). As E.F. Schumacher noted in his philosophical work ‘small is beautiful’, our economies should be focused around the needs of communities and not corporations. We should challenge the current state of excessive consumption and should appreciate both human needs and limitations (Schumacher, 1973). His philosophy of ‘enoughness’ is all the more relevant today and this necessary consciousness shift is closely interrelated with the waste hierarchy and therefor the ‘reduce’ aspect should always be denoted.

This philosophy also resonates with increasing consumer preference for locally sourced products and there seems to be a shift towards anti economic globalization. Concern with the development of international trade seems to be growing as emissions from global freight transport are expected to quadruple in the next thirty years (International Transport Forum, 2016). The exponential growth of international trade has an adverse effect on sustainability and seems to negatively affect consumer preference and has therefor led to a rise of consumer interest in products that are produced locally rather than globally. Grebitus et al. have pointed out that there is a negative correlation between the associated transport distance of food products and consumer’ willingness to pay for these products. They conclude that consumers think that they are improving regional economic situations and that they are reducing their environmental impact by buying local. They list several socio-demographic characteristics as potential drivers (Grebitus, Lusk, & Nayga, 2013).

2.1.4. Relation between Circularity and Sustainability

So how are the concepts of circularity and sustainability interrelated? Kirchherr et al. have indicated that there are few explicit linkages mentioned in academic literature of the sustainable development concept and circular economy. They concluded that many authors mainly put emphasis on the concept of CE as a means of generating economic prosperity and that pursuing environmental aims is often seen as supplementary (Kirchherr et al., 2017). As Prieto-Sandoval et al. mentioned the CE concept is not just a modern manifestation of the sustainability concept nor is it a "panacea of sustainability". However, as they concluded, it is a vital component of the CE concept provided that CE is "a means to achieve the ends of sustainable development" (Prieto-Sandoval et al., 2018).

Figure 6: The Doughnut: a 21st Century Compass - adapted from Raworth (2017)

This relationship is possibly best illustrated by the visual representation sketched up by Raworth in the '*Doughnut Economy'* provided in **Figure 6**. In this publication she depicts the concept of CE as a donut with a social foundation and ecological ceiling comprised by the various United Nations Sustainable Development Goals (UNSDGs) that are to be achieved by 2030 and that were agreed upon in 2015 by 193 countries. As Saidini et al. noted, circular economy principles can be a problem solving toolset for achieving sustainability goals (Saidani, Yannou, Leroy, Cluzel, & Kendall, 2019). The doughnut, or the space between the social foundation and the ecological ceiling is "the safe and just space for humanity" (Raworth, 2017). This clearly illustrates how the CE concept and sustainable development are interwoven and inextricably linked.

Figure 7: The United Nations' Sustainable Development Goals , from United Nations (2013)

2.1.5. Circular economy in the European Union

In 2015 the European Commission (EC) first published an action plan with 54 measures aimed at "closing the loop" of product lifecycles in order to accelerate the circular economy transition of the European Union (European Commission, 2015). It is intended as a primary instrument for the EU Member States in achieving the UNSDGs by 2030. This variety of ambitious CE policies was later updated in 2018 and promotes close collaboration between Member States, institutions, commercial companies and other stakeholders in tackling sustainability issues with regard to production, consumption and waste management. The EC and the European Investment Bank have made various European funding programmes available in financial support of the transition proposed in their 'Circular Economy Package'. These include programmes such as Horizon 2020, the European Fund for Strategic Investments (EFSI), the LIFE programme and the European Structural and Investment Funds and in 2017 a Circular Economy Finance Support Platform was launched (European Commission, 2015, 2018a, 2018c, 2018b).

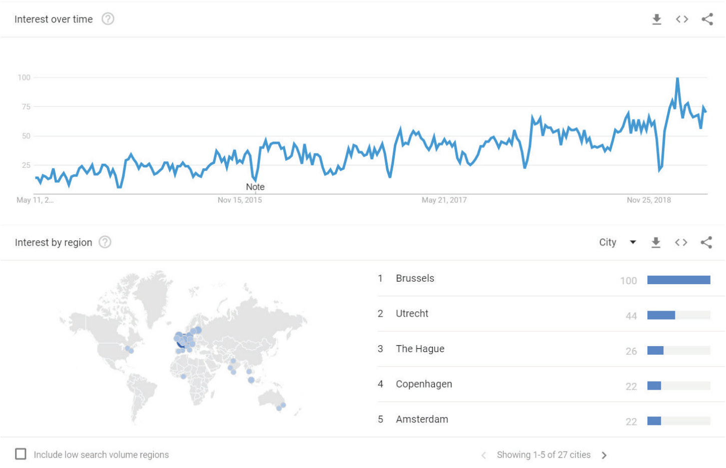
The EC has stated that the transition of the EU to a circular economy will not only stimulate sustainable activity offering benefits for both human health and the natural environment, but it will also stimulate innovation, increase investments, create jobs and add value. The commission has estimated that CE related sectors employed over 3.9 million across the EU and accounted for approximately 141 billion of value added in 2014 (European Commission, 2018b). Eurostat continues to monitor the CE transition for the various member states of the EU through several CE indicators for production & consumption, waste management, secondary raw materials and competitiveness & innovation (Eurostat, 2018a).

The introduction of the CE concept by the European Commission has also popularized the topic as a research field for both academics as well as EU researchers. Türkeli et al. examined many scientific CE publications published in recent years by institutes in both China and the EU. Although China is the world leader with regard to the amount of global CE publications, the EU is also a major global contributor to CE related scientific knowledge and it was pointed out that scientific research is highly in line with recent policy developments (Türkeli, Kemp, Huang, Bleischwitz, & McDowall, 2018).

2.1.6. Circular economy in the Netherlands

The Netherlands is often seen as a frontrunner with regard to the implementation of CE. In 2016 the Dutch government produced a government wide programme aimed at aiding the transition of the Netherlands towards a circular economy by 2050 (Dutch Ministry of Environment & Ministry of Economic Affairs, 2016). According to Eurostat a total of over a hundred thousand people were employed in circular economy related sectors in 2018, roughly 1.19% of the Dutch population. Private investments, jobs and gross value added related to CE sectors accounted for 0.79% of GDP for the Netherlands in 2018. However, if we compare these statistics with other EU member states, the Netherlands does not rank among the top 5, neither in terms of GDP share nor in terms of percentage of the population employed in CE related sectors (Eurostat, 2018a).

This indicates that the Netherlands would be underperforming with regard to the implementation of CE compared to other member states, it appears that the concept itself has been a vastly popular topic in the Netherlands over the past five years as illustrated in **Figure 8**. Türkeli et al. have indicated that a total number of 40 publications have been published in the Netherlands on the subject of CE in the past year (2017-2018) only surpassed by England and China with 47 and 142 publications respectively. It is stated that the Delft University of Technology and TNO are the most important institutes with regard to CE related scientific knowledge creation, both in the Netherlands as well as the EU due to high publication numbers as well as citation performance (Türkeli et al., 2018).



1	Brussels	100
2	Utrecht	44
3	The Hague	26
4	Copenhagen	22
5	Amsterdam	22

☐ Include low search volume regions

Showing 1-5 of 27 cities

Figure 8: Indication of the popularity of the concept of circular economy in the Netherlands - derived from Google Trends

2.1.7. Metrics for measuring sustainable development in a CE

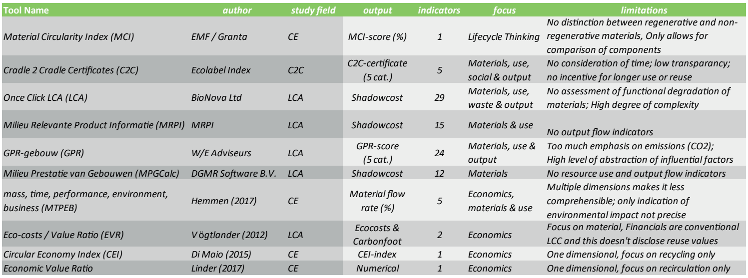
As mentioned in the previous paragraphs, the CE concept has been vastly gaining in popularity over the recent years both in the EU as a whole as well as on a national scale in the Netherlands. With political agendas pushing for a CE transition and the concept being increasingly interwoven in both European and national policies, it becomes a central question how we should measure and quantify circularity and progress in achieving sustainable development goals. Many researchers and institutions have tried to define sets of metrics and indicators in an attempt to assess circularity (Di Maio & Rem, 2015; Ellen MacArthur Foundation, 2015a; Eurostat, 2018a; Iacovidou et al., 2017; Linder, Sarasini, & van Loon, 2017; Saidani, Yannou, Leroy, & Cluzel, 2017). Most of these methods try to define circularity as a specific value for the potential of materials and resources to be maintained in the economy for as long as possible. Although closing economic cycles is indeed an important aspect of CE, solely quantifying circularity as a sort of degree of value retention neglects various other important aspects related to sustainability such as e.a. limiting harmful emissions, prevention of resource depletion and the distinction between technical and biological cycles. As stated by Iacovidou et al. any attempt in assessing circularity should acknowledge that it is a rather complex multi-dimensional and time dependent value, representing a holistic sum of various environmental, economic, social and technical impacts (Iacovidou et al., 2017).

Various studies have pointed out this superficial character of aggregating various factors into a one-dimensional indicators and have opted for multi-dimensional evaluation instead in order to ensure validity, transparency and unambiguousness (Linder et al., 2017; Saidani et al., 2017; Walker, Coleman, Hodgson, Collins, & Brimacombe, 2018). Walker et al. argue that LCA methodologies might therefore be more suited for evaluation of CE strategies for the building industry as they aggregate input and output values into a variety of environmental indicators rather than a single metric (Walker et al., 2018). Although, it should be noted that LCA, in and by itself, solely focusses on the environmental impact due to CE strategies (rendering it inconclusive with regard to other relevant CE domains) LCA indicators do provide useful metrics for attempting to evaluate specific CE strategies with respect to achieving the various UNSDGs.

Although various authors have indicated that current methods are inconclusive and that assessment methods should include both environmental as well as economic indicators, few attempt to address their relationship with the social and technical domains (Di Maio, Lotfi, Bakker, Hu, & Vahidi, 2017; Linder et al., 2017; Saidani et al., 2017; van Hemmen, 2016; Walker et al., 2018). Iacovidou et al. state that existing theoretical frameworks and assessment methods therefore lack a whole systems approach. They suggest that an effective CE assessment framework for materials, products and components should consider and combine environmental, economic, social and technical domains in order to capture all benefits and limitations relevant for the various stakeholders (Iacovidou et al., 2017).

It is also important to note that time plays an important role with regard to quantifying circularity. As one can imagine, increasing the potential lifecycle of a product will offer certain advantages as the specific product will have to be replaced after an increasing period of time, thereby limiting resource demand. However, as Hemmen noted, although LCA methods do employ a lifecycle in their assessment, they often only regard a single lifetime (van Hemmen, 2016). This complicates the assessment of for e.a. materials (partly) consisting of recycled material or reused components. There is no distinction between a 10 year old component that has been reused several times or a 2 year old component that had a single lifetime. This is also clearly illustrated by the complications that arise when we take a closer look at the ‘fast-track LCA approach’, which will be discussed in paragraph 4.4.1.

The most commonly used LCA-tools for the Dutch building industry are; GPR-gebouw, One-Click LCA, MRPI and MPGCalc. These LCA-tools have been briefly tested and evaluated as well as several theoretical models for assessing circularity which have been found in scientific publications (Di Maio & Rem, 2015; Ellen MacArthur Foundation, 2015a; Linder et al., 2017; van Hemmen, 2016; Vögtlander & Mestre, 2009). It generally seems that these circularity based models have a primary focus on reuse and recycling strategies and give less priority to environmental impact in contrast to LCA methods. Most theoretical models share a common basis in the framework described by the Ellen MacArthur Foundation. They thereby highly depend on recycling and reuse ratios as well as service life as primary indicators for circularity. Below in **Figure 9** is an overview of the various tools and theoretical models that have been evaluated as well as a brief summary of their most important limitations.



Tool Name	author	study field	output	indicators	focus	limitations
Material Circularity Index (MCI)	EMF / Granta	CE	MCI-score (%)	1	Lifecycle Thinking	No distinction between regenerative and non-regenerative materials, Only allows for comparison of components
Cradle 2 Cradle Certificates (C2C)	Ecolabel Index	C2C	C2C-certificate (5 cat.)	5	Materials, use, social & output	No consideration of time; low transparancy; no incentive for longer use or reuse
Once Click LCA (LCA)	BioNova Ltd	LCA	Shadowcost	29	Materials, use, waste & output	No assessment of functional degradation of materials; High degree of complexity
Milieu Relevante Product Informatie (MRPI)	MRPI	LCA	Shadowcost	15	Materials & use	No output flow indicators
GPR-gebouw (GPR)	W/E Adviseurs	LCA	GPR-score (5 cat.)	24	Materials, use & output	Too much emphasis on emissions (CO2); High level of abstraction of influential factors
Milieu Prestatie van Gebouwen (MPGCalc)	DGMR Software B.V.	LCA	Shadowcost	12	Materials	No resource use and output flow indicators
mass, time, performance, environment, business (MTPEB)	Hemmen (2017)	CE	Material flow rate (%)	5	Economics, materials & use	Multiple dimensions makes it less comprehensible; only indication of environmental impact not precise
Eco-costs / Value Ratio (EVR)	V ögtlander (2012)	LCA	Ecocosts & Carbonfoot	2	Economics	Focus on material, Financials are conventional LCC and this doesn't disclose reuse values
Circular Economy Index (CEI)	Di Maio (2015)	CE	CEI-index	1	Economics	One dimensional, focus on recycling only
Economic Value Ratio	Linder (2017)	CE	Numerical	1	Economics	One dimensional, focus on recirculation only

Figure 9: Overview of various tools frequently used for LCA and CE assessment

2.1.8. Existing design strategies facilitating a CE

But how should we design constructions in a CE? In an attempt to increase material efficiency, several design methods associated with CE for the building industry have already been proposed in the past. Design methodologies such as Design for Dissassembly (DfD), Cradle to Cradle (C2C), Reverse Logistics (RL) or Lifecycle Thinking have been opted in order to reduce the environmental impact by the building industry. In order to improve construction waste management, these strategies try to close the loop of materials by considering end-of-use scenarios and by upholding a waste hierarchy (Durmisevic & Yeang, 2009; Hosseini et al., 2015; McDonough & Braungart, 2002). Various authors have made a compelling argument for increased standardization of components and dimensions and have stressed the importance of demountability on a component level for more effective reuse and recycling (Hosseini et al., 2015; Rios et al., 2015). Although there seems to be an increasing demand for standardization across various branches of the building industry, ingeniously opted as 'LEGOlisation' by Hennis de Ridder (de Ridder, 2011), there has been limited implementation of the concept for primary structural systems so far. Various knowledge institutes and commercial companies in the Netherlands are making significant progress with regard to demountable components and systems for the building industry, e.a. for demountable composite flooring systems and innovative connection methods for hollow-core slabs (Brambilla et al., 2019; Heebing & Bunk, 2017; Wind, 2018). However, it appears to be complicated to realize industry wide changes with regard to the application of demountable building components and reversible assembly processes as widespread adoption is lacking. Moreover, these design strategies primarily focus on improving the end-of-life scenario which is by definition an assumption with regard to the future state of the building industry and the available prospective re-use and recycling methods. Also, it does not provide a means to tackle current waste management issues but only potentially improves the future of the building industry.

Other methods are centered around the use of renewable resources and biodegradability of materials. Design strategies such as Eco-Design, Biomimicry, Bioengineering, Biomorphism, Biophilia or other derivates specifically focus on an analytical understanding of biological structures, the regenerative capacity of nature and more explicitly address the difference between biological and technical cycles. These are strategies primarily inspired by nature and intend to improve human processes, products or systems by closely observing the natural environment and through reverse engineering gain understanding of their functional basis (Dellasala, Goldstein, Valdecasas, & Wheeler, 2018). In the built environment we are witnessing a strategic shift towards increasingly closed loop models and 'green' architecture in which technology and the natural environment are increasingly interwoven. There has been a steadily increasing demand for resource efficiency through e.a. improved insulation, solar energy, passive heating and cooling and gradual water drainage by vegetative roofs.

However, although significant advances have been made in recent years, improvements have been primarily focused on resource use of buildings throughout their lifetime. Resource efficiency of buildings themselves and their inherent components and materials are often disregarded. An increase in resource efficiency during a buildings lifetime might thereby actually lead to a contradicting effect for the building itself for which resource efficiency might actually decrease due to lower rates of recyclability and reuse of materials and products. For example more strict insulation requirements positively affect thermal insulation of a building by decreasing the energy demand for heating and cooling but this generally also causes an increase in the use of non-organic materials which are often hard to recycle such as e.a. polystyrene and polyurethane (Dylewski & Adamczyk, 2014). Also, energy resources which are deemed sustainable such as silicon-based photovoltaic (Si-PV) panels, contain considerate amounts of heavy metals such as Lead and Cadmium and there are currently no effective means of recycling (Yue, You, & Darling, 2014). Therefore, in order to design truly sustainable buildings, it is increasingly important to focus on this interconnection between system and construction. This requires improved understanding of the difference between technological and biological cycles and a systematic shift towards more biologically inspired design. Focus should not be on increasingly integrating complex technological systems but rather on considering the built environment as a biological system with certain living constraints

2.2. Perceived barriers for adoption of the CE concept by the building industry

Although the CE concept is a popular topic of debate in both the European parliament as well as on the national political agenda in the Netherlands, only limited progress has been made with regard to actual implementation. Some showcase projects for the built environment, highlighting CE aspects, have been realized in recent years but there does not seem to be any indication of an industry wide shift towards CE adoption. However, a significant rise in interest on the topic can be observed from the amount of publications on the subject of circular economy barriers over the past years, especially from 2016 onward (Araujo Galvão, De Nadae, Clemente, Chinen, & De Carvalho, 2018). In order to understand the industry specific barriers and opportunities with regard to the adoption of CE principles various scientific studies on the subject were collected and used to construct an initial framework of potential barriers.

Data collection was done by means of desk research to find relevant publications and studies and to identify the most important authors on the subject. Various search queries have been used in Elsevier's ScienceDirect with the keyword 'barriers' in combination with 'circular economy', 'design for disassembly' , 'reverse logistics' or 'construction' or relevant synonyms to build an initial overview of recent and relevant literature on the subject. Over 25 potentially relevant articles were found. A definitive selection of 10 articles was made by reading the abstracts and omitting less relevant publications e.a. articles from before 2015, articles that are focused on different industries, or publications with significant overlap with other used studies by comparing bibliographies. An initial list of perceived barriers was constructed by listing all barriers identified in the various publications. The initial framework focusses on macro level barriers and therefore meso or micro level factors were omitted. Consecutively the list was brought back to a more comprehensive list by making a distinction between attitudinal, financial, operational, technological and legislative barriers in a similar manner as proposed by Kircherr et al. and others (Araujo Galvão et al., 2018; Kirchherr et al., 2018; Tura et al., 2019). The initial framework of macro level barriers preventing CE adoption by the construction industry is provided in **Figure 10** below.

				1	2	3	4	5	6	7	8	9	10
				DfD	SSR	DfD	SSR	CE	CE	RL	CE	CE	CE
Barriers to CE adoption	MACRO (construction industry specific)	Attitudinal	lack of client demand / perception as inferior material		x		x	x	x		x		x
			industry resistance to change / lack of involvement	x	x		x	x	x			x	x
		Financial	potential risks and benefits of CE unclear / no quantative data	x	x	x	x	x	x		x	x	x
			high upfront investment / CE shift requires far-reaching internal changes throughout organisation				x	x	x		x	x	
			low price virgin material / low pollutant emission tax	x	x		x			x			x
			unequal distribution of risks and benefits among actors of supply chain	x					x				
			long lifecycle of buildings / uncertainty revenue flows for long-term investments in sustainability			x				x	x		
		Structural	lack of awareness environmental conseq. / no responsibility for sustainability or understanding of CE	x	x	x			x	x	x	x	x
			lack of trust, communication / large number of stakeholders, parties and decision makers involved				x	x		x	x	x	
			lack of integration / linear, sequential relationship between the design and construction phase	x	x	x	x	x	x	x	x	x	
		Operational	lack of recovery facilities, infrastructure, technology and immaturity of markets	x			x	x	x	x	x	x	x
			supply chain gaps / need for specialized actor								x	x	
		Technological	technical challenges products & take-back systems / uniqueness of each building			x				x	x	x	
			lack of performance guarantees / lack of certification of products	x	x	x	x			x	x		
		Legislative	lack of government incentives / legislative imperatives	x	x	x		x	x	x		x	x
			limited amount of points awarded for building deconstruction in sustainability appraisal			x							x
			lack of governmental rules & guidelines / prohibitive international policy		x							x	x

$_1$Cruz Rios et al., 2015 ; $_2$Densley Tingley et al., 2017 ; $_3$Akinade et al., 2017 ; $_4$Dunant et al., 2017 ; $_5$Kirchherr et al., 2018; $_6$Mahpour, 2018; $_7$Hosseini et al., 2015 ;$_8$Ritzén et al., 2017 ;$_9$Tura et al., 2019 ;$_{10}$Darla Araujo Galvao et al., 2018

Figure 10: Identified main perceived barriers for CE adoption by construction industry

From the figure above several main initial conclusions can be drawn with regard to the perceived barriers that currently seem to prohibit more widespread adoption of CE principles by the construction industry:

- *Attitudinal*: Industry resistance to change & lack of client demand
- *Financial*: Lack of quantitative data in support of potential risk & benefits of CE
- *Structural*: Lack of industry awareness & responsibility with regard to sustainability
- *Operational*: Fear of immature market; lack of necessary facilities and infrastructure
- *Technological*: Fear for liability & increased complexity; no performance guarantees
- *Legislative*: Currently no government incentives; pollution & virgin material is cheap

2.3. Conclusions and recommendations

From the literature study on CE elaborated on in the previous paragraphs the following conclusions and recommendations can be made:

- It can be concluded that over the past decade, the concept of CE has become *an important, well-established topic in the sustainable development debate* and it is seeing widespread adoption by government entities, NGO's, and academic institutes across the European Union.
- Although CE is an important topic for policy- and decision makers, there seems to be *little coherence with regard to the exact definition of the concept* across literature and it seems that there is no collective consensus on its exact meaning.
- However, there is general consensus that the concept is focused on the *recirculation* of resources and energy, it is strongly *multi-level*, closely related to *innovation* and it can be regarded as a *means to achieve the ends of sustainable development*.
- The CE framework is currently being integrated in both European and national policies and regulations. However, there currently seems to be *no appropriate method for multi-dimensional evaluation available for quantifying CE*.
- It was concluded that currently LCA is the *most suited method for evaluation of CE strategies for the building industry*. This methodology provides the most useful set of metrics for this purpose and is a well-established scientific assessment method.
- From a literature study on various CE related subjects it was found that various macro level barriers exist preventing widespread adoption of CE strategies. It was concluded that *several of these barriers can be classified as perceived* and might not actually be observed in practice.

3 Structural steel

This paragraph briefly discusses how the modern steel industry operates, what the structural steel production cycle looks like, what the currently available technologies are and the potential future technologies that could make the industry increasingly sustainable. It elaborates on the environmental impact of the industry as a whole and the various difficulties and opportunities it currently faces with regard to the adoption of CE principles.

3.1.1. The global steel industry

Steel is one of the most common manmade materials and combines excellent mechanical properties such as, a high strength to weight ratio, toughness and high tensile strength with excellent durability characteristics, making it one of the pre-eminent building materials for effective light-weight constructions. Steel beams and columns consist of a range of highly optimized standardized shapes which have hardly changed over the past couple of decades making these elements one of the most suited available building products for reuse. This will be further explained in paragraph 3.1.2. Steel is an alloy consisting mainly of iron and a small percentage (less than 2%) carbon and is primarily produced from three basic raw materials; iron, carbon and limestone. These primary resources are still abundantly available across the globe (Worldsteel Association, 2018c). Through various consecutive industrial processes these raw materials are refined, heated and mixed converting them to pig iron and steel consecutively. This virgin steelmaking process is further explained in paragraph 3.1.4.

After the fossil fuel industry, the steel industry is the second biggest industry in the world (Cramb & Amuda, 2017). The annual global crude steel production in 2017 was 1689 million tons with Chinese production accounting for 49.2%. The modern steel industry is a highly competitive globalized industry dominated by large multinational corporations, the biggest being ArcelorMittal which had a total annual crude steel production of roughly 97 million tons in 2017. The industry depends heavily on international trade of both raw materials as well as finished and semi-finished products. For example 74.6% of the mined iron ore in 2017 was exported and 29.4% of the total amount of produced finished and semi-finished products (Worldsteel Association, 2018e). Most iron ore is extracted from mines in Brazil and Australia from which it is transported to the coast by rail and from there on shipped to steel plants in Europe and Asia (Worldsteel Association, 2018c). According to Worldsteel the total demand for steel is estimated to increase 50% by 2050 in order to meet the needs of the growing world population (Worldsteel Association, 2018b).

In 2017 the European steel industry produced approximately 168,4 million tonnes of crude steel. According to Worldsteel 40% of this European production was produced via recycling of ferrous steel scrap. **Figure 11** provides an overview of steel production facilities in Europe. From this figure it can be concluded that the amount of EAF facilities in Europe is relatively high compared to BOF plants. The recycled steel production in Europe is thereby relatively high compared to newly industrialized countries, especially compared to China where recycling of ferrous scrap accounts for only 9% of the total production (Worldsteel Association, 2018e). As the production of steel is highly energy intensive and the virgin production process involves processing of large quantities of coal, the steel industry is considered to be a major contributor to carbon dioxide emissions and responsible for various other environmentally harmful effects due to the emission of various combustion gasses. However, significant differences exist with regard to emissions between production facilities globally due to specific national environmental rules and regulations. Moreover, highly developed countries generally have more technologically advanced facilities and production processes which allow for increasingly efficient production and a lowering of harmful emissions. Also, the steel production process through recycling requires significantly lower energy and material resources and this process causes a significantly lower environmental impact. Approximately a third of GHG emissions and less than a quarter of energy requirements, are associated with recycling compared to the virgin steel making process (Dorota Burchart-Korol, 2013; Oda, Akimoto, & Tomoda, 2013). Overall this results in a significantly higher relative environmental impact per ton of steel for example steel produced in China compared to steel produced in the EU. Emissions from the Chinese steel industry account for 12% of the national CO2 emissions compared to an average of 6.7% of global emissions by the steel industry as a whole (Li, Lei, & Pan, 2016; Montalbo, Koffler, & Morrison, 2018).

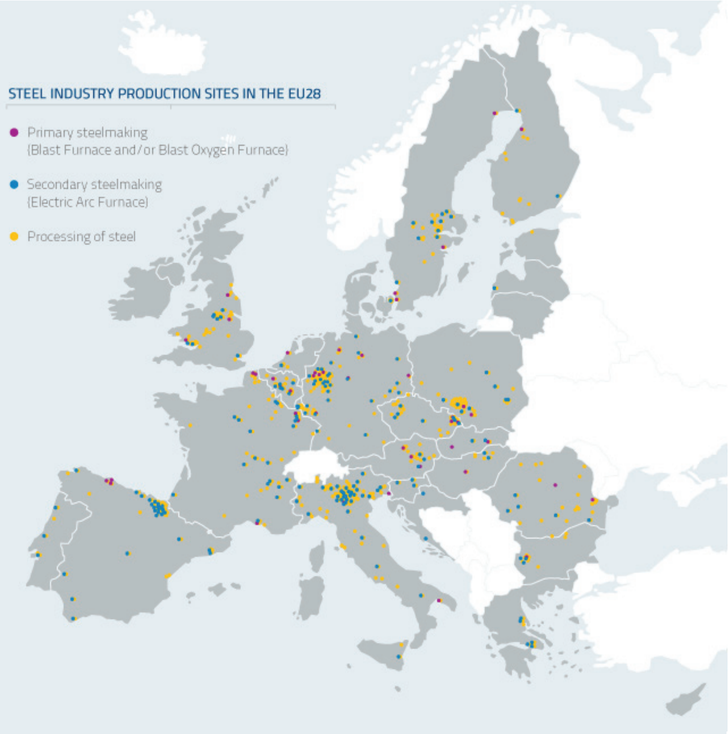


Figure 11: Overview of steel industry production sites in the EU28, from Worldsteel (Worldsteel Association, 2018a)

As previously noted, the recovery rate of steel is very high as steel has excellent recyclability characteristics. Steel is technically almost 100% recyclable as steel scrap can simply be reheated and melted to produce new products. This is often done by means of an electric arc in a so called EAF which is explained in paragraph 3.1.3.

In order to further improve specific mechanical properties of steel, small quantities of alloyants can be added to the mixture such as manganese, chromium, nickel, silicon or molybdenum. Research in the field of metallurgy has sparked a tremendous increase in the variety of available alloys as 75% have been developed over the past 20 years. Currently there are over 3500 different grades of steel commercially available (Worldsteel Association, 2018a). The structural steel production process is highly regulated and the chemical composition and mechanical properties of various structural steel grades are specifically specified by industry standards. In Europe the most common steel grades are depicted by standard classifications according to European Standard EN 10025; here the symbol ‘S’ denotes structural steels, followed by a number for the minimum yield strength and potentially additional symbols indicative of a particular special property. In the European construction sector the most commonly used grades are S235, S275 and S355. These alloys contain only small quantities of common alloyants Manganese, Phosphorus, Silicon and Sulfur which makes these materials significantly more economical than high-grade alloys (European Committee for Standardization, 2018).

3.1.2. Standardized structural steel profiles

As incidents in the construction industry tend to lead to disastrous consequences such as possible injuries, fatalities and huge economic losses, the industry historically has had to adhere to increasingly strict rules and safety regulations with regard to design and building activities. The increasing scale and complexity of modern building structures goes hand in hand with a significant increase of risk and responsibility as buildings are housing more and more people and are subjected to more complex loadings. It is essential for the structural design and engineering practice to have access to accurate and guaranteed information on the mechanical and physical properties of construction elements. In order to continuously ensure structural safety and to minimize the risk of deficiencies there has been an increasing demand for certification, regulation and standardization over the past decades.

The European structural steel industry is therefore already highly regulated and standardized which makes steel one of the most suited structural materials for reuse. Standardized elements are used in all sorts of structural steel designs and specific elements can therefore be fairly easily reinserted in the value chain after careful disassembly, testing and remanufacturing. Hot-rolled structural steel profiles are available in a limited range of standardized shapes; the most frequently used profiles in structural engineering are respectively H-, I- (EN 10034) and U-shapes (EN 10162) and are widely applied across the building industry. Moreover, as previously stated in paragraph 3.1.1 the chemical composition and mechanical properties are specified by industry standards as defined by a set of Euronorms and strictly controlled by the steel industry. This makes it fairly easy to provide a concise estimation of the mechanical properties of structural elements by examining historical records and drawings or by manual inspection and measurements. As EN 10034 as well as EN 10025 date back to 1993 and

1994 respectively this allows for very concise estimation of initial structural tolerances and inherent properties of structural steel members as used in buildings built over the past 25 years throughout Europe.

Moreover, all components which are part of a load-bearing steel constructions have to be provided with an additional CE-marking according to NEN-EN 1090, since the 1st of July 2014, in order to ensure adherence by manufacturers across the EU to harmonized production quality management obligations (NEN, 2014).

3.1.3. BOF route – virgin steel

An important distinction between various steel products with regard to assessing their environmental impact is the differentiation between steel produced from predominantly raw materials and steel produced through recycling of ferrous scrap. In 2017 steel produced from raw materials by the Basic Oxygen Furnace (BF-BOF) production route accounted for 71.5% of the total global crude steel production (Worldsteel Association, 2018e). On average, the production of 1 kg of steel by the BF-BOF process requires 1,4 kg of iron ore, 0,8 kg of coal and 0,3 kg of limestone. Often there is also a small percentage of ferrous steel scrap added, generally about 5% (0,12kg) up to a maximum of 30%, which acts as a coolant controlling excessive temperatures of liquid steel (Worldsteel Association, 2018c).

Iron ores are only naturally found in the form of iron oxides in the earth's crust. In order to create steel, firstly an intermediate product called pig iron is produced. Firstly, the rough iron ores need to be refined by a thermal agglomeration process called sintering in which the fine iron ore particles are compacted into larger agglomerates of approximately 5-50 mm. This sintering process is rather energy-intensive and fuel consumption causes significant CO_2 emissions; roughly 0,24 - 0,33kg CO_2 per kg of sinter. Moreover, the chemical processes also result in significant other environmental impacting emissions of CO, NO_x, SO_2 and particle dust (Dorota Burchart-Korol, 2013; LI et al., 2015). Through the sintering process the permeability and metallurgic properties of the iron ores are significantly increased which is required for effective Blast Furnace (BF) processing (Lu & Ishiyama, 2015). The majority of pig iron is produced from the BF operation. This technology accounts for roughly 94% of the global liquid iron production market (Cramb & Amuda, 2017). In a BF cokes, ores and flux are continuously supplied at the top of the furnace and heated by a forced stream of combustion air causing chemical reactions while particles fall downward. Coking coals are added in the BF process in order to remove the combined oxygen from the ores, a process called 'reduction'. These cokes are a very pure form of carbon which is generally produced by heating metallurgic coal to temperatures around 1100 °C in the absence of oxygen causing the coal to practically melt thereby removing impurities such as hydrogen, oxygen, nitrogen and sulfur. Flux, a purified form of calcium carbonate made from limestone, is decomposed during its descend into calcium oxide and carbon dioxide. The calcium oxide reacts with acidic impurities in the iron and forms fayalitic slag by binding with silica (Cramb & Amuda, 2017). One of the biggest drawbacks in the BF process are the emissions of carbon dioxide associated with the consecutive sintering and smelting process. According to Burchart-Korol these combined processes account for rougly 85% of the associated eCO_2 emissions due to the production of steel (Dorota Burchart-Korol, 2013).

Consecutively pig iron is converted to steel in a Basic Oxygen Furnace (BOF). In this primary steelmaking method the carbon content of the pig iron is reduced by blowing high purity oxygen through a lance over the molten pig-iron. The required thermal energy for this operation is generated by the oxidation process and overall temperature of the mixture is maintained by adding precise and controlled amounts of steel scrap. Modern furnaces have capacities of roughly 400tons of iron which is converted to steel in about 40 minutes. Consequently, fluxes (burnt lime or dolomite) are fed to the mixture producing significant amounts of BOF slag, 100-150 kg per ton of steel slag; a sub-product with high contents of free lime and magnesia. The slag accounts for 15-20% of the total final volume of steel (Fernández-González et al., 2019). In contradiction to BF slag, which can be used as a raw material in the cement industry, BOF slag has very limited applicability due to large fluctuations in quality and composition and therefore most of it is disposed in controlled landfills making it one of the major waste streams of BF-BOF steel production. Finally alloying metals can be added to the mixture in order to enhance the specific properties of the steel.

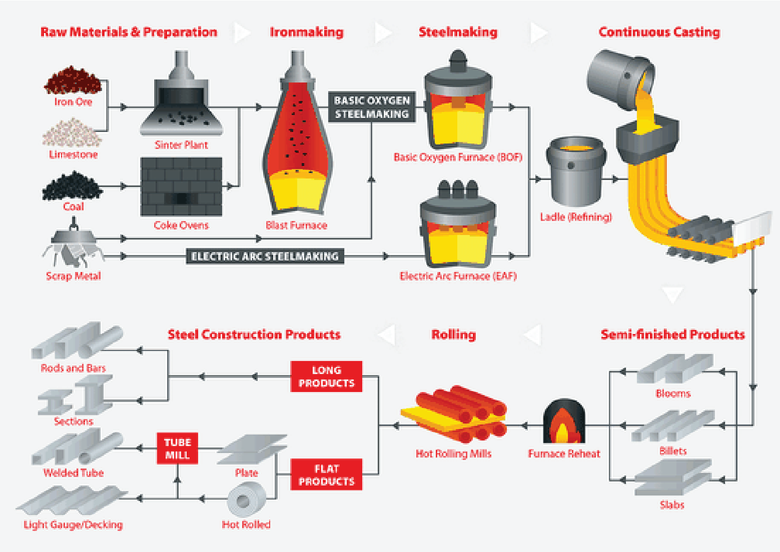


Figure 12: Overview of primary steel production processes (NSC, 2019).

3.1.4. EAF route - recycled steel

The second most important liquid steel production process is the Electric Arc Furnace (EAF) method. It is the most important ferrous steel scrap recycling method and according to Worldsteel 40% of European steel is produced via this secondary steelmaking process (Worldsteel Association, 2018e). Typically EAFs are used to produce, steel structural components and sections, reinforcing steel and small steel items. In general the EAF production method for carbon steel primarily uses non-alloyed steel scrap as input material. The scrap is charged and melted by means of an electric arc between two or three graphite electrodes. A general distinction can be made between obsolete scrap (e.a. cut, shredded and compacted cars and appliances) and industrial scrap (e.a. heavy melt large slabs, beams and billets) which is placed in layers into the EAF baskets. Furnace capacity ranges from 1 – 400 ton of scrap and the average energy consumption for the modern EAF process is estimated to be around 350 kWh/t (Madias, 2014). The EAF production route has a significantly smaller carbon footprint than the primary steelmaking process and requires far lower amounts of energy, roughly only 20-25%, compared to the BF-BOF steelmaking process (Cramb & Amuda, 2017). Moreover, the EAF production process can be rapidly started and stopped where BFs will generally stay in continuous operation for many years for efficiency purposes. The main byproducts of the EAF production process are EAF steel and slag. For every ton of crude steel approximately 100 kg of EAF slag is generated (Madias, 2014). EAF slag is a porous, strong and dense by-product which can effectively be used as an aggregate for asphalt and road surface treatment. However, for every ton of steel also approximately 20 kg of EAF dust is produced. This by-product poses significant environmental concerns as it contains large quantities of heavy metals (Cholake, Farzana, Numata, & Sahajwalla, 2018). Another important problem is dioxin generation during scrap melting (Cramb & Amuda, 2017).

3.1.5. Issues in sustainable steel production

Steel plays an important role in the future of sustainable development. The primary materials needed for steel production are abundantly available in the Earth's crust as noted in paragraph 3.1.1 making it one of the most produced materials in the modern world with widespread applicability throughout various industries. It has great potential as a sustainable material due its inherent durability properties and the fact that it can practically be infinitely recycled without any loss of properties. It can therefore be used over and over again either in its original form or as a completely different product without any loss of quality. This makes steel quite unique as various other materials and products often lose quality when they are recycled, i.e. downcycling, or require additional resources in order to create similar quality products.

The main restraints limiting the development of the steel sector as an increasingly sustainable industry are the high energy costs and vast emissions of carbon dioxide and other pollutants. It is estimated that international iron & steel production is responsible for 4-6% of global anthropogenic carbon dioxide emissions (Carbon Trust, 2011; Columbia Climate Center, 2012; Cramb & Amuda, 2017; Worldsteel Association, 2017a). Moreover, it is an important challenge to improve current production processes with regard to byproduct streams, waste production and emissions of harmful pollutants such as solid waste, toxic gasses and particle dust emissions. According to Worldsteel the industry is continuously investing in technological innovation and process improvement. They estimate that the industry invested 13% of revenue in process improvement and capital investment projects in 2016. The sector has made significant progress in recent years limiting global energy consumption per tonne of crude steel to approximately 39% of the 1960 reference level and a current average of 1.9 tonnes of CO_2 emissions per ton of crude steel produced (Worldsteel Association, 2017b, 2018e). However, it is important to note that the share of recycled steel in the total crude steel production has been increasing annually and will continue to do so in the coming years. This implies that both average energy consumption as well as the global average CO_2 emissions per ton of steel will decline accordingly as steel produced via the EAF process rather than the BF-BOF process has a much lower carbon footprint.

In order to genuinely transform the steel sector into an increasingly sustainable industry, significant progress is still to be made for both the primary BF-BOF as well as the secondary EAF steelmaking as current processes still require large investments of both energy and resources. Steel is already the most recycled material in the world and global recycling rates are improving annually with a global estimated recycling rate of 86% in 2017 (Worldsteel Association, 2018e). However, it is estimated that BF-BOF steelmaking will remain the dominant steel production process at least up until 2050 (Oda et al., 2013). World crude steel production is still growing and the current supply of ferrous steel scrap simply can’t meet the needs of current global steel demand. In 2017 primary steelmaking was still the dominant production process responsible for 72% of global crude steel production (Worldsteel Association, 2018e). Continuation of the historical trend indicates that there will simply not be enough scrap availability for EAF production to surpass primary steelmaking in the next couple decades. It should be noted that the BOF process also requires an average quantity ferrous steel scrap of approximately 15% for cooling purposes as noted in paragraph 3.1.3. Also taking these scrap requirements in account for ore-based steelmaking indicates that a total of about 40% of the world’s steel production consists of scrap (Björkman & Samuelsson, 2014).

Modern steel plants operate at almost their maximum capacity, according to practical thermodynamic energy efficiency limits, for currently used technologies. Moreover, in recent years a lot of progress has been made with regard to heat and energy recovery from recirculation of process exhaust gasses. Innovation therefore mainly focusses on adaptation of the current BF-BOF processes and is looking at options for possible replacement of cokes and coal in the iron ore reduction processes to cut CO_2 emissions. Currently there are various research projects targeted at using hydrogen as a reducing agent replacing carbon (coal). The reaction of iron oxide with hydrogen gas only produces water vapour. The hydrogen reduction process unfortunately requires 4-5 times the energy currently needed so it is vital to first secure a carbon-free energy source for the production process before this technology can actually be implemented. Furthermore, various options are explored for the capture and storage of carbon dioxide, such as Carbon Capture and Storage Technology (CCS), so it can effectively be used for other purposes (Worldsteel Association, 2018d). An example is the Hiserna technology which has been successfully tested by TATA steel in Ijmuiden over 2018. The Hiserna installation consists of a pig-iron production reactor which produces 20% less CO_2 and 60-80% less particle dust, SO_2 and NO_x (TATA steel, 2018). The gas which is emitted has a much higher concentration of CO_2 making the exhaust gas well suitable for CCS.

The most important drawbacks for the EAF process are related to electricity generation, which is generally still produced from fossil-fuel resources, and the issues with the current collection and sorting processes for recycling. Steel scrap is only rarely sorted for the various different alloys that exist in the market, therefore the recovery of alloyed steels of the same quality is practically impossible and the trace metals that exist in alloyed steels are often lost in the recycling process (Björkman & Samuelsson, 2014; Braungart, 2018). This makes the recycling process much less adequate as high-grade steels are largely down-cycled and made into low-grade non-alloyed carbon steel such as rebar or structural steel profiles. The current global consumption rate, and our inability to recover rare earth metals from alloyed steels, will ultimately lead to global depletion of these rare earth elements in the near future as illustrated in **Figure 13**.

Figure 13: Indication of the depletion rate of rare earth elements – adapted from: A. Reller & T. Graedel (2009)

Another important issue is the possible radioactive contamination of recycled steels due to possible recycling of waste material from decommissioned nuclear installations. Occasionally scrap from decommissioned steel products from nuclear installations is found in EAF and BOF cooling scrap feed. In case this contaminated scrap is not detected and discarded end-products will be contaminated, potentially emitting intolerable levels of radiation energy. This poses significant health and safety risks for end-users or other people along the supply chain who come in contact with the contaminated scrap or final products. According to Steele and Murgatroyd China, who is the world's leading steel producer and scrap importer, does not monitor steel scrap for contamination. They highlight that especially structural steel profiles and steel reinforcement are at risk since these are mainly produced through EAF production. Both product categories are classified as high risk due to the world wide trading in steel and their high scrap content (Brooks, Gaustad, Gesing, Mortvedt, & Freire, 2019; Steele & Murgatroyd, 2010). Most European steel producers have radioactive contamination monitoring equipment installed to check the scrap feed of their processes. This was underpinned by an employee from Tata steel who indicated that in recent years they have started “strictly monitoring the scrap input for their BOF cooling process of their steelplant in Ijmuiden for radioactive contamination”.

3.2. Potential for structural steel reuse in the Dutch building industry

According to various authors, the reuse of structural steel is a widely overlooked end-of-life strategy which could offer significant benefits in making the steel industry increasingly sustainable. Although structural steel is already being recycled to a very large extent, with global steel recovery for the construction industry estimated at 85% and almost a 100% for the developed world (Worldsteel Association, 2018c) there is still room for improvement as the recycling process still requires significant energy resources. There is general consensus on the fact that the reuse of structural steel components, that are retrieved through systematic deconstruction of old buildings, in new structural designs could drastically lower the embodied carbon footprint of these buildings with a primary steel construction (Densley Tingley et al., 2017; Dunant et al., 2017; Iacovidou & Purnell, 2016; Sansom & Avery, 2014; Tingley & Allwood, 2014).

However, current measures primarily focus on improving the deconstruction process for future buildings (Akinade et al., 2017; Densley Tingley & Davison, 2012; Eckelman et al., 2018) rather than facilitating the use of circular components in current buildings designs. Although DfD does provide a means to reduce material waste at the end-of-life, this design strategy does not contribute to reducing the embodied carbon content of newly designed buildings. The latest special report by the IPCC once again emphasized the need for immediate climate action (Allen et al., 2018a). Therefore, it is essential that we also find new and innovative ways to improve reuse ratios of structural steel elements for the current building stock in order to reduce GHG emissions associated with the building industry. Various authors have been concerned with identifying the main barriers and opportunities for structural steel reuse and have tried to provide a framework of the most important. In the following paragraphs an overview will be provided of the most important barriers and opportunities for structural steel reuse on an organizational or meso level for various key actors along the supply chain. Moreover, specific enabling conditions that currently exist for the Dutch building industry will be discussed.

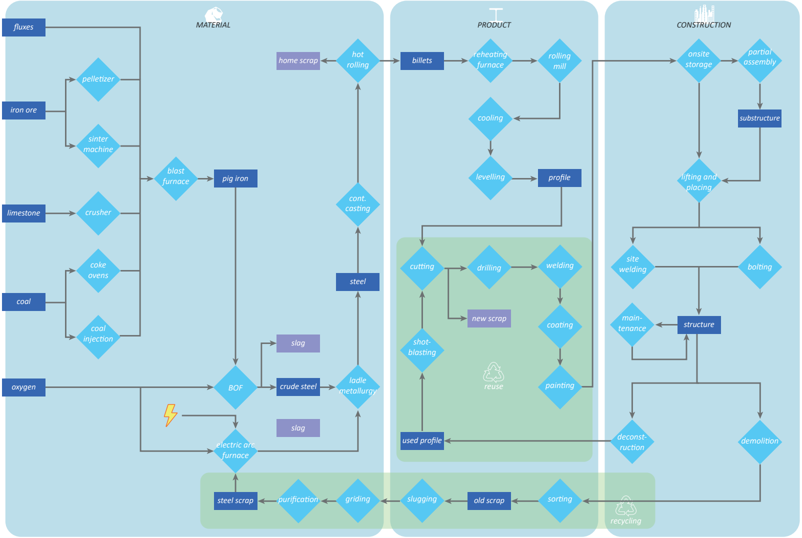


Figure 14: Overview of structural steel value chain and the reuse and recycling process scope.

3.2.1. Barriers for structural steel re-use

In order to identify the major bottlenecks limiting the development of a re-use market for circular steel profiles in the Netherlands, and to understand where in the national steel construction value chain changes are most likely to lead to improvements, an initial framework of potential barriers is constructed. Literature reviews on potential barriers for reuse on an organisational level, from the fields of Design for Disassembly and Reverse Logistics are combined with outcomes from studies on the industry specific barriers preventing reuse for various actors in the structural steel value chain in the UK. A research group under Prof. Julian Allwood, focused on material demand reduction, at The Department of Engineering of the University of Cambridge has been investigating the potential of structural steel reuse in the UK. In collaboration with various industry professionals this research group has published several studies in recent years on the perceived barriers to structural steel reuse in the UK, identification of the potential costs and risks associated with reuse, and how to overcome current practical barriers. Although the structural steel industry in the UK and the Netherlands are not identical and reciprocal differences are bound to exist due to differences with regard to norms, habits and industry structure (Dunant et al., 2017), there are also significant similarities due to the strongly international character & maturity of the structural steel market, the modularity & standardization of components and European-wide legislation. The outcomes of these studies can therefore provide a useful initial framework of potential barriers and opportunities which is evaluated and corrected for the Dutch building industry.

As this study is specifically targeted at improving the current structural design and engineering practice it is important to identify the meso level barriers that exist for the various actors in the value chain. For this purpose, various studies have been used to collect potential barriers and to build an extensive list (Akinade et al., 2017; Densley Tingley et al., 2017; Dunant et al., 2017; Hosseini et al., 2015; Kirchherr et al., 2018; Mahpour, 2018; Rios et al., 2015). The obtained barriers are subsequently evaluated and attributed to one or more specific actors that would likely operate in a steel reuse supply chain. This comprehensive list can be found in **Figure 15**. According to Dunant et al. there is a significant difference between real and perceived barriers to structural steel reuse (Dunant et al., 2017). However, as both the real and perceived barriers hinder the development of a circular steel market both typologies will need to be addressed in order to create a climate in which a reuse market can develop.

From the specific influential factors found for the structural design & engineering discipline it can be concluded that there is a sense of fear that the current practice will likely have to change in order to facilitate the incorporation of circular elements in new designs. One option to overcome this barrier would be to demonstrate that the tool under development would not significantly impede the current design process at structural engineering firms.

After compiling the list the various barriers were evaluated according to the fact if *quantifying the environmental benefits of reuse* would contribute to overcoming these obstacles. The factors for which it is deemed possible that this will lead to alleviation of the barriers are highlighted in the figure below. It can be concluded that addressing the issue, of accurately measuring the environmental benefits of reuse, will help to negate barriers for several actors that prohibit the development of a circular steel market.

				Cruz Rios et al., 2015	Densley Tingley et al., 2017	Akinade et al., 2017	Dunant et al., 2017	Kirchherr et al., 2018	Mahpour, 2018	Hosseini et al., 2015
identified barriers	MESO (organisational)	clients	long lifespan buildings/changes in ownership			x			x	x
			lack of facilities/services for recovery and storage	x					x	x
			consumer preferences, taste and perceptions	x	x				x	x
			reuse perceived as more expensive / low virgin material prices				x	x	x	
			possibility of delays due to increased complexity				x		x	
			difficulties in procurement and legal obstacles to obtain insurance				x			
			high upfront investment costs					x		
		architects	visible (aesthetic) degradation of steel	x	x		x			
			limited availability of materials	x						
			higher design costs / limited budget		x		x			
			lack of experience / training	x		x				
			possibility of delays due to additional complexity				x		x	
			spatial limitations due to limited product supply				x			
		structural engineers	lack of contract clauses that favour building material recovery and reuse			x				
			buildings are not designed for dissassembly by the architect				x			
			lack of, or impracticality imposed by standards, codes and guidelines	x	x	x		x		x
			limited availability of materials / non-availability of required dimensions	x			x			
			higher design costs / additional complexity		x		x		x	
			lack of experience / training	x		x				
			restrictions with regard to possible jointing techniques							
			simpler and more cost-effective to rely on standard specifications				x			
			time-constraint / 'could do a better job if they had more time'						x	
		main contractors	certification				x			x
			non-availability of materials	x						
			logistics; traceability issue / wide variety of origin points							x
			liability and risk		x		x		x	x
			competition		x					
			limited recognition for deconstruction in sustainability appraisal			x	x		x	
		demolition contractors	building not designed for disassembly / lack of information, guidelines and	x	x	x	x		x	x
			composite construction	x	x	x				
			jointing technique / inaccessibility joints	x	x	x				
			size and weight of building components	x		x				x
			extra time, resources and labour costs for deconstruction	x	x	x				x
			time constraint / tight scheduling	x	x				x	x
			health & safety risks / use of hazardous substances	x	x	x				x
			low costs for disposal of materials	x					x	x
			training expenses	x						
			higher costs for worker insurance	x	x					
			necessity of having suitable storage area on-site	x					x	x
		stockists	perceived risk						x	
			limited demand for reused materials, regional & long storage time	x	x					
			size of building components	x		x				x
			transportation costs	x						
		fabricator	reconditioning costs		x					
			liability and risk of recertification	x	x	x				x
			no perception of added value					x		
			low price of steel scrap		x					

Figure 15: Barriers on a meso level derived from literature allocated to specific actors in the supply chain

3.2.2. Enabling conditions: Initiatives in the Dutch building industry in support of CE transition

As discussed in paragraph 2.1.6 CE has become an increasingly popular topic of debate over the past five years in the Netherlands. As legislation in support of CE is starting to be implemented and financial incentives and subsidies are made increasingly available by both national and regional government (Dutch Ministry of Environment & Ministry of Economic Affairs, 2016; Gemeente Amsterdam, 2018), circular initiatives are starting to penetrate the Dutch consumer market. At the forefront of the Dutch CE building industry transformation are several initiatives and commercial companies, e.g. Madaster, Excess Material Exchange or BAMB, which aim to re-imagine buildings as material banks; depots offering large quantities of useful resources at the end of their life rather than being an assembly of various waste materials. By collecting vast amounts of detailed information on buildings, and the inherent components they are comprised of, these ventures aim to provide material passports; documents listing all materials included in a specific building construction. These material passports are collected in an online database which can be accessed by various third parties potentially interested in these materials. Linking these parties could potentially aid in closing material loops by diverting potential waste streams from landfill.

As design professionals in the building industry increasingly use Building Information Modelling (BIM) to generate, exchange and manage building design information, accurate digital representations of these physical buildings are available even before these structures get built. Various authors have indicated that increased BIM implementation could hereby improve building lifecycle management and it could enhance identification of recoverable materials at the end-of-life (Akanbi et al., 2018; Akinade et al., 2015; Ness et al., 2015). This provides an interesting opportunity for the beforementioned startups, as they would be able to rapidly build extensive databases of recently realized buildings stock, if they can get access these BIM models.

Although these initial CE related ventures seem to be mainly concerned with BIM data gathering for the purpose of material mapping and component tracking, successfully establishing these databases will likely stimulate the development of a market for used building materials and components. As described by Dunant et al. in order to build a business case for the reuse of structural steel components, a specialized actor should be introduced in the supply chain bearing responsibility for procurement, storage, remanufacturing and redistribution of steel elements (Dunant et al., 2018). According to Ness et al. the introduction of BIM modelling and tracking methods will improve identification and traceability of recoverable materials and could thereby open up new business opportunities for such specialized actors (Ness et al., 2015).

Legislative measures, such as tax on resources or emissions which is increasingly speculated on will likely stimulate the development of new circular business models further (The Ex'Tax project et al., 2016). There is a current trend in the Netherlands of products which are offered as a 'Product as a Service' in which the producer bears responsibility for his product rather than the end user. The manufacturer offers the consumer a product which he is free to use, as long as he pays a recurring service fee, but the product will remain property of the manufacturer. Thereby the producer is increasingly concerned with repair and maintenance thereby extending the product lifetime and he will be more inclined to pursue efficient recycling and reuse. Several business models based on this principle are currently being rolled out for the building industry such as Philips offering ‘Light as a Service’ and Ikea offering furniture as a service. If these business models prove successful this could potentially open up new business opportunities for the building industry, possibly also for the steel industry. Furthermore, circular incentives such as the initiative of various municipalities around Amsterdam to specifically incorporate circularity aspects as part of their tenders, will likely further stimulate reuse market development as procurement competition will not primarily be driven by economics but will also include a circularity or sustainability component. Design professionals will have increased incentive to include a predefined ratio of circular components as part of their bids.

3.3. Key bottlenecks

This paragraph will discuss several key barriers identified by the literature study that currently prevent the disassembly of structural steel construction works and the reuse of structural steel elements in new building structures in the Netherlands.

3.3.1. Attitudinal

Although the construction industry is generally reluctant to change, it seems that the topic of CE has also caught the interest of both national and international branch organizations for the steel industry. For example, on the 10th of September 2018 Worldsteel organized a Circular Economy Conference in Brussels and Bouwen met Staal organized an innovation session ‘Circular Constructions in Steel’ at the BouwBeurs on the 7th of February 2019 (national building industry fair). During one of the presentations here, TATA steel Ijmuiden indicated it acknowledges the targets laid down in the Paris agreement and that they intend to become completely carbon neutral by 2050. Although it can be questioned how realistic these statements are and if this target will actually be met it does indicate that efforts will be made to further reduce emissions and pollution due to the steel production process.

The current zeitgeist makes the future of the steel industry 50 years from now quite unpredictable. If steel producers succeed in becoming carbon neutral by 2050 this would imply that the environmental impact post service-life for new structures would be negligible as recycling will become the dominant end-of-life scenario and the associated environmental impact will become insignificant. Although the future of the steel industry is quite uncertain there are positive signs that it will become increasingly sustainable in the coming years. It should be noted that DfD and the reuse of elements will become less interesting from an environmental viewpoint as recycling becomes increasingly sustainable. Therefore it can be concluded that preference should be given to developing a circular business model for the current market conditions rather than designing for a future scenario which is to a large extent uncertain.

Limited client demand was also frequently found across literature as an important attitudinal barrier preventing structural steel reuse. However, the current market conditions in the Netherlands actually seem quite favorable of structural steel reuse as CE targets are being increasingly incorporated in design briefs. This trend is witnessed on a national governmental procurement level but is also supported by example the municipality of Amsterdam who wants to be a frontrunner in the field of CE. This invites design professionals in the building industry to experiment with circular alternatives to traditional building methods and provides an opportunity to improve the current practice with regard to sustainability.

3.3.2. Financial

Another important aspect is the economic feasibility of structural steel reuse. It is often estimated that disassembly of structural elements will require significantly more time and effort than BAU with regard to demolition practice (Dunant et al., 2018). However, the additional financial investment in the disassembly process is generally negated by the price difference between used components and new steel. When the issue of disassembly was discussed with national steel contractors it was indicated that given the right circumstances; for example the disassembly of a warehouse, disassembly would require less effort than the construction process. This could indicate that the often coined financial barrier for deconstruction might be a perceived barrier rather than an actual critical factor. Other important factors that influence the cost of reuse are storage, remanufacturing and testing. However, as the market will mature on the long run these processes will become cheaper over time. The study by Dunant et al. showed that steel reuse under the current conditions is not much more expensive than using new steel. They indicate that the distribution of risks is the primary barrier rather than the economic feasibility of structural steel reuse (Dunant et al., 2018). The idea of including environmental costs in the selling price as discussed in paragraph 3.2.2 could stimulate a reuse market by eliminating the price difference between the current practice and reuse or it could even make reuse the more economically attractive option.

3.3.3. Structural

Several structural barriers exist that prevent the adoption of structural steel reuse. From the literature study it can however be concluded that the key bottleneck seems to be the availability of information. Frequently mentioned barriers are *lack of awareness of environmental consequences*, *lack of communication within the value chain* and *unawareness of the benefits of reuse*. The shortage of quantitative data on the potential risks and benefits of reuse has been indicated as an important barrier in various studies (Araujo Galvão et al., 2018; Densley Tingley et al., 2017; Kirchherr et al., 2018; Rios et al., 2015; Tura et al., 2019). Additional research on this topic could improve the current understanding of the risks and benefits and alleviate some of these barriers.

The public image of reuse might also be an important bottleneck. As the failure of civil structures can have disastrous consequences potentially leading to injuries or fatalities, the reuse of structural steel elements is a sensitive topic for the general public. People tend to identify the term ‘reuse’ with ‘decreased quality’. It will therefore require additional effort to convince the general public that these products are consistent with the quality of new products but with the added value that circular elements have a significantly lower environmental impact. As the general public depends on governments for legislation, there is an important role for policy- and decision makers in providing accurate and transparent information on the benefits and drawbacks of reuse in order to positively influence the public opinion. Furthermore, the current popularity of the concept of CE could prove to be useful in marketing the reuse of structural steel elements by labeling used components as ‘circular’. By doing so the general opinion on used building products might be improved in the same manner that ‘vintage’ implies a higher quality that the term ‘second-hand’.

3.3.4. Operational

In order for reuse to become an effective well establish end-of-life strategy for structural steel profiles in the Netherlands, firstly this market will have to mature implicating changes along the construction value chain and the introduction of new specialized actors. It is important that a single party will take responsibility for the acquisition, testing, reconditioning and redistribution of reused elements (Dunant et al., 2017). Dunant et al. have indicated that specifically the operations of steelwork contractors and stockists will have to change in order to facilitate a reuse market for structural steel elements. Moreover, it will be likely that new business models should be developed in which reservations for certain components are made in an early design stage. As demand for circular profiles is still low at this point, the storage of elements is rather costly. Under current market condition it is therefore more economically feasible to have a storage facility in a rural area as concluded during a site visit to A. van Liempd in St. Oedenrode, **Figure 16**.

Figure 16: Temporary storage of circular building materials in St. Oedenrode – site visit A. van Liempd 18/05/2018

3.3.5. Technological

Another often indicated barrier are the specific remanufacturing needs for used elements. During site visits to various steel contractors & manufacturers, this concern was discussed. It was indicated that it would require minimal extra processing compared to new steel. Removing excess material from used elements, such as sheer studs or continuity plates, can be done fairly easily and fast by hand and nearly all other manufacturing processes, such as cutting, drilling, endplate welding, sandblasting and coating, would be consistent for new steel. Furthermore the steel manufacturing process has become increasingly automated in recent years significantly reducing labor and time requirements. Some steel manufacturers even use fully automated assembly lines capable of cutting, drilling, marking and even welding as illustrated in **Figure 17**.

The problem of verifying the structural capacity and mechanical properties of structural steel elements post service-life poses another issue. Although steel products have excellent durability characteristics, primary load-bearing elements have to adhere to strict rules and guidelines with regard to structural safety and reliability as discussed in paragraph 3.1.2. In order to ensure that mechanical properties of used products are still within the predefined acceptable limits of newly produced steel elements, it seems inevitable to introduce testing procedures. Another option would be to introduce certain safety factors into structural designs which incorporate circular steel members taking into account that these used products will likely have anomalies and/or deformations with certain specified limits.

Possible degradation mechanisms for steel are corrosion, deformation (due to example demolition) and plasticization due to vibrations (such as earthquakes). Fujita et al. have proposed several non-destructive testing procedures, such as ultrasonic hardness test and chemical composition testing, that could be introduced in order to ensure mechanical properties are still sufficient (Fujita & Masuda, 2014). Technological advances in the field of computer science such as deep learning algorithms could potentially provide more economical damage assessment methods in the future as indicated by Liu & Zhang who proposed an image-driven structural steel damage condition assessment using deep learning algorithm (H. Liu & Zhang, 2019). Moreover, research by Ness et al. has pointed out that other technological advances in the more established field of BIM such as digital tracking and modeling could potentially offer perspectives for new business opportunities for the circular building product market (Ness et al., 2015).

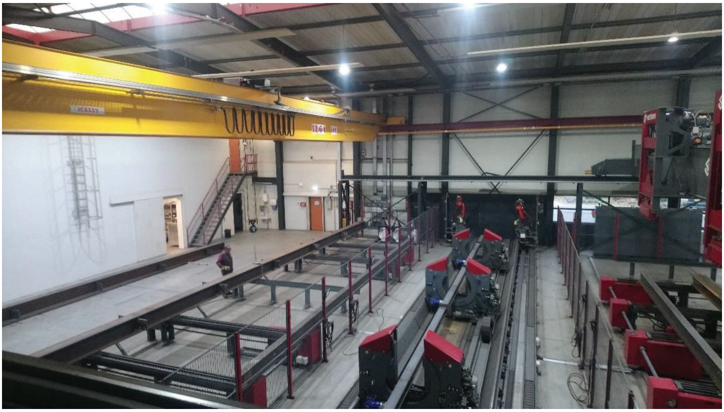


Figure 17: ‘The Fabricator’ a fully automated assembly line by Voortman – site visit Voortman 20/11/2018

3.3.6. Legislative

The main legislative bottleneck for deconstruction is currently the necessity of providing CE-certificates for any new steel construction works which are to be built. Currently the branch organization for the steel industry in the Netherlands, Bouwen met Staal, is investigating how testing and recertification procedures for used structural steel elements could be developed. They advise to keep a record of all documentation related to steelworks.

3.4. Quantifying environmental benefits

In the previous paragraphs various barriers and bottlenecks, preventing the development of a circular steel market, have been discussed. Research has pointed out that several of the identified barriers might however be classified as perceived barriers as no quantitative data was found in support of these claims. It could be concluded that there is a lot of fear and perceived risk associated with the reuse of structural steel elements. Expanding the body of research and available information on the topic of structural steel reuse could potentially alleviate some of these barriers. According to various studies empirical demonstration of the environmental benefits of structural steel reuse is limited (Araujo Galvão et al., 2018; Densley Tingley et al., 2017; Kirchherr et al., 2018; Rios et al., 2015; Tura et al., 2019). However, there does seem to be general consensus on the fact that reuse as a design strategy for structural steel building structures will lead to a significant reduction in greenhouse gas emissions and other harmful pollutants. The desktop study on CE and structural steel reuse which was carried out, has brought to light that there is currently limited academic research in support of this claim proving the expected reductions.

From paragraph 2.1.1, 2.1.5 and 2.1.6 it could be concluded that the concept of CE is gaining in popularity. Legislation on both a European and a national level is increasingly targeted towards stimulating circular initiatives. It is expected that successful development of a method to accurately quantify the environmental advantages of reuse will help to overcome several of the current barriers and will stimulate the development of a market for circular structural steel products.

3.5. Conclusions and recommendations

From the previous paragraphs on the properties of structural steel and the international steel industry the following conclusions and recommendations can be made:

- It was concluded that the outstanding mechanical properties of steel in combination with excellent durability & recyclability make *steel a promising circular material* in a future CE.
- The steel industry is a highly globalized industry in which both raw materials and final products are transported over large distances around the globe. China has by far the largest share of crude steel production and the majority of the steel produced here is virgin material. *Europe mainly produces EAF steel and production processes are considered to have less environmental impact than those of Asian facilities*.
- Although there is general consensus that *reuse could greatly reduce global environmental impact due to steel production*, the reuse of steel products is still a rare practice. It is recommended that the possibilities for reuse should be improved and that the reuse of structural steel elements should be considered as a serious option.
- The environmental impact of virgin steel production (BF-BOF) is considerably higher than the production of recycled steel (EAF). As the EAF process primarily requires scrap metal and electricity as input the *energy transition towards renewable resources will gradually reduce the impact of the EAF process*.
- Although significant progress has been made in recent years in reducing the environmental impact of virgin steel production. The BOF process still causes significant strain on the environment. *Possible further improvements for BF-BOF are targeted towards direct processing of iron ore* omitting the need to manufacture agglomerates. This could potentially further reduce the CO_2 emissions of the BOF process by 50%.
- An important downside to the recycling of steel is the current lack of sorting for various alloys. As all sorts of steel products are mixed together to produce scrap, the valuable rare earth elements that were added to specific alloys are lost in the recycling process. These additives are extremely scarce and rare, it is thus recommended that the steel industry should improve sorting capabilities to salvage these metals during recycling.
- There are various barriers in place preventing steel re-use. Among the most dire issues are the need for new business models & specialized actors, lack of standardized testing procedures and *demonstration of the financial feasibility and environmental benefits*.
- Several key bottlenecks were identified and categorized as *attitudinal, financial, structural, operational, technological or legislative*.
- It can be concluded that *accurately measuring the environmental benefits of reuse, will help negate barriers* for several actors prohibiting development of a circular steel market.
- It is to be expected that the steel industry in Europe will be making efforts in reducing the environmental impact of its processes. Therefore, on the long run recycling will become an increasingly interesting end-of-life scenario. It is therefore *recommended to focus on re-using structural steel components NOW* rather than designing buildings for disassembly that won't be deconstructed in the coming 50-100 years.

4 Environmental Impact

Chapter 4 will elaborate on the methods frequently used to assess the environmental impact of buildings and building products. A critical review of the most popular sustainability and circularity assessment tools for the Dutch market is conducted providing insight with regard to the effectiveness and limitations of these methods. The potential of the underlying metrics to evaluate complex systems is discussed and the most suitable set of metrics that accurately describe the environmental impact for structural steel products will be defined. Concludingly the process of monetarizing and aggregating the environmental impact for the individual categories to construct the total environmental cost will be discussed.

4.1. Establishing a sustainable selling price

As discussed in paragraph 2 our current linear economical system is inherently flawed and a paradigm shift towards an inclusive, cyclic economic system is necessary to ensure that the current planetary balance is maintained. Various institutions have opted to establish sustainable selling prices for goods and services by means of legislative measures that shift taxes from labor to taxes on resources and emissions (The Ex'Tax project et al., 2016). Doing so will stimulate circular business models for structural steel reuse. By ensuring that the use of virgin resources becomes increasingly expensive relative to reuse it will open up the market for new business models as reuse becomes more attractive from an economic perspective. The concept of adding external costs to the selling price is indicated in **Figure 18** below.

Figure 18: Adding external costs to the selling price of products in order to improve sustainable practice

The following paragraphs will elaborate on how valuating external costs could prove to be a valuable tool in ensuring that the Netherlands meets emission reduction targets as agreed upon in national as well as international legislation.

4.1.1. Emissions Trading

One of the first attempts by the EU, in curbing pollution by providing economic incentives for reducing emissions, was the European Union Emissions Trading System (EU ETS) an international market-based approach launched in 2005 by the United Nations Framework Convention on Climate Change (UNFCCC). Targets are expressed as levels of allowed emissions and divided between the EU member countries. Emission rights can be sold by countries which have excess capacity to other countries which have under capacity (United Nations Framework Convention on Climate Change, 1997). The European Union Emissions Trading System (EU ETS) was the first large GHG trading scheme in the world and remains the biggest up to date.

4.1.2. Paris Agreement

As mentioned in paragraph 1.1 The Intercontinental Panel on Climate Change (IPCC) has indicated that it is crucial to limit global warming to 1.5 °C above pre-industrial levels as a further rise of planetary temperatures will have a disastrous impact on natural, managed and human systems on a planetary scale (Allen et al., 2018b). The international community acknowledges these reasons for concern and the vast majority of world leaders have committed to significantly reduce national greenhouse gas emissions by ratifying the United Nations' Paris Climate Agreement in 2015 (UNFCCC, 2015). The Paris Climate Agreement urges countries to make a maximum effort to significantly lower greenhouse gas development over the coming decades limiting anthropogenic global warming to a maximum of 1.5 °C above pre-industrial levels. Moreover, during the United Nations general Assembly in 2015, member states agreed to Resolution 70/1 which laid down 17 ambitious goals (UNSDGs) for 2030 that address the major global sustainable development challenges (United Nations General Assembly, 2015). Consequently, the European Union has issued the 2030 climate & energy framework which laid out key targets for the year 2030 including a 40% reduction of GHG emissions, from 1990 levels (European Council, 2014a).

4.1.3. Dutch Legislation

Moreover, in June 2018 the Dutch House of Representatives has passed a bill which mandates a 95% reduction of GHG emissions by 2050, with respect to 1990 reference levels (Klaver et al., 2018). On the 9th of October 2018, the Hague Court of Appeal upheld the judgement of the District Court in Urgenda's Climate Case of 2015. This judgement confirms that the Netherlands is obligated to reduce its national GHG emissions by 25% before 2020 under national law (The Hague District Court, 2018).

4.2. Measuring the Environmental Impact of Materials and Products

The building industry is responsible for a large share of global GHG emissions. It is therefore of utmost importance that the industry continuously improves production methods and comes up with innovative solutions in order to reach global sustainability goals. To do so we need to be able to accurately determine the life-cycle impact of building products and constructions so we can identify the most influential factors with regard to environmental impact. In order to accurately represent complex systems and to empirically assess the environmental impact of materials, components or products a wide range of metrics need to be considered in order to effectively evaluate processes and products. This often involves extensive, time-consuming analysis and can generally only be conducted by specialists in the field of environmental studies and life cycle assessment.

4.2.1. Key Metrics for measuring environmental impact

As mentioned by Iacovidou metrics should at least meet three generic criteria; in the first place metrics need to be measurable, either quantitively or qualitatively. Secondly, there needs to be general consensus on the risk and impact associated with the metric and thirdly the metric should be relevant for the specific environmental evaluation at hand (Iacovidou et al., 2017). Measurements should always be verifiable, transparent and unambiguous. Where possible, datasets should be made available by manufacturers and producers and should include all factors that affect our environment such as resource use, emissions, transportation, energy consumption and water consumption for the entire life-cycle of products from cradle to grave. An initial framework of relevant metrics for the structural steel production process can be derived from environmental literature and environmental techniques such as Life-Cycle Assessment.

4.3. Legislation on emissions and environmental impact

Type III environmental declarations are voluntary and it is not mandatory for manufacturers or companies to disclose environmental information with regard to their products and production processes to the general public. However, companies do have to adhere to national and international legislation with regard to maximum emissions and non-financial statements in order to obtain permits.

4.3.1. Industrial Environmental Disclosure

On a European level environmental requirements and operating conditions for the industry are laid down in the Directive Industrial Emissions 2010/75/EU. It requires companies to have an environmental permit issued by the government before installations can be put into service and it requires them to file for an additional permit in case changes are made to the existing process (European Council, 2010). Industrial companies in the Netherlands also have to abide to national legislation such as the *Activiteitenbesluit* and *Wet Milieubeheer* in which measuring procedures are described and maximum emissions for certain greenhouse gasses and other pollutants are listed. However, this only requires companies to prove to the government that emissions are within certain margins and this obligation therefore does not provide an incentive for companies to invest in sustainable innovations beyond compliance. Information with regard to environmental impact such as resource use and emissions is only disclosed to the responsible government entity and not available to the general public. This non-transparency complicates scientific research and hinders change towards a more sustainable global economy.

Moreover, the building industry relies heavily on international trade and products generally consist of materials or sub products that originate from outside of the European Union. Countries outside of the EU abide to different rules and regulations. This can lead to large uncertainties with regard to the environmental circumstances under which products have been produced.

4.3.2. Corporate Environmental Disclosure

It has been historically mandatory for companies to provide full, accurate and timely disclosure of information on a range of financial subjects however corporate environmental disclosure has generally been largely voluntarily. In order to stimulate sustainable development, governments are now increasingly developing requirements for corporations covering environmental, social and governance issues. For all member states of the European Union from 2018 onwards Directive 2014/95/EU is in effect requiring companies to include non-financial statements in their annual reports. As mentioned by the European Council: “disclosure of nonfinancial information is vital for managing change towards a sustainable global economy by combining long-term profitability with social justice and environmental protection.” (European Council, 2014b). Although, the EU directive now requires large companies to publish reports on non-financial policies, it also allows for significant flexibility in the information they disclose. In order to accurately quantify environmental impact and to put it on the balance sheet it is necessary to establish legal requirements as regards to the extent of this information as company transparency rarely goes beyond compliance. Research indicates that merely 28% of companies in the Netherlands measure their carbon dioxide footprint and there seems little consistency with regard to the method used in doing so (Bijlo, 2018).

4.4. Life-cycle analysis

Life-cycle Assessment (LCA) is a general systematic analysis methodology used for evaluating the environmental impact associated with all stages of a material, component or product’s life from material extraction to disposal (or reuse / recycling). By quantifying all input and output flows of material and energy for the various life-cycle stages a compilation and evaluation is constructed for the total life cycle of a product. It is an internationally used methodology to improve industrial processes and products with regard to sustainability and is also a popular assessment tool in the building industry.

4.4.1. Life-cycle assessment in the building industry

LCA is also frequently used in the building industry for assessing the energy consumption and environmental impact of buildings and to quantify their sustainable properties. It provides designers and decision makers with an analytic evaluation method for assessing environmental benefits and impact. By listing all the various building products and materials from which a design is composed and by combing individual LCA outcomes of products from a database, an overview can be compiled of the total environmental impact of a structure. The methodology is often used to compare different options and to quickly evaluate several alternatives of a design in terms of sustainability.

As Vogtländer explains, there is a distinct difference between this so called ‘Fast Track’ approach, where the output of individual LCA studies provides the input for an LCA of a larger assembly of different products, and the formal ‘classical’ approach laid down in ISO 14040. The classical LCA approach is an extensive, time-consuming and expensive effort generally performed by scientists and professional LCA consultants and it can take up to 2-3 months to conduct (Vogtländer, 2010). It starts from scratch and aims to quantify all mass and energy inputs and outputs in a well-organized, unambiguous and transparent way, in order to determine the required material resources and environmental impact. It starts with an explicit statement on the goal and scope of a system and includes technical details on the functional unit, system boundaries, assumptions and limitations, allocation methods and impact categories (International Organization for Standardization, 2006b).

As buildings consist of all kinds of materials, components and products and there are countless inherent processes it would be an insurmountable task to do perform an LCA using the ‘classical’ approach. The ‘Fast-Track’ method is specifically focused on evaluating design alternatives and essentially combines the results of LCA’s produced by third parties. This approach is therefor much less time-consuming as it takes only 2-4 hours if all the required information is available. Users are generally not interested in the specific details of the individual underlying LCAs and want to spend a limited amount of time on life-cycle analysis. They are mainly interested in results and not in formalities and deliberations on accuracy (Vogtländer, 2010).

However, buildings are distinctive, complex structures that consist of many different materials, components and products. They are generally large, site dependent and their realization involves many different manufacturing, transportation, fabrication, and construction processes. Their inconsistent and unique character makes it difficult to accurately and objectively quantify their total environmental impact. Quantitative data on the environmental impact of building products is generally limited to the production phase as the system boundaries for building product analysis typically consist of a cradle-to-gate approach. Information on the consecutive construction, use and demolition & processing phases is therefor often unavailable (Abd Rashid & Yusoff, 2015).

The validity of the results on the one hand depends on the integrity of the end-user as he is flexible in his specific choice of input data. And on the second hand the ‘Fast-Track’ approach depends heavily on the availability and accuracy of third party LCA data available from extensive product databases (e.g. GaBi, Ecoinvent, Nationale Milieudatabase, USDA). What if information on a specific building product is not yet available? Or what if there are multiple LCA’s for a specific product but there are considerable differences between them? In order to guarantee that the outcome of a fast-track LCA is accurate, non-misleading and unambiguous a critical review of the underlying source data is therefore crucial.

4.4.2. International Standards for LCA

The formal principles and framework of a ‘classic’ LCA are laid down in ISO 14040:2006 as part of the ISO 14000 environmental management standards. This international standard provides an outline of the key procedures and states that an LCA should be carried out in four distinct interdependent phases; goal and scope definition, inventory analysis (LCI), impact assessment (LCIA) and the interpretation phase. It also describes the procedures for reviewing and reporting and provides a framework on how to denote conditions for use, relationships between the different phases and the LCA limitations (International Organization for Standardization, 2006b). Additionally, the specific requirements and guidelines for the different LCA phases are laid down in ISO 14044:2006 (International Organization for Standardization, 2006c). The complexity and uniqueness of buildings makes it hard to formulate a standardized methodology for LCA research in the building industry. However, a general LCA framework for the building industry is illustrated below as proposed by Abd Rashid and Yusoff (Abd Rashid & Yusoff, 2015). This framework illustrates the general process needed to conduct an LCA for the building industry.

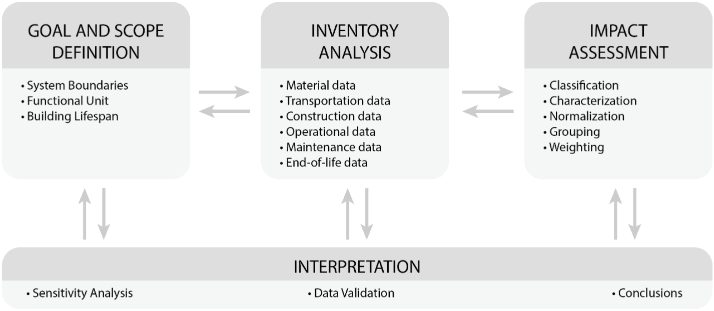


Figure 19: LCA framework for the building industry as proposed by Abd Rashid and Yusoff (Abd Rashid & Yusoff, 2015)

4.4.3. Environmental Product Declarations (EPDs)

In order to draw comparisons on the environmental performance between products fulfilling the same function a standardized methodology and conformity of pre-determined parameters in necessary. Therefore the concept of specific Type III environmental declarations was developed and laid down in ISO14025:2006. This international norm describes the principles and procedures for presenting quantified and consistent environmental information on the life cycle of products. These Environmental Product Declarations (EPDs) shall be based on verified LCA or LCI data which is compiled and evaluated in accordance with ISO 14040 and ISO 14044. The organization producing the declaration is required to ensure independent verification and declarations are subject to administration by a programme operator. (International Organization for Standardization, 2006a). In order to ensure comparability; harmonization of the content and format of EPDs for groups of similar products is provided by Product Category Rules (PCR) (Greenspec, 2018). For manufacturers in European member states these rules are described in the European standard EN15804:2012. This European norm defines parameters, the product lifecycle stages to be included, specification of the data quality as well as calculation rules and reporting procedures (CEN, 2017). An overview of the various lifecycle stages and modules is represented below.

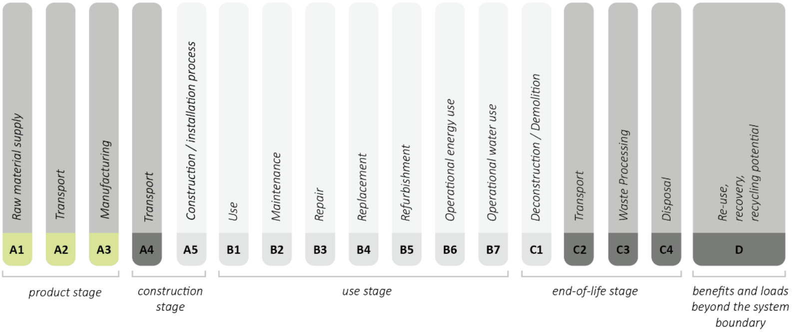
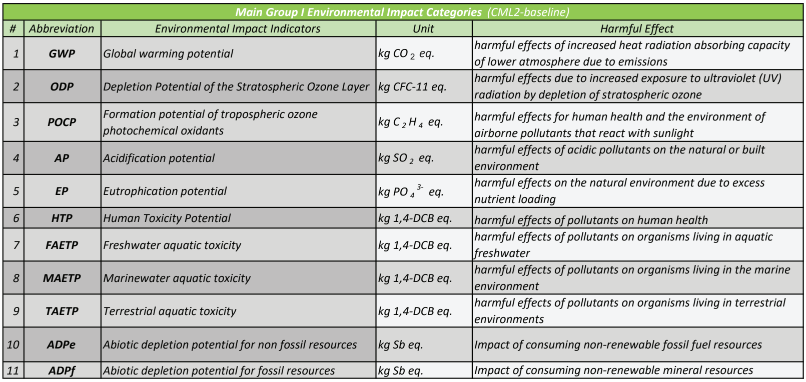


Figure 20: Types of EPD with respect to the life cycle stages covered and modules for the building industry

4.4.4. LCI Results & Environmental Impact Categories

In order to compare various environmental effects and to present the results of LCA studies in an orderly and comprehensible way, extensive lists of emissions, resource extraction and waste streams are converted into a manageable set of environmental indicators. The selection of the specific environmental research method and corresponding environmental impact categories is bound by the LCA Goal and Scope definition as defined according to ISO 14040. According to Blengini and Di Carlo the selection of specific indicators depends on the purpose of the analysis and is therefore of a rather subjective nature. However, there does seem to be general consensus on some of the most broadly recognized environmental concerns (Blengini & Di Carlo, 2010). Environmental life cycle analysis studies generally include the eleven specified group I main environmental impact categories listed below (Jonkers, 2018). These core environmental impact indicators represent the main areas of environmental concern based on international concerns, agreements and guidelines.



Main Group I Environmental Impact Categories (CML2-baseline)				
#	Abbreviation	Environmental Impact Indicators	Unit	Harmful Effect
1	**GWP**	Global warming potential	kg CO_2 eq.	harmful effects of increased heat radiation absorbing capacity of lower atmosphere due to emissions
2	**ODP**	Depletion Potential of the Stratospheric Ozone Layer	kg CFC-11 eq.	harmful effects due to increased exposure to ultraviolet (UV) radiation by depletion of stratospheric ozone
3	**POCP**	Formation potential of tropospheric ozone photochemical oxidants	kg C_2H_4 eq.	harmful effects for human health and the environment of airborne pollutants that react with sunlight
4	**AP**	Acidification potential	kg SO_2 eq.	harmful effects of acidic pollutants on the natural or built environment
5	**EP**	Eutrophication potential	kg PO_4^{3-} eq.	harmful effects on the natural environment due to excess nutrient loading
6	**HTP**	Human Toxicity Potential	kg 1,4-DCB eq.	harmful effects of pollutants on human health
7	**FAETP**	Freshwater aquatic toxicity	kg 1,4-DCB eq.	harmful effects of pollutants on organisms living in aquatic freshwater
8	**MAETP**	Marinewater aquatic toxicity	kg 1,4-DCB eq.	harmful effects of pollutants on organisms living in the marine environment
9	**TAETP**	Terrestrial aquatic toxicity	kg 1,4-DCB eq.	harmful effects of pollutants on organisms living in terrestrial environments
10	**ADPe**	Abiotic depletion potential for non fossil resources	kg Sb eq.	Impact of consuming non-renewable fossil fuel resources
11	**ADPf**	Abiotic depletion potential for fossil resources	kg Sb eq.	Impact of consuming non-renewable mineral resources

Figure 21: Group I main environmental impact categories

Perhaps the most important and most commonly recognized category is the Global Warming Potential (GWP). It is focused around the emission of carbon dioxide which is frequently used as the primary environmental impact indicator with regard to global warming. However, there are various other greenhouse gases that influence global warming on both the short and long term. To allow comparison of different gasses the GWP was developed. It is an indication of the ability of a gas to absorb a specific amount of energy compared to a similar amount absorbed by a specific mass of carbon dioxide calculated over a specific time interval (US Environmental Protection Agency, 2017). Aggregation for the various other categories works in a similar way. Various emissions and/or resources depleted are expressed in similar units and accumulated under a common environmental impact indicator.

The European Committee for Standardization has published EN15978 with regard to the specific assessment of environmental performance of buildings. It provides the means for standardized reporting and communication of LCA results by definition of specific environmental impact indicators for the sustainability of construction works and it elaborates on their specific calculation procedures. EN 15978 is part of the suite of standards which are at the core of EN 15804 (which ensures harmonization as explained in paragraph 4.4.2). Therefore EPDs also explicitly use the environmental impact indicators described in EN15978. The specific impact categories as used in EPDs are listed below (CEN, 2011).

Environmental Impact Indicators

#	Abbreviation	Environmental Impact Indicators	Unit	Harmful Effect
1	**GWP**	*Global warming potential*	*kg CO_2 eq.*	*harmful effects of increased heat radiation absorbing capacity of lower atmosphere due to emissions*
2	**ODP**	*Depletion Potential of the Stratospheric Ozone Layer*	*kg CFC-11 eq.*	*harmful effects due to increased exposure to ultraviolet (UV) radiation by depletion of stratospheric ozone*
3	**POCP**	*Formation potential of tropospheric ozone photochemical oxidants*	*kg NMVOC eq.*	*harmful effects for human health and the environment of airborne pollutants that react with sunlight*
4	**AP**	*Acidification potential*	*kg SO_2 eq.*	*harmful effects of acidic pollutants on the natural or built environment*
5	**EP**	*Eutrophication potential*	*kg PO_4^{3-} eq.*	*harmful effects on the natural environment due to excess nutrient loading*
6	**ADPe**	*Abiotic depletion potential for non fossil resources*	*kg Sb eq.*	*Impact of consuming non-renewable fossil fuel resources*
7	**ADPf**	*Abiotic depletion potential for fossil resources*	*MJ*	*Impact of consuming non-renewable mineral resources*

Resource Indicators

#	Abbreviation	Environmental Impact Indicators	Unit	Harmful Effect
1	**PERE**	*Renewable primary energy as energy carrier*	*MJ*	*Use of renewable primary energy excluding renewable primary energy resources used as raw materials*
2	**PERM**	*Renewable primary energy resources as material utilization*	*MJ*	*Use of renewable primary energy resources used as raw materials*
3	**PERT**	*Total use of renewable primary energy resources*	*MJ*	*Total use of renewable primary energy resources*
4	**PENRE**	*Non renewable primary energy as energy carrier*	*MJ*	*Use of non-renewable primary energy excluding non-renewable primary energy resources used as raw materials*
5	**PENRM**	*Non renewable primary energy as material utilization*	*MJ*	*Use of non-renewable primary energy resources used as raw materials*
6	**PENRT**	*Total use of non renewable primary energy resources*	*MJ*	*Total use of non-renewable primary energy resources*
7	**SM**	*Use of secondary material*	*kg*	*Use of secondary material*
8	**RSF**	*Use of renewable secondary fuels*	*MJ*	*Use of renewable secondary fuels*
9	**NRSF**	*Use of non renewable secondary fuels*	*MJ*	*Use of non-renewable secondary fuels*
10	**FW**	*Use of net fresh water*	*m^3*	*Net use of fresh water*

Output Flows and Waste Indicators

#	Abbreviation	Environmental Impact Indicators	Unit	Harmful Effect
1	**HWD**	*Hazardous waste disposed*	*kg*	*Hazardous waste disposed*
2	**NHWD**	*Non hazardous waste disposed*	*kg*	*Non-hazardous waste disposed*
3	**RWD**	*Radioactive waste disposed*	*kg*	*Radioactive waste disposed*
4	**CRU**	*Components for re-use*	*kg*	*Components for re-use*
5	**MFR**	*Materials for recycling*	*kg*	*Materials for recycling*
6	**MER**	*Materials for energy recovery*	*kg*	*Materials for energy recovery*
7	**EEE**	*Exported electrical energy*	*MJ*	*Exported electrical energy*
8	**EET**	*Exported thermal energy*	*MJ*	*Exported thermal energy*

Figure 22: Environmental impact categories according to EN15987

4.4.5. LCA in the Dutch Building Industry

The national building decree 2012 (Bouwbesluit 2012) dictates that an environmental performance calculation for buildings (MPG) is an obligatory part of the documentation that is required to apply for a building permit in the Netherlands. Thereby, all residential buildings and offices with a GFA of 100m2 or more, will require a ‘fast-track’ LCA calculation to be performed. (Rijksdienst voor Ondernemend Nederland, 2018). The government prescribes the use of the Nationale Milieu Database (NMD); the national environmental database on building products, as a primary source of information for the purpose of these calculations. The ‘fast-track’ LCAs should include all eleven CML2 environmental impact categories and the corresponding weighting factors to calculate the total shadowprice. The final MPG score is expressed in shadowcost per square meter GFA per year (€ / m^2 GFA /year). On January 1st 2018 new legislation was introduced requiring a maximum value of the MPG of 1,0. The most commonly used LCA-tools for this purpose within the Dutch building industry are; GPR-gebouw, One-Click LCA, MRPI and MPGCalc. These tools use the NMD as a primary source of input. Thereby, calculations heavily rely on the selection of EPDs that are registered by the SBK and the accuracy of the information disclosed in these certificates. The accuracy of these calculations and their suitability for assessing environmental impact thus heavily depends on the EPD quality. The EPD system and its limitations will be discussed in the following paragraph.

4.4.6. Sustainability Certification

In order to minimize the negative environmental impact of buildings there is an increasing demand for sustainable building design. In an attempt to quantify the sustainability of buildings various certification schemes have been introduced such as BREEAM, LEED, DGNB and Greenstar which translate and summarize LCA output into sustainability scores on various subjects and provide an overall sustainability certificate. The most commonly used assessment method in the Netherlands is BREEAM-NL operated by the Dutch Green Building Council. These environmental assessments and certifications are becoming more important as tenders increasingly incorporate sustainability and/or circular indicators. As environmental certificates are becoming an influential factor in decision making, it is essential to ensure the accuracy and verifiability of these certificates. An LCA is only as valid as its source data. It is essential that this data is accurate, detailed and not outdated. EPDs are at the foundation of the 'fast-track' LCA method and it is therefore important that these certificates truly provide transparent, verifiable, accurate and unambiguous information.

4.5. Data resources

There is limited publicly accessible information on the environmental impact of the primary steel production process other than the pool of EPDs for specific steel products and general information on emissions and waste streams as measured by the local government. During the course of this research frequent attempts were made to acquire more extensive LCA information from steel mills and industry associations. Unfortunately it seems that most of the industry is reluctant to disclose any kind of additional information on the subject of emissions, material use or waste streams to the general public or research institutes. In order to ensure the reliability of the information provided in these certificates, a sensitivity study was therefore performed by comparing environmental impact data available from the Dutch national database with scientific literature and other resources. The various data resources that have been considered are elaborated on below.

4.5.1. EPDs

As previously mentioned the majority of data on the production process of structural steel products is available by means of EPD certificates. A desktop study was performed and various certificates have been found for heavy duty structural steel products which are listed in **Appendix 1**.

4.5.2. Data from industry associations

Although it was not possible to acquire data from steel production plant or suppliers directly, a small selection of LCA information on steel production published by industry associations was found online. Worldsteel has published a generalized LCA from compiled data provided by several steel manufacturers in 2010 (Hughes & Hare, 2012). They also annually provide general data for the steel industry on subjects such as worldwide crude steel production, steel use, raw material use and steel trade (Worldsteel Association, 2018e).

4.5.3. Data by the Dutch Central Bureau of Statistics

The Dutch Central Bureau of Statistics (CBS) publishes data on a wide range of topics relevant for Dutch society. It is an independent organization whose primary objective is to publish transparent, verifiable and accurate data. For this research information on the import and export of raw materials such as iron ore, limestone and coal, as well as scrap and finished products such as H-, I- and C-profiles was used.

4.5.4. Data on Emissions by the Dutch National Institute for Public Health and the Environment

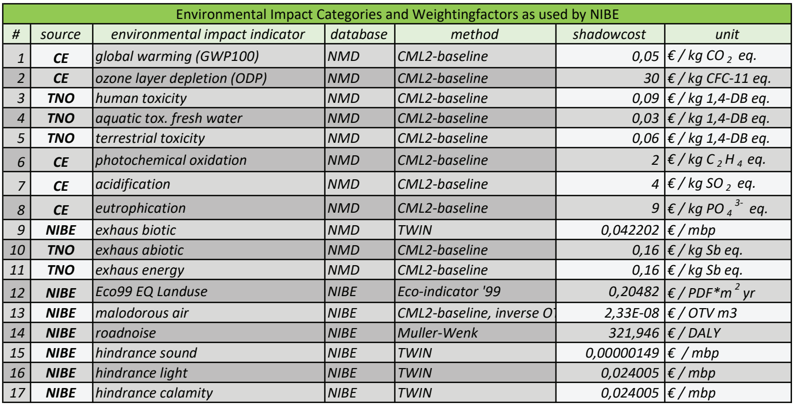
Other government institutes such as the National Institute for Public Health and the Environment (RIVM). also publish valuable environmental information on pollutants and environmental effects. The institute continuously monitors emissions measured at various points throughout the Netherlands by the Ministry of Health which can be accessed online (Atlas Leefomgeving, 2018; Ministry of Health, 2018).

4.5.5. National Environmental Database

The most important source of information on the environmental impact of raw construction materials and building products for the Netherlands is the Dutch National Environmental Database (NMD). This specific national database has been developed in order to facilitate unambiguous calculation of the environmental impact of buildings in the Netherlands and is managed by the Dutch Association for Quality of the Building Industry (SBK). In order to be admitted into the database building product manufacturers have to file a request with the SBK. The procedure is defined in a specific protocol (Stichting Bouwkwaliteit, 2014). The SBK collects environmental impact information for building products and specifically expressed for the eleven specified group I environmental impact categories as defined in ISO 14040. These main categories will be elaborated on in paragraph 4.4.4. It is directly linked to the various LCA-tools described in paragraph 4.4.4 and hence provides the core information for environmental impact analyses.

4.5.6. Dutch Institute for Biology and Ecology of the Building Industry

There are also more specific design tools available which are aimed at more easy comparison between products with a similar required functionality. This allows the user to make quick and effective choices with regard to the products which will be used in a design in order to minimize environmental impact costs of construction (Jonkers, 2018). The Dutch Institute for Biology and Ecology of the Building Industry (NIBE) is a Dutch program that provides such a design tool. It allows users to view and select environmental profiles for various building products which provide extensive information on e.a. general product characteristics, various environmental impact categories, the various lifecycle phases and end-of-life scenarios. Every product is classified under an environmental impact class and it’s specific impact is expressed in monetary terms. This monetarization method also known as the shadowcost method which will be further elaborated on in paragraph 4.6.4. The assessment method as proposed by NIBE is partially consistent with the CML2 method and uses the NMD as a data resource. However, it differs from current ‘fast-track’ LCA methods due to the consideration of a more extensive range of environmental impact factors as indicated in **Figure 23** below. The differences in terms of the impact factors, assessment methods used and the corresponding weighting factors are indicated in the table. Although the framework proposed by NIBE is more comprehensive than the currently used methods, it should be noted that it still uses the NMD data for most of the environmental impact categories thereby inheriting its vulnerabilities.



Environmental Impact Categories and Weightingfactors as used by NIBE

#	source	environmental impact indicator	database	method	shadowcost	unit
1	**CE**	global warming (GWP100)	NMD	CML2-baseline	0,05	€ / kg CO_2 eq.
2	**CE**	ozone layer depletion (ODP)	NMD	CML2-baseline	30	€ / kg CFC-11 eq.
3	**TNO**	human toxicity	NMD	CML2-baseline	0,09	€ / kg 1,4-DB eq.
4	**TNO**	aquatic tox. fresh water	NMD	CML2-baseline	0,03	€ / kg 1,4-DB eq.
5	**TNO**	terrestrial toxicity	NMD	CML2-baseline	0,06	€ / kg 1,4-DB eq.
6	**CE**	photochemical oxidation	NMD	CML2-baseline	2	€ / kg C_2H_4 eq.
7	**CE**	acidification	NMD	CML2-baseline	4	€ / kg SO_2 eq.
8	**CE**	eutrophication	NMD	CML2-baseline	9	€ / kg PO_4^{3-} eq.
9	**NIBE**	exhaus biotic	NMD	TWIN	0,042202	€ / mbp
10	**TNO**	exhaus abiotic	NMD	CML2-baseline	0,16	€ / kg Sb eq.
11	**TNO**	exhaus energy	NMD	CML2-baseline	0,16	€ / kg Sb eq.
12	**NIBE**	Eco99 EQ Landuse	NIBE	Eco-indicator '99	0,20482	€ / PDF*m^2 yr
13	**NIBE**	malodorous air	NIBE	CML2-baseline, inverse O	2,33E-08	€ / OTV m3
14	**NIBE**	roadnoise	NIBE	Muller-Wenk	321,946	€ / DALY
15	**NIBE**	hindrance sound	NIBE	TWIN	0,00000149	€ / mbp
16	**NIBE**	hindrance light	NIBE	TWIN	0,024005	€ / mbp
17	**NIBE**	hindrance calamity	NIBE	TWIN	0,024005	€ / mbp

Figure 23: Overview of Environmental Impact Categories for building products as prescribed by NIBE (NIBE, 2019)

4.5.7. Scientific Publications

Various publications were found on the life cycle assessment of crude steel production; three papers on European plants respectively in Poland, Italy and Turkey (Dorota Burchart-Korol, 2013; Olmez, Dilek, Karanfil, & Yetis, 2016; Renzulli, Notarnicola, Tassielli, Arcese, & Di Capua, 2016) and one LCA conducted in China (Ma et al., 2018). Moreover publications were found on lung cancer risks associated with exposure to emissions from a large steel plant in the Netherlands (Breugelmans et al., 2013), the identification of main influencing factors of life cycle CO_2 emissions (Huang, Ding, Sun, & Liu, 2010) and on the depletion of abiotic resources in the steel production industry (D. Burchart-Korol & Kruczek, 2016). It should be noted that most of these scientific publications use the more recently developed ReCiPe LCIA method rather than CML. The differences between these two methods will be elaborated on more in debt in paragraph 4.6.

4.5.8. External cost of Transport

Another important topic is the external costs of transport. Currently the environmental impact is assessed according to the data provided by the NMD as provided in **Appendix 7**. This data for various modes of transport is in line with the CML2 method. In order to quantify and compare traffic-related environmental issues with scientific literature, another publication by CE Delft on freight transport was used, namely STREAM handbook on external costs of transport. It is a more recent national publication which explicitly quantifies the impact of various modes of transport and lists various emission factors and environmental prices for road, rail, inland- and sea shipping expressed in tonkilometer. The publication includes average emission factors per mode of transport as well as average values for fuel types and energy sources which could be considered. (Otten, 't Hoen, & den Boer, 2017). It includes the most important environmental impact indicators for major air-pollutants such as greenhouse gas, particulate matter, NO_x, SO_2 and NMVOC and environmental prices that can be used for the impacts concerned. An overview of the values found in the publication can be found in **Appendix 8**.

4.6. Common LCIA methods and Weighting Factors

As this research is specifically focused on the Dutch building industry, the most commonly used life cycle impact assessment (LCIA) methods will be addressed in the following paragraphs. The specific environmental impact categories, calculation method as well as the most suitable national monetarized weighting indices for these methods are described below. Subsequently a comparative case-study analysis will be performed for the commonly used CML method and its successor ReCiPe to determine the sensitivity of the results for the selected LCA method.

4.6.1. CML as an LCIA method

LCIA methods translate emissions and resource extraction by means of characterization factors into a manageable set of environmental indicators as described in paragraph 4.4.4. These so-called midpoints represent the impact of emissions aggregated on several crucial environmental themes. The most frequently used assessment method in the Netherlands for determining the environmental impact of building products and civil structures is the CML2-method. CML is the abbreviation of the Institute of Environmental Sciences at Leiden University where this method was developed by Guinée et al in 2001 (Guinée et al., 2002) and contains 1700 substances and their corresponding characterization factors by which LCIA results can be aggregated and attributed to either eight (CML baseline) or eleven (CML non-baseline) environmental impact categories. Impact pathway models have been defined which describe the relationship between the concentration of emissions and the endpoint impacts for natural, managed and human systems. The characterization factors and normalization data is freely available and can be obtained from the Leiden University website (Leiden University Institute of Environmental Sciences, 2016).

4.6.2. ReCiPe as an LCIA method

The ReCiPe method was developed in 2008 as part of a collaborative effort between the RIVM, Radboud University Nijmegen, Leiden University and Pré Consultants. It is an increasingly popular LCA method which was developed as a successor to the beforementioned CML-2 method and the Eco-indicator 99. Characterization factors translate the LCI results into indicators which help the user to interpret the results. It offers three levels of impact analysis; *midpoint impact categories*, *damage pathways* and *endpoints*. Below is a schematic representation of the ReCiPe approach inspired on the visual representation by Goedkoop et al. which illustrates the relationship between emissions, midpoints, damage pathways and endpoints. (Goedkoop et al., 2013). ReCiPe is a more developed LCIA method than its predecessor CML and is frequently used in the Netherlands for LCA studies. An updated version was published in 2016.

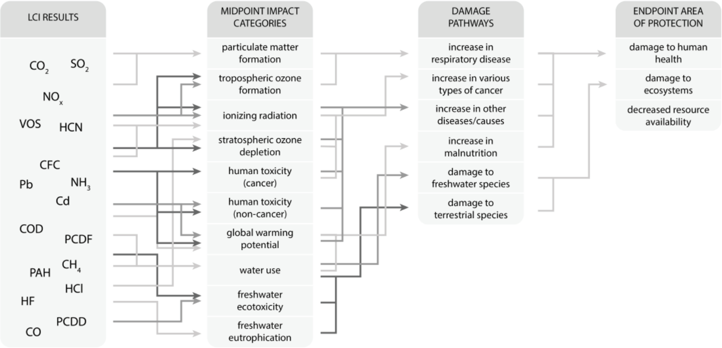


Figure 24: Schematic representation of the ReCiPe characterization method (Goedkoop et al., 2013)

The ReCiPe method distinguishes eleven relevant midpoints namely (Goedkoop et al., 2013): *ozone depletion, global warming, particulate matter formation, photochemical oxidant formation, acidification, eutrophication, human toxicity, ecotoxicity ionizing radiation, nuisance and land use*. Because the method is based on the CML2 and Eco-indicator 99 methods, certain similarities between the impact categories exist. However, the methods cannot be used interchangeable as some themes base their impact on different pollutants. Therefore simple conversion is not possible for several impact categories. The most relevant impact categories for the steel production industry will be discussed more in depth in paragraph 5. There are several other well developed characterization methods such as for example the International Reference Life Cycle Data System (ILCD) published by the European Commission. However, as this study is focused specifically on the Dutch building industry this study will be limited to the most prominent methods in the Netherlands; CML-2 and ReCiPe.

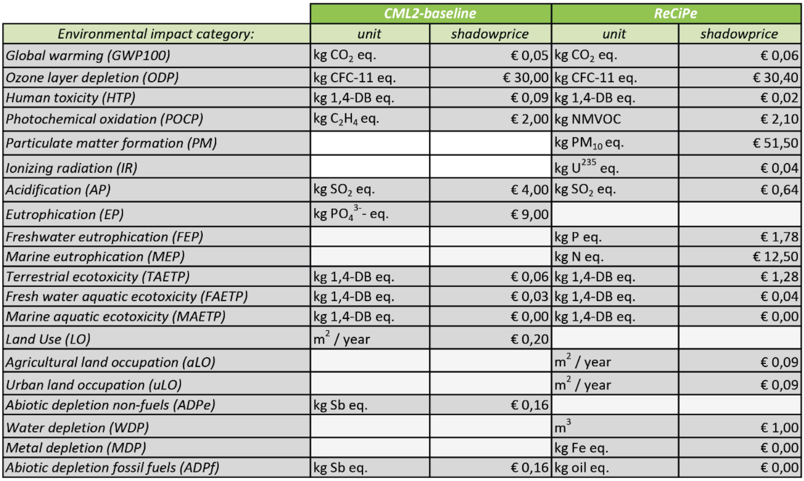
4.6.3. Weighting Methods

In order to compare results for the various indicators valuation and weighting methods can be used to aid with interpretation of results. The suitability of certain methods depends on the purpose of the analysis as mentioned in paragraph 4.4.4. A distinction can be made between multi-value indicators and single-value indicators. According to Ahlroth a further distinction can be made between monetary and non-monetary methods for weighting environmental impacts (Ahlroth, 2014). Quantification in terms of money makes the output of complex LCAs easier to comprehend for policy- and decision makers and allows for comparison between various categories or individual pollutants. It also provides an indication of the damage cost for society and inclusion of this monetarized environmental impact in the total cost of a material or product would allow for measures to abate the environmental damage (Jonkers, 2018). Various weighting factors have been developed that describe the relation between endpoint impacts and the economic changes in welfare by means of economic valuation of the damage costs. It is important to ensure that the correct weighting factors are used that correspond with the LCIA method used. Moreover, weighting factors are often dependent on local conditions and it is therefore advised to use national values rather than generic averages.

4.6.4. Shadowprice

Although assigning a specific economic valuation to the various environmental impact categories might seem arbitrary it does provide us with a means to aggregate results and provide an overall indication of the environmental impact of a product or process. Various attempts have been made by environmental institutes and government organizations to quantify the environmental prices for various pollutants. By monetarizing the impact a total environmental price can be determined which can be added to the total cost of a product or service to obtain a sustainable selling price as indicated in **Figure 18**.

CE Delft has published an environmental research method on the valuation and weighting of emissions for the ReCiPe method that is characteristic for the Netherlands. This so called environmental prices (or shadowcosts) are “indices that calculate the social marginal value of preventing emissions, or interventions like noise and land-use changes, expressing it in Euros per kilogram pollutant or per decibel, for example.” (Ahdour et al., 2018) This method can be used by sustainable initiatives and organizations to conduct practical environmental cost-benefit analyses and provides a foundation for investment decision making for products and services. It is also frequently used by the Dutch government to gain insight into the value of environmental quality for society. The handbook provides monetary environmental prices for over 2500 pollutants in terms of both abatement costs as well as damage costs. It also presents environmental prices which can be used as weighting factors for the various specified environmental categories used in environmental studies and LCA software packages as defined by ISO 14040 (de Bruyn, 2016). It should be emphasized that these environmental prices are specifically suited for use in LCAs conducted according to the ReCiPe methodology (Goedkoop et al., 2013). As mentioned before there are several other characterization methods such as CML, ILCD and PEF. Although these methods of characterization might seem quite similar for most midpoints, there are considerable differences for the impact categories for *human toxicity*, *ecotoxicity* and *land use* for which the proposed environmental prices cannot be applied. The environmental price indices as determined by CE Delft for the ReCiPe method as well as the price indices for CML can be found in the table below.



	CML2-baseline		ReCiPe	
Environmental impact category:	*unit*	*shadowprice*	*unit*	*shadowprice*
Global warming (GWP100)	kg CO_2 eq.	€ 0,05	kg CO_2 eq.	€ 0,06
Ozone layer depletion (ODP)	kg CFC-11 eq.	€ 30,00	kg CFC-11 eq.	€ 30,40
Human toxicity (HTP)	kg 1,4-DB eq.	€ 0,09	kg 1,4-DB eq.	€ 0,02
Photochemical oxidation (POCP)	kg C_2H_4 eq.	€ 2,00	kg NMVOC	€ 2,10
Particulate matter formation (PM)			kg PM_{10} eq.	€ 51,50
Ionizing radiation (IR)			kg U^{235} eq.	€ 0,04
Acidification (AP)	kg SO_2 eq.	€ 4,00	kg SO_2 eq.	€ 0,64
Eutrophication (EP)	kg PO_4^{3-}- eq.	€ 9,00		
Freshwater eutrophication (FEP)			kg P eq.	€ 1,78
Marine eutrophication (MEP)			kg N eq.	€ 12,50
Terrestrial ecotoxicity (TAETP)	kg 1,4-DB eq.	€ 0,06	kg 1,4-DB eq.	€ 1,28
Fresh water aquatic ecotoxicity (FAETP)	kg 1,4-DB eq.	€ 0,03	kg 1,4-DB eq.	€ 0,04
Marine aquatic ecotoxicity (MAETP)	kg 1,4-DB eq.	€ 0,00	kg 1,4-DB eq.	€ 0,00
Land Use (LO)	m^2 / year	€ 0,20		
Agricultural land occupation (aLO)			m^2 / year	€ 0,09
Urban land occupation (uLO)			m^2 / year	€ 0,09
Abiotic depletion non-fuels (ADPe)	kg Sb eq.	€ 0,16		
Water depletion (WDP)			m^3	€ 1,00
Metal depletion (MDP)			kg Fe eq.	€ 0,00
Abiotic depletion fossil fuels (ADPf)	kg Sb eq.	€ 0,16	kg oil eq.	€ 0,00

Figure 25: Environmental impact categories, units and shadowprices for CML2 and ReCiPe method (Ahdour et al., 2018)

4.7. Conclusions and recommendations

From the previous paragraphs on the methods and available data to assess the environmental impact of buildings the following conclusions and recommendations can be made:

- Historic measures to curb environmental impact only required companies to prove to the government that emissions are within certain margins. This sort of *legislation therefore does not provide an incentive for companies to invest in sustainable innovations* beyond compliance.
- It is recommended that an effort should be made to *include external costs in the total costs of products and construction works* in order to establish the actual sustainable selling price. These costs can be added on top of the selling price, for example by the means of taxes, which could subsequently be used by the government to take countermeasures negating the negative environmental impact of a product.
- Buildings are complex assemblies of many different products, which in turn consist of various different materials. It is therefore simply impossible to assess their environmental impact by means of a ‘classic’ LCA. The idea of performing a ‘fast-track’ LCA based on the individual assessments of subproducts and aggregating results provides a valid alternative. However, it was concluded that the *‘fast-track’ LCA method relies heavily on the accuracy of the used data*.
- The Bouwbesluit 2012 dictates that an environmental performance calculation for buildings (MPG) is an obligatory part the request for a building permit in the Netherlands. The *government prescribes the use of the Nationale Milieu Database (NMD*) for this purpose. On January 1st 2018 new legislation was introduced requiring a mnaximum value of the MPG of 1,0. Thereby, calculations heavily rely on the selection of EPDs that are registered by the SBK and the accuracy of the information disclosed in these certificates.
- The most *commonly used LCA-tools for this purpose within the Dutch building industry are; GPR-gebouw, One-Click LCA, MRPI and MPGCalc*.
- These tools are all based on the CML2 methodology and its corresponding impact categories, however in recent years a *more up-to-date method; ReCiPe, has been developed as a successor to CML 2*. It is therefore recommended that efforts should be to also unroll this methodology for the Dutch building industry as it is more thorough.
- Although the recent framework proposed by *NIBE is more comprehensive than the currently used methods, it should be noted that it still uses the NMD data* for most of the environmental impact categories thereby inheriting its vulnerabilities.

Part II: Critical Review

5 Critical Review of Current Assessment Methods

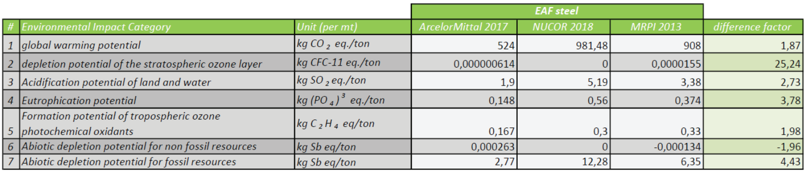
As mentioned in paragraph 4.4.5 the use of EPDs raises several questions with regard to accuracy, consistency and verifiability. By critically reviewing and comparing various EPD results for structural steel products and by comparing these to LCA study outcomes published in scientific literature it will be evaluated if EPDs indeed provide an accurate representation of the environmental impact of structural steel construction products. Furthermore, in this chapter we will discuss the suitability of the frequently used CML2 method for structural steel LCA studies as well as the more comprehensive ReCiPe approach which is the successor to CML2 often used in scientific LCA studies.

5.1. Environmental Product Declarations

The EPD document is aimed at providing verified, unambiguous, transparent and comparable information on material use, efficiency, energy use, emissions, waste generation, reuse and recycling. It is a voluntary, independently verified and registered document which is primarily used as a business-to-business communication method. The systematic representation allows for easy aggregation of environmental data for various products which facilitates the 'Fast-Track' LCA approach thereby providing quick and supposedly complete environmental information for building and other construction works.

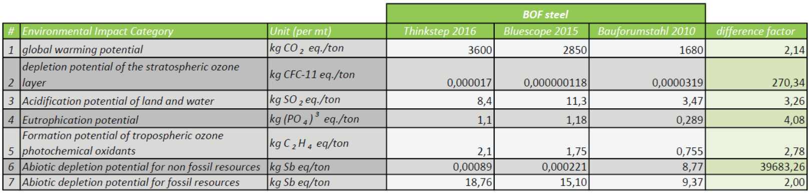
5.1.1. Comparison of several Structural Steel EPDs

However, the present situation leads to market confusion as the international and European standards can be interpreted in different ways by the various programme operators. This can be observed when various EPDs for the same product are compared. For example below in **Figure 26** and **Figure 27** a comparison is made between different EPDs for structural steel construction products EAF and BOF steel respectively.



			EAF steel			
#	Environmental Impact Category	Unit (per mt)	ArcelorMittal 2017	NUCOR 2018	MRPI 2013	difference factor
1	global warming potential	kg CO_2 eq./ton	524	981,48	908	1,87
2	depletion potential of the stratospheric ozone layer	kg CFC-11 eq./ton	0,000000614	0	0,0000155	25,24
3	Acidification potential of land and water	kg SO_2 eq./ton	1,9	5,19	3,38	2,73
4	Eutrophication potential	kg $(PO_4)^3$ eq./ton	0,148	0,56	0,374	3,78
5	Formation potential of tropospheric ozone photochemical oxidants	kg C_2H_4 eq/ton	0,167	0,3	0,33	1,98
6	Abiotic depletion potential for non fossil resources	kg Sb eq/ton	0,000263	0	-0,000134	-1,96
7	Abiotic depletion potential for fossil resources	kg Sb eq/ton	2,77	12,28	6,35	4,43

Figure 26: Comparison of the lowest and highest values for various impact factors of three EAF steel EPDs



			BOF steel			
#	Environmental Impact Category	Unit (per mt)	Thinkstep 2016	Bluescope 2015	Bauforumstahl 2010	difference factor
1	global warming potential	kg CO_2 eq./ton	3600	2850	1680	2,14
2	depletion potential of the stratospheric ozone layer	kg CFC-11 eq./ton	0,000017	0,000000118	0,0000319	270,34
3	Acidification potential of land and water	kg SO_2 eq./ton	8,4	11,3	3,47	3,26
4	Eutrophication potential	kg $(PO_4)^3$ eq./ton	1,1	1,18	0,289	4,08
5	Formation potential of tropospheric ozone photochemical oxidants	kg C_2H_4 eq/ton	2,1	1,75	0,755	2,78
6	Abiotic depletion potential for non fossil resources	kg Sb eq/ton	0,00089	0,000221	8,77	39683,26
7	Abiotic depletion potential for fossil resources	kg Sb eq/ton	18,76	15,10	9,37	2,00

Figure 27: Comparison of the lowest and highest values for various impact factors of three BOF steel EPDs

All certificates comply with both EN15804 and ISO 14025 but considerable differences can be observed between the certificates. Logically, individual differences are to be expected since production processes can differ significantly between various production sites. However, the difference between the certificates are of a magnitude which are hard to explain solely by the production processes. A total of thirteen EPD's for structural steel products have been examined which all comply with ISO14040 and for which the majority EN15804 serves as the core PCR. An overview can be found in **Appendix 1**. Therefore it can be concluded that the observed EPDs are comparable. However the EPDs show widespread results for the various categories and there is considerable inconsistency with regard to the LCA stages included in the certificates. The only stages which are consistently mentioned for all certificates are stages ***A1***-***A3*** as well as stage D. Moreover, various of these EPDs state that results are valid for products from several steel mills. For example Bauforumstahl (EPD-BFS-20130094-IBG1-EN, 2013) states that their certificate is valid for products produced in various plants in Luxembourg, England, Spain, Germany, the Czech Republic and Poland. This implies that production processes actually would be rather consistent for European steel mills and individual differences would be relatively small and neglectable. From this, it can be concluded that there is relatively little consistency between certificates for the same products which challenges the accuracy and unambiguousness of EPDs.

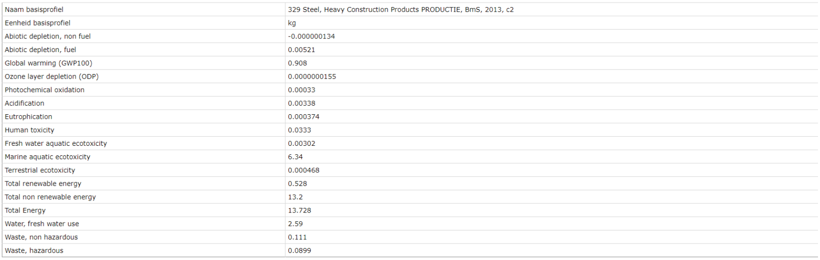
Furthermore it should be noted that most certificates only provide the CML2 baseline environmental impact factors which means that the categories *Human Toxicity*, *Freshwater exotoxicity*, *Marine ecotoxicity* and *Terrestrial ecotoxicity* are not included. The NMD however provides CML non-baseline data. Therefore, these additional values are included in the registered certificate by the MRPI as well as some others.

5.1.2. Conflicts of Interest

It is stated in ISO14025:2006: "Type III environmental declarations are subject to the administration of a programme operator, such as a company or a group of companies, industrial sector or trade association, public authorities or agencies, or an independent scientific body or other organization.". This implies that it is possible for organizations or companies to become an approved EPD programme operator which can issue and manage EPDs for their own products. It directly allows large steel production companies to become an approved operator which thereby have the ability to create product specific EPDs for their own product as can be read on their website (Tata Steel Construction, 2018). This imposes a credibility problem as the current verification protocol for EPD's specifically states that document verification is limited to validating the procedures and requirements as described in EN15804. This implies that only the methodology is verified by an independent party but that the factual integrity of the declaration is the responsibility of the owner. This can be found back in verification protocols of various programme operators such as the MRPI which states that “the declaration owner is responsible for its factual integrity” in their third party verification protocol (Stichting MRPI, 2017).

5.1.3. EPD certificate MRPI

The primary source of environmental impact information used by both the NMD and NIBE for product profiles of various structural steel products is an EPD certificate issued by the MRPI dating back to 2013. This specific certificate raises several questions with regard to accuracy which are elaborated on below.



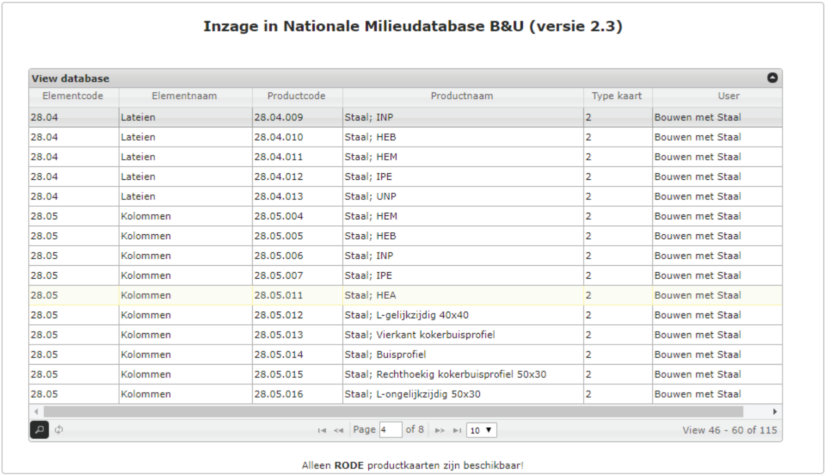
Naam basisprofiel	329 Steel, Heavy Construction Products PRODUCTIE, BmS, 2013, c2
Eenheid basisprofiel	kg
Abiotic depletion, non fuel	-0.000000134
Abiotic depletion, fuel	0.00521
Global warming (GWP100)	0.908
Ozone layer depletion (ODP)	0.0000000155
Photochemical oxidation	0.00033
Acidification	0.00338
Eutrophication	0.000374
Human toxicity	0.0333
Fresh water aquatic ecotoxicity	0.00302
Marine aquatic ecotoxicity	6.34
Terrestrial ecotoxicity	0.000468
Total renewable energy	0.528
Total non renewable energy	13.2
Total Energy	13.728
Water, fresh water use	2.59
Waste, non hazardous	0.111
Waste, hazardous	0.0899

Figure 28: EPD data on *329 Steel, Heavy Construction Products* publicly available at NMD Version 2.2 (September 2018)

Firstly, the assumed reuse and recycling rates of respectively 49 and 51 percent are highly questionable. Literature indicates that reuse of heavy construction products is very uncommon and reuse rates of structural steel profiles are estimated to be between 5-10% (Beurskens & Durvisevic, 2017; Sansom & Avery, 2014; Sansom & Meijer, 2012). This is also in line with statements made during various interviews performed throughout the course of this study. Various parties in the construction industry have indicated that reuse of structural steel profiles is a very uncommon practice. Recycling rates however are generally high and there is general consensus that recycling rates are around 90-100 percent across Europe (Durmisevic & Binnemars, 2014; Sansom & Avery, 2014). Other EPDs listed in **Appendix 1**. which indicate recycling and reuse rates of respectively 90 and 10 percent are considered to be more accurate in this respect.

Secondly, the specific emission values for the various environmental impact categories denoted are relatively low compared with the average values found from the comparison with various other EPDs in **Appendix 1**. Also, the absence of some crucial environmental indicators could pose a problem. This will be elaborated further in paragraph 5.

Moreover, This certificate expired on the 8th of January 2018 and should have actually been renewed with a new certificate. However, the MRPI has indicated that this process is being hindered by the willingness of steel producers to provide data with regard to production processes. The organization has been working on a new EPD for the past one and a half years but does not expect to be able to publish a new certificate before the end of the year. Perhaps that is also the reason why the certificate details are no longer publicly available in the latest release of the NMD, version 2.3 as can be seen in **Figure 29**.



Inzage in Nationale Milieudatabase B&U (versie 2.3)

View database

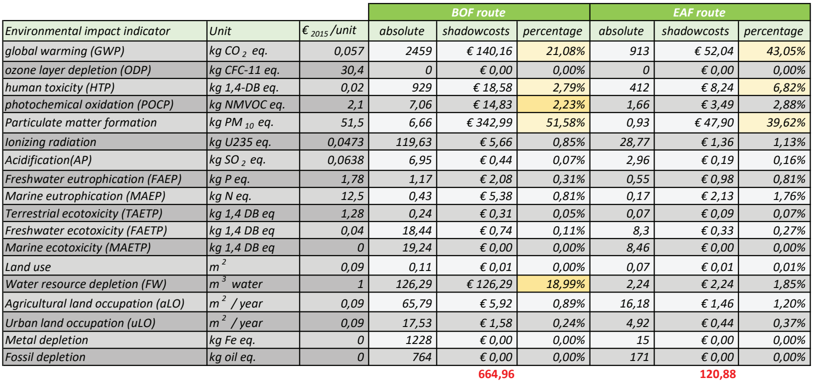
Elementcode	Elementnaam	Productcode	Productnaam	Type kaart	User
28.04	Lateien	28.04.009	Staal; INP	2	Bouwen met Staal
28.04	Lateien	28.04.010	Staal; HEB	2	Bouwen met Staal
28.04	Lateien	28.04.011	Staal; HEM	2	Bouwen met Staal
28.04	Lateien	28.04.012	Staal; IPE	2	Bouwen met Staal
28.04	Lateien	28.04.013	Staal; UNP	2	Bouwen met Staal
28.05	Kolommen	28.05.004	Staal; HEM	2	Bouwen met Staal
28.05	Kolommen	28.05.005	Staal; HEB	2	Bouwen met Staal
28.05	Kolommen	28.05.006	Staal; INP	2	Bouwen met Staal
28.05	Kolommen	28.05.007	Staal; IPE	2	Bouwen met Staal
28.05	Kolommen	28.05.011	Staal; HEA	2	Bouwen met Staal
28.05	Kolommen	28.05.012	Staal; L-gelijkzijdig 40x40	2	Bouwen met Staal
28.05	Kolommen	28.05.013	Staal; Vierkant kokerbuisprofiel	2	Bouwen met Staal
28.05	Kolommen	28.05.014	Staal; Buisprofiel	2	Bouwen met Staal
28.05	Kolommen	28.05.015	Staal; Rechthoekig kokerbuisprofiel 50x30	2	Bouwen met Staal
28.05	Kolommen	28.05.016	Staal; L-ongelijkzijdig 50x30	2	Bouwen met Staal

Alleen **RODE** productkaarten zijn beschikbaar!

Figure 29: Structural steel product EPD certificates are no longer public in latest version 2.3 of the NMD (December 2018)

5.2. Critical factors according to Scientific Literature

In order to evaluate the current system of EPDs as a method of representation of the environmental impact of materials and building products a first comparison will be made with the LCA performed by Burchart-Korol (Dorota Burchart-Korol, 2013). This research is the most suitable for this purpose as an assessment is made for both the EAF and BOF production process. It extensively describes the LCA process, the data used, the functional unit and the specific boundary conditions. ReCiPe is used as an impact assessment method. Below is an overview of the characterization factors established in the report for both the BOF as EAF route. Consecutively the factors are weighted according to the ReCiPe weighting method provided in **Figure 25** in paragraph 4.6.4. This allows for comparison between the various environmental impact factors and identification the most dominant influential factors.



			BOF route			EAF route		
Environmental impact indicator	Unit	€ $_{2015}$/unit	absolute	shadowcosts	percentage	absolute	shadowcosts	percentage
global warming (GWP)	kg CO_2 eq.	0,057	2459	€ 140,16	21,08%	913	€ 52,04	43,05%
ozone layer depletion (ODP)	kg CFC-11 eq.	30,4	0	€ 0,00	0,00%	0	€ 0,00	0,00%
human toxicity (HTP)	kg 1,4-DB eq.	0,02	929	€ 18,58	2,79%	412	€ 8,24	6,82%
photochemical oxidation (POCP)	kg NMVOC eq.	2,1	7,06	€ 14,83	2,23%	1,66	€ 3,49	2,88%
Particulate matter formation	kg PM_{10} eq.	51,5	6,66	€ 342,99	51,58%	0,93	€ 47,90	39,62%
Ionizing radiation	kg U235 eq.	0,0473	119,63	€ 5,66	0,85%	28,77	€ 1,36	1,13%
Acidification(AP)	kg SO_2 eq.	0,0638	6,95	€ 0,44	0,07%	2,96	€ 0,19	0,16%
Freshwater eutrophication (FAEP)	kg P eq.	1,78	1,17	€ 2,08	0,31%	0,55	€ 0,98	0,81%
Marine eutrophication (MAEP)	kg N eq.	12,5	0,43	€ 5,38	0,81%	0,17	€ 2,13	1,76%
Terrestrial ecotoxicity (TAETP)	kg 1,4 DB eq	1,28	0,24	€ 0,31	0,05%	0,07	€ 0,09	0,07%
Freshwater ecotoxicity (FAETP)	kg 1,4 DB eq	0,04	18,44	€ 0,74	0,11%	8,3	€ 0,33	0,27%
Marine ecotoxicity (MAETP)	kg 1,4 DB eq	0	19,24	€ 0,00	0,00%	8,46	€ 0,00	0,00%
Land use	m^2	0,09	0,11	€ 0,01	0,00%	0,07	€ 0,01	0,01%
Water resource depletion (FW)	m^3 water	1	126,29	€ 126,29	18,99%	2,24	€ 2,24	1,85%
Agricultural land occupation (aLO)	m^2 / year	0,09	65,79	€ 5,92	0,89%	16,18	€ 1,46	1,20%
Urban land occupation (uLO)	m^2 / year	0,09	17,53	€ 1,58	0,24%	4,92	€ 0,44	0,37%
Metal depletion	kg Fe eq.	0	1228	€ 0,00	0,00%	15	€ 0,00	0,00%
Fossil depletion	kg oil eq.	0	764	€ 0,00	0,00%	171	€ 0,00	0,00%
				664,96			120,88	

Figure 30: Environmental impact assessment of structural steel production according to Burchart-Korol (Dorota Burchart-Korol, 2013)

It can be concluded from **Figure 30** above that the most critical environmental impact categories for steel production for both the BOF as EAF route are *global warming*, *human toxicity*, *particulate matter formation* and for BOF steel *water depletion* is also an important factor. It should be noted that PM was not explicitly expressed as a separate category in the predecessor to ReCiPe; CML2. Here, the environmental impact due to particulate matter formation was attributed to various of the other categories. However, as over the recent years it has become increasingly evident that particulate matter poses a major health concern for human health, ReCiPe denotes this impact as a separate category with increased weighting factors leading to a significant share of the total impact. The environmental impact indicated by these categories will be investigated more in depth in the following paragraphs.

5.2.1. Global Warming Potential

As indicated by the recent report of the IPCC (Allen et al., 2018a) one of the current primary environmental concerns is climate change. In order to put a halt to the continuous rise in global temperatures and to prevent global warming of 1.5°C above pre-industrial levels, global greenhouse gas emissions will have to decrease significantly within the next 12 years. The widely used midpoint characterization factor for climate change is the GWP100 which is an indication of the additional radiative forcing integrated over time caused by various GHG expressed in CO_2 equivalents. From the work of Burchartt-Korol mentioned above it can be concluded that the GWP for steel production would approximately be 2500kg eCO_2 per ton of steel for the BOF route and approximately 900kg eCO_2 per ton of steel for the EAF route. Two other research papers on the LCA of steel production for the BOF route by Ma et al. and Renzulli et al. indicate GWPs of respectively 3800 and 1600 kg eCO_2 per ton of steel (Ma et al., 2018; Renzulli et al., 2016). A GWP range of 1700-3800 eCO_2 for the BOF route seems to be largely in line with various statements by both the industry (Tata Steel IJmuiden BV, 2016; Worldsteel Association, 2017b) as well as independent institutions (IPCC, 2007; MIT, 2013). It can therefore be concluded that the specific GWP of steel production is largely dependent on the specific steel production plant. The average seems to lie around 2300 eCO2 per ton of steel within a range of 1700-3800. Moreover, it can also be concluded that European steelplants generally outperform plants in China, India and the U.S with regard to GWP (IPCC, 2007).

When we look at the various EPDs for structural steel elements in **Appendix 1**, we see that the estimated GWP ranges from 524-3600 kg eCO_2 per ton of steel produced with an average of 1630 kg eCO_2. The upper boundary seems to be in line with scientific publications, however the lower boundary is lower than expected. This can partly be explained by the average recovered content (EAF route) rate noted on the EPD published by Institut Bauen und Umwelt e.V.. The GWP for the EAF route is naturally significantly lower than steel produced for the BOF route as can be seen in **Figure 30** . The Differdange plant in Luxembourg mentioned on the specific certificate does indeed only produce steel products via the EAF route (Arcelor Mittal, 2018). The low GWP listed can be denoted as questionable as a difference factor of 1.75 in comparison with the GWP indicated in scientific literature indicates that the Arcelor Mittal plant would be significantly more efficient than other plants. As the primary source of GWP of the EAF process is the eCO^2 emissions due to electric energy input this would indicate that this plant requires either much less energy for production, or that it uses a larger share of renewables. However, there is no available information on the specific production facility in support of this claim.

It should be noted that EPD certificates should strictly be used for products produced at the facilities listed on the certificate. Steel produced at plants that use the BOF route will have a significantly higher GWP and usage of EAF route certificates is therefore not acceptable. Moreover, it can be questioned to what extent the need for structural steel can be sufficed by products produced via the EAF route as it depends on the amount of steel scrap available. Also the origin of steel scrap used for EAF production influences the environmental impact by means of necessary transportation distances. The origin of structural steel products and steel scrap will be further elaborated on in paragraph 5.5.

Another issue arises with the application of category D, which serves as an indication of the expected end-of-life scenario of the product. Since steel is fully recyclable category D allows for subtraction of GWP emissions since it is assumed that the material will either be re-used or recycled at the end-of-life stage instead of being used as landfill. Next to the fact that this is a gross advance on future deconstruction scenarios, it also takes into account the recyclability of steel on both ends of the product lifecycle, both as an input and output advantage. The overall impact score indicated on the EPD often includes this reduction factor. This leads to a representation of significantly lower and inaccurate GWP values. Moreover, re-use and re-cycling rates are generally already included in fast-track LCA's as software users can manually assign end-of-life reuse and recycling ratios to specific products.

This thesis is focused on quantifying the environmental benefits of circular steel re-use. Therefore comparisons will need to be made between building designs in virgin steel and designs that (partially) use circular steel. In order to accurately quantify the differences we need quantitative data on the production of virgin material without any reduction factors taken into account. This makes the overall EPD values unsuitable for evaluation of the environmental impact.

5.2.2. Human Toxicity

The Human Toxicity Potential is another important environmental impact indicator for the steel production process. It represents the adverse effect of pollutants on human health (Jonkers, 2018). This includes emissions of various harmful compounds to air, water or soil. Their relative contribution to the HTP is determined by the specific toxicity of the compound and it's concentration. According to Renzulli et al. some of the most harmful compounds released during the steel production process include dioxins, polychlorinated dibenzofurans (PCDDs and PCDFs), polycyclic aromatic hydrocarbons (PAHs) and heavy metals such as Mercury, Cadmium and Lead (Renzulli et al., 2016). Coal burning is a big source of PAHs, PCDDs and PCDFs hence why these pollutants are largely emitted during the coke oven and sintering process for the BOF route. Dioxins, PAHs and PCDDs are also an important source of high toxic airborne pollutants for the EAF route as described by Liu (Gomes, 2016; G. Liu et al., 2012). There is general consensus that these compounds can cause carcinogenic effects and they have been linked to various sorts of cancers in well-established studies. Breugelmans et al. have investigated the correlation between emissions emitted by the Tata steel plant in Ijmuiden and lung cancer cases in the surrounding areas. Although no indisputable conclusion could be drawn due to limited availability of data, an increased lung cancer incidence risk was observed (Breugelmans et al., 2013). As indicated in **Figure 30** the HTP is an important environmental indicator for both the BOF and EAF steel production process. However, this is not included in most EPD certificates as mentioned in paragraph 5.1.1.

It should be noted that the database from both the NIBE and NMD do include the human toxicity potential. However, as stated in paragraph 5.1.3 the values represented here are based on an expired EPD and the value denoted here of 33,3 kg 1,4-DB eq. per ton of steel is significantly lower than values found in scientific literature 929 and 424 kg 1,4-DB eq. respectively for virgin and recycled steel (Dorota Burchart-Korol, 2013). Since the difference factor is more than a tenfold the results for the human toxicity potential represented on this EPD can be considered questionable.

5.2.3. Particulate Matter Formation

Particulate Matter Formation is another important environmental impact indicator for the steel production process. This indicator is not included on the EPD certificate. According to the study by Burchart-Korol the emissions of fine particles account for 6,6kg PM_{10} eq. per ton of steel for the BOF route (Dorota Burchart-Korol, 2013). According to **Figure 30** this environmental impact indicator seems to have a major influence on to the total environmental impact, especially for the BOF route. This is in line with results from research by Ma et al. and Renzulli et al. which found 2,34 and 0,74 kg $PM_{2.5}$ eq. respectively for the BOF route (Ma et al., 2018; Renzulli et al., 2016).

Particulate matter formation is the sum of all organic and inorganic solid particles and liquid droplets emitted to air categorized by a specific aerodynamic diameter. The ReCiPe impact assessment method uses the PM_{10} categorization factor which is used to assess the fraction of particles with an aerodynamic diameter of 10µm or smaller. This complex mixture of inhalable particles contains various harmful microscopic particles which can be inhaled deep into the lungs where they can cause serious health problems (Goedkoop et al., 2013).

The European Union has extensive legislation on air quality standards and objectives (European Commission, 2018d). There is general consensus that emissions of both PM_{10} and $PM_{2.5}$ can cause serious health issues and annually leads to millions of premature deaths globally (European Environment Agency, 2017; World Health Organization, 2014). Therefore, it can be concluded that this specific environmental indicator should be taken into account when evaluating the environmental impact of steel production.

5.2.4. Acidification

The Acidification Potential (AP) is an environmental impact category indicative of the combined effect of various acidic pollutants or non-acidic compounds that produce acids in reaction with water. It is expressed in kg SO_2 equivalent. Acids can have detrimental effects on both soil and water, aquatic and terrestrial ecosystems or the individual organisms that form an integral part of these systems (Jonkers, 2018). For example the continuous increase of CO_2 levels in the atmosphere leads to an ongoing decrease in the pH of the Earth's oceans, caused by the uptake of carbon dioxide. Moreover, acids can also affect the built environment. Important acidifying compounds for the built environment are for example combustion gasses such as SO_2, NO_x and NH_4^+ which can lead to degradation of various building materials or structures.

Acidification Potentials in the examined EPDs range from 1,9 to 11,3 kg SO_2 eq. per ton of steel produced with an average value of 4,93 kg SO_2 eq. per ton of steel. Burchart-Korol indicates an AP of 6,95 eSO_2 for the BOF route and 2,96 eSO_2 for the EAF route (Dorota Burchart-Korol, 2013). For the BOF route the main contribution is due to NO_x and SO_x formation during the sinter process. For the EAF route the main contribution is due to the use of electricity which is mainly grey energy. This seems to be largely in line with the values published in the individual EPDs. It should however be noted that differences between the EAF and BOF route are significant and should be considered when assessing the environmental impact of a steel product.

5.2.5. Abiotic Resource Depletion

It should furthermore be noted that considering the long term future, iron ore reserves are not unlimited and on the long run this will exert extra pressure on steel markets. The crossover point between the amount of iron ore extracted and the amount left could be met as early as 2032. This will impact both the environmental impact as well as the costs of raw materials as ore grades will become lower due to depletion of reserves, there will be an increase of waste rock and mines will have to become deeper (Giurco, Mason, Prior, Mudd, & Behrisch, 2010; Yellishetty, Mudd, & Ranjith, 2011).

Moreover, the production of alloy steels requires addition of various scarce metals such as copper, manganese and nickel or rare metals to the mixture in order to enhance the mechanical qualities of steels. There are currently thousands of different alloys with small percentages of additive metals on the market. It is however impossible to extract these metals when recycling steel, these additives will therefore be lost in the recycling process. (D. Burchart-Korol & Kruczek, 2016; Yellishetty et al., 2011)

5.3. Comparison NMD & ReCiPe

In order to identify potential weaknesses in the current assessment method by the NMD a sensitivity analysis will be performed for the CML2 and ReCiPe method according to data by the NMD and a literature study by Burchart et al. which uses the more recent ReCiPe approach as a means of environmental impact assessment of the steel production process. For the purpose of this study a structural steel design with a total weight of 265,5 ton is considered which will be further elaborated in chapter 7. The total shadowcost of the steelwork is calculated for four different scenarios and is indicated in **Figure 31**. The specific data and weighting methods used for the four different scenarios are defined below:

- ***NMD***: For this scenario the certificate by the MRPI is used as registered in the NMD (MRPI, 2013). Module ***D*** is consciously excluded from the LCA as it should be according to ISO 14040. The impact is calculated with the use of the CML2 methodology.
- ***NMD + module D***: This scenario uses the same certificate as in the previous case but category ***D*** is included here in order to quantify the effect of including the end-of-life potential in the total shadowprice. For this method CML2 is used.
- ***BAU***: The BAU scenario assumes that the structural steel elements originate from Differdange, Luxemburg for which a different EPD is advised issued by ArcelorMittal (ArcelorMittal, 2018). For this method CML2 is used.
- ***Literature***: The literature scenario uses the values derived from the LCA study by Burchart et al. which uses the ReCiPe approach. Consecutively the specific weighting factors that correspond with this method have been used to determine the shadowprices.

	CML-2 baseline						***ReCiPe***	
	NMD		*NMD + module D*		*BAU*		*Literature*	
category	*unit*	*shadowprice*	*unit*	*shadowprice*	*unit*	*shadowprice*	*unit*	*shadowprice*
GWP	179250	€ 8.962,50	78175	€ 3.908,75	231615	€ 11.580,75	189157	€ 10.781,97
ODP	0,00306	€ 0,09	0,00233	€ 0,07	0,00049	€ 0,01	0	€ 0,00
HTP	6573,8	€ 591,64	4826,7	€ 434,40	9470,6	€ 852,35	84317	€ 1.736,93
POCP	65,146	€ 130,29	28,822	€ 57,64	14,397	€ 28,79	358,86	€ 753,61
PM							216,66	€ 11.157,74
IR							6203,8	€ 263,66
AP	667,25	€ 2.669,01	369,16	€ 1.476,64	479,15	€ 1.916,59	607,36	€ 387,50
EP	73,832	€ 664,49	43,628	€ 392,65	48,951	€ 440,56		
FEP							112,15	€ 199,63
MEP							35,06	€ 438,25
TAETP	92,39	€ 5,54	64,75	€ 3,89	136,67	€ 8,20	53,52	€ 68,50
FAETP	596,18	€ 17,89	227,02	€ 6,81	838,98	€ 25,17	1692,35	€ 67,69
MAETP	1251591	€ 125,16	900198	€ 90,02	196259	€ 19,63	1732	€ 0,00
LO	0	€ 0,00	0	€ 0,00	0	€ 0,00		
aLO							3480,37	€ 327,16
uLO							1044,60	€ 98,19
ADPe	-0,02645	€ 0,00	-0,00760	€ 0,00	0,09639	€ 0,02		
WDP							1157,97	€ 1.157,97
MDP							9960,19	€ 0,00
ADPf	1028,5	€ 164,56	606,76	€ 97,08	148,7	€ 23,79	46186,2	€ 0,00
		€ 13.331,16		**€ 6.467,96**		**€ 14.895,86**		**€ 27.438,80**

Figure 31: Impact assessment for production module A1 of a structural steel design using different LCA methods

From the results we can conclude that the specific method considered has a very significant impact on the estimated total environmental impact costs. If the total shadowprice for EAF steel is calculated according to ReCiPe the external costs of steel production are estimated to be twice as high as estimated by the means of CML2 and data from the NMD. Moreover, **Figure 31** illustrates that including module ***D*** in the calculation will lead to a significant underestimation of the external costs as the total price is approximately only half as much as would be the case without its use. Furthermore, **Figure 32** illustrates that *particulate matter formation* which is not explicitly included in the CML2 method as a single separate category, but rather distributed between various of the basic environmental impact categories, is a very important impact factor.

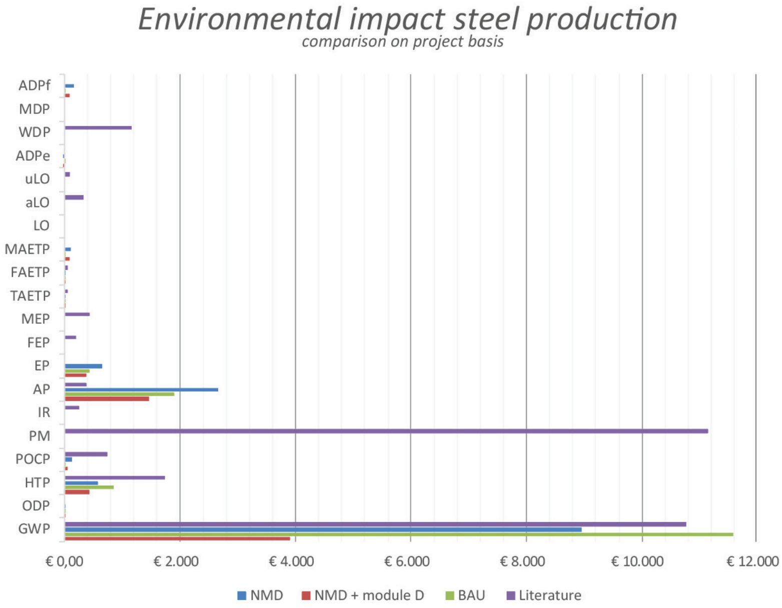
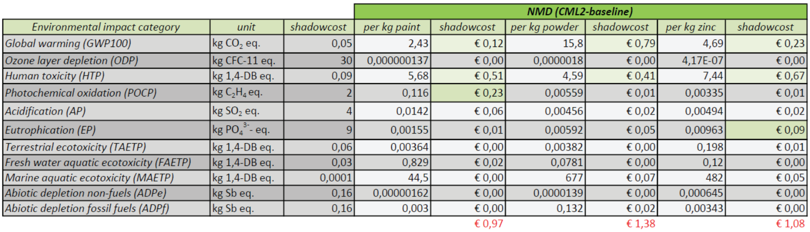


Figure 32: Impact assessment for production module A1 of a structural steel design using different LCA methods

5.4. Influence of coatings, galvanizing and spray painting

Finishing procedures such as fireproofing, powder coating, hot dip galvanizing or spray painting are generally outside of the scope of structural steel EPDs. There are many different coatings available and the environmental impact of these finishes is denoted on separate EPDs. In order to get a clear picture of the total environmental impact of a structural steel construction, the specific finishing procedures should always be included in the overall evaluation. From **Figure 33** it can be concluded that especially the influence on *human toxicity* and *the global warming potential* can be quite considerable. Moreover, for wet paint *photochemical oxidation* is an important factor.

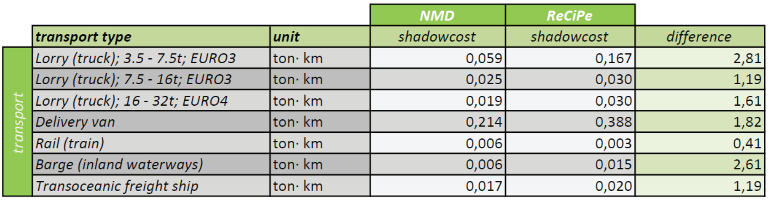


			NMD (CML2-baseline)					
Environmental impact category	*unit*	*shadowcost*	*per kg paint*	*shadowcost*	*per kg powder*	*shadowcost*	*per kg zinc*	*shadowcost*
Global warming (GWP100)	kg CO_2 eq.	0,05	2,43	€ 0,12	15,8	€ 0,79	4,69	€ 0,23
Ozone layer depletion (ODP)	kg CFC-11 eq.	30	0,000000137	€ 0,00	0,0000018	€ 0,00	4,17E-07	€ 0,00
Human toxicity (HTP)	kg 1,4-DB eq.	0,09	5,68	€ 0,51	4,59	€ 0,41	7,44	€ 0,67
Photochemical oxidation (POCP)	kg C_2H_4 eq.	2	0,116	€ 0,23	0,00559	€ 0,01	0,00335	€ 0,01
Acidification (AP)	kg SO_2 eq.	4	0,0142	€ 0,06	0,00456	€ 0,02	0,00494	€ 0,02
Eutrophication (EP)	kg PO_4^{3-}- eq.	9	0,00155	€ 0,01	0,00592	€ 0,05	0,00963	€ 0,09
Terrestrial ecotoxicity (TAETP)	kg 1,4-DB eq.	0,06	0,00364	€ 0,00	0,00382	€ 0,00	0,198	€ 0,01
Fresh water aquatic ecotoxicity (FAETP)	kg 1,4-DB eq.	0,03	0,829	€ 0,02	0,0781	€ 0,00	0,12	€ 0,00
Marine aquatic ecotoxicity (MAETP)	kg 1,4-DB eq.	0,0001	44,5	€ 0,00	677	€ 0,07	482	€ 0,05
Abiotic depletion non-fuels (ADPe)	kg Sb eq.	0,16	0,00000162	€ 0,00	0,0000139	€ 0,00	0,000645	€ 0,00
Abiotic depletion fossil fuels (ADPf)	kg Sb eq.	0,16	0,003	€ 0,00	0,132	€ 0,02	0,00343	€ 0,00
				€ 0,97		€ 1,38		€ 1,08

Figure 33: Impact factors for finishing methods; *wet paint*, *powder coating* and *galvanization* as defined by the NMD

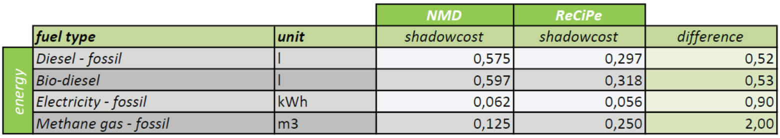
5.5. External cost of Transport

The NMD includes environmental impact factors for various modes of transport as illustrated in **Appendix 7**. In order to ensure that these values provide an accurate estimation of the environmental impact costs due to transportation values for various modes of transport according to CML2 will be compared with their ReCiPe counterparts derived from the STREAM report on freight transport, provided in **Appendix 8** (Otten et al., 2017). In **Figure 34** and **Figure 35** the total shadowcosts are calculated according to both CML2 and ReCiPe for various modes of transport and various fuel types. Subsequently, the calculated shadowcosts according to the ReCiPe method are divided by the calculated shadowcosts for CML2 which provides a difference factor. The difference factors indicate inaccuracies in the calculated external costs in the order of 0,5 – 2 times the outcomes as defined by the NMD. Hereby, we can conclude that the specific LCIA methodology and weighting factors used significantly influences the calculated total environmental impact due to transport. Large differences are to be expected for the estimated external costs between the various methods.



			NMD	ReCiPe	
	transport type	***unit***	*shadowcost*	*shadowcost*	*difference*
transport	*Lorry (truck); 3.5 - 7.5t; EURO3*	ton· km	0,059	0,167	2,81
	Lorry (truck); 7.5 - 16t; EURO3	ton· km	0,025	0,030	1,19
	Lorry (truck); 16 - 32t; EURO4	ton· km	0,019	0,030	1,61
	Delivery van	ton· km	0,214	0,388	1,82
	Rail (train)	ton· km	0,006	0,003	0,41
	Barge (inland waterways)	ton· km	0,006	0,015	2,61
	Transoceanic freight ship	ton· km	0,017	0,020	1,19

Figure 34: Comparison between the total shadowcost of various modes of transport for CML2 & ReCiPe



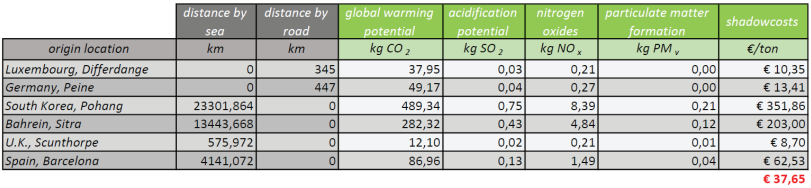
			NMD	ReCiPe	
	fuel type	***unit***	*shadowcost*	*shadowcost*	*difference*
energy	*Diesel - fossil*	l	0,575	0,297	0,52
	Bio-diesel	l	0,597	0,318	0,53
	Electricity - fossil	kWh	0,062	0,056	0,90
	Methane gas - fossil	m3	0,125	0,250	2,00

Figure 35: Comparison between the total shadowcost of various energy resources for CML2 & ReCiPe

5.6. Origin of steel construction products

The Netherlands has no production facilities for structural steel profiles and therefore depends on international trade to acquire structural steel products. This paragraph elaborates on the origin of steel products as an influential factor on the total environmental impact of steel construction works.

Firstly, the transportation module ***A2*** is directly dependent on the origin facility of structural steel products. Transport can become a significant contribution to the total impact when products are intercontinentally shipped. Most structural steel elements for the Dutch building industry originate from Germany and Luxembourg. However, statistics from the Dutch Central Bureau for Statics reveal that a share of about 20-30% of structural steel profiles is imported from other countries inside or outside of the EU as can be seen in **Figure 37**, **Figure 38** and **Figure 39**. In some cases this can significantly contribute to the environmental impact profile of a product. For example, when steel is imported from South Korea, the GWP caused by transport from the steel plant to a construction site in the Netherlands is estimated to be nearly 500 kg eCO_2 per ton of steel as indicated in **Figure 36** below. Other emissions will also increase accordingly which leads to a total amount of shadowcosts of approximately 350 €/ton of steel, according to the weighting factors determined by CE Delft (Otten et al., 2017). The average shadowcosts due to transportation from the production site to a manufacturing facility for profiles used in the Netherlands are calculated for the individual origin locations with the use of the import statistics from the CBS. Subsequently these values can be aggregated to determine an average for the environmental impact costs due to transportation of approximately 38 €/ton of steel as illustrated below.



	distance by sea	distance by road	global warming potential	acidification potential	nitrogen oxides	particulate matter formation	shadowcosts
origin location	*km*	*km*	*kg CO_2*	*kg SO_2*	*kg NO_x*	*kg PM_v*	*€/ton*
Luxembourg, Differdange	0	345	37,95	0,03	0,21	0,00	€ 10,35
Germany, Peine	0	447	49,17	0,04	0,27	0,00	€ 13,41
South Korea, Pohang	23301,864	0	489,34	0,75	8,39	0,21	€ 351,86
Bahrein, Sitra	13443,668	0	282,32	0,43	4,84	0,12	€ 203,00
U.K., Scunthorpe	575,972	0	12,10	0,02	0,21	0,01	€ 8,70
Spain, Barcelona	4141,072	0	86,96	0,13	1,49	0,04	€ 62,53
							€ 37,65

Figure 36: Environmental impact profile for emissions caused by transportation from various steel plants to a fabrication site in the Netherlands calculated according to ReCiPe methodology & STREAM data (Otten et al., 2017)

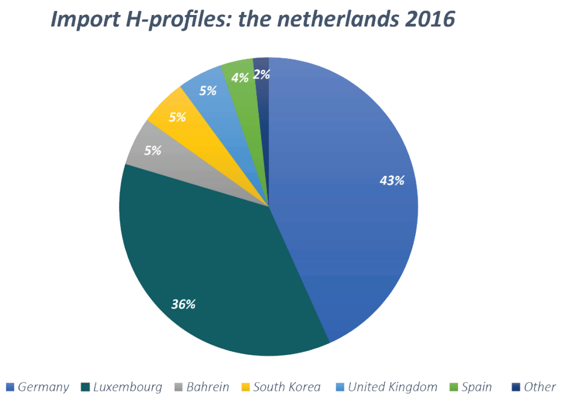


Figure 37: Import of structural steel H-profiles for the Netherlands (CBS, 2016)

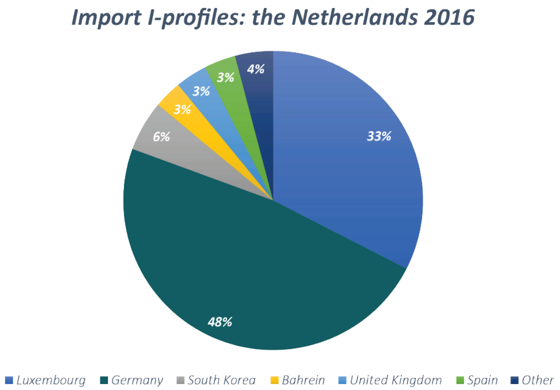


Figure 38: Import of structural steel I-profiles for the Netherlands (CBS, 2016)

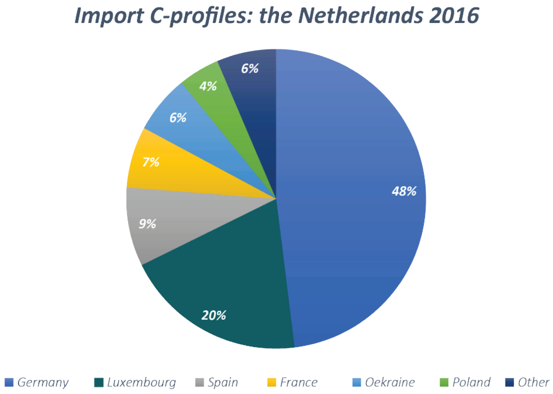


Figure 39: Import of structural steel C-profiles for the Netherlands (CBS, 2016)

Secondly, the international trade in steel products leads to uncertainty with regard to the specific production process of structural steel products. According to a report by the World Steel Association structural steel products originating from Luxembourg are solely produced by the EAF route. However, other countries such as Germany (71.2%), South Korea (67.1%), China (91%) and the United Kingdom (80.1%) mainly produce steel via the BOF route (Worldsteel Association, 2018e). Since the environmental impact profile for steel products produced via the EAF route significantly differs from steel produced via the BOF route, the origin of products is an essential influential factor for environmental impact assessment. EPDs such as the Dutch certificate from the MRPI assume that 90% of the steel used in the Netherlands is produced via the EAF route. However this percentage varies significantly between the various certificates analyzed ranging from 25-100% average recycled content (EAF route) as can be seen in **Appendix 1**.The actual national share of EAF route steel annually used is hardly verifiable since there is no transparent source of information on the specific origin of steel products available for the Netherlands.

Moreover the efficiency with regard to the environmental impact also depends on the origin of steel scrap. For example a small country with a very large EAF steel production capacity such as Luxembourg will have to import large quantities of steel scrap in order to fulfill its steel scrap demand. Unfortunately no data on the trade of steel scrap for Luxembourg could be obtained. However, information from the CBS on the export of steel scrap for the Netherlands, represented in **Figure 40,** indicates that the trade of steel scrap is a highly international trade and steel scrap is often transported over large distances to e.a. China or India.

Figure 40: Export of steelscrap for the Netherlands (CBS, 2016)

5.7. Origin of raw materials

Essential raw materials required for the virgin steel production process (BOF route) include iron ore, coal and limestone as discussed in paragraph 3.1.3. Import statistics from the CBS for the Netherlands indicate that there is a vivid international trade for these materials as illustrated in **Figure 41** and **Figure 42**. Iron ore mainly originates from Brazil and Scandinavia, coal is imported from Colombia and Russia and limestone generally comes from Belgium. This is in line with data from both international branch organizations as well as scientific literature on the origin of raw materials for steel production for the European market (Worldsteel Association, 2018e; Yellishetty, Ranjith, & Tharumarajah, 2010).

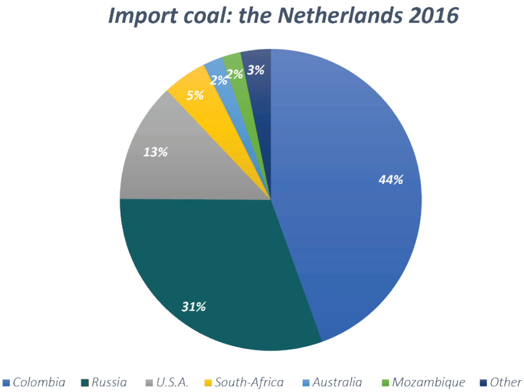


Figure 41: Import of coal for the Netherlands (CBS, 2016)

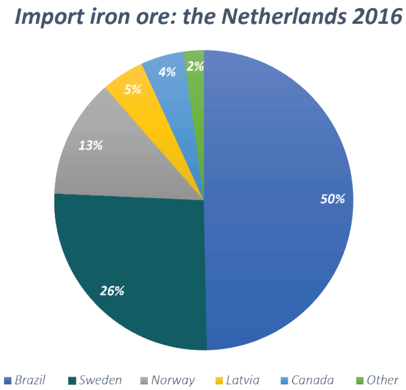


Figure 42: Import of iron ore for the Netherlands (CBS, 2016)

The transportation distances associated with the import of these materials are quite significant thereby resulting in considerate environmental impact due to transport as illustrated in **Figure 43** below. It can be questioned to what extent the environmental impact of transportation is considered for EPDs since for example the environmental cost of the sum of transportation of all raw materials needed to produce a ton of steel via the BOF route would attribute to approximately 500 kg CO_2 eq. per ton of steel produced alone. It is therefore questionable to what extent this is included in current EPDs. Without unrestricted access to the full LCA study it is impossible to determine which materials and processes are taken into account and evaluation of the accuracy and validity of the results is simply impossible.

	distance by sea	distance by road	distance by inland waterways	global warming potential	acidification potential	nitrogen oxides	particulate matter formation	shadowcosts
	km	km	km	kg CO_2	kg SO_2	kg NO_x	kg PM_v	€/ton
Colombia, Cerrejon	11828,724	330	0	284,70	1,56	11,36	0,24	€ 188,51
Russia, Raspadskaya	5796,76	0	3704	121,73	0,77	5,56	0,12	€ 125,76
U.S.A., North Antelope Rochelle	7256,136	3000	0	482,38	0,96	6,97	0,15	€ 199,57
South-Africa, Kangala	15264,184	560	0	382,15	2,01	14,65	0,31	€ 247,29
Australia, Peaks Down	23527,808	200	0	516,08	3,11	22,59	0,47	€ 361,27
Mozambique, Moatize	15064,168	30	444,48	319,65	1,99	14,46	0,30	€ 232,96

Figure 43: Environmental impact due to transportation of coal to NL as a raw material for steel production (CBS, 2016)

		impact due to transport (ReCiPe)	
		global warming potential (GWP100)	total shadowcosts
Raw Material	kg/ton steel	kg CO_2/ton	€/ton
Iron Ore	1400	254,40	152,98
Coal	800	213,13	140,47
Limestone	300	10,76	2,93
		478,29	296,38

Figure 44: Estimated average environmental impact due to transport of raw materials based on data by CBS & Worldsteel

5.8. Conclusions

According to the evaluation in the previous paragraph 5 it can be concluded that the current EPD system has several serious shortcomings with regard to transparency and accuracy. Thereby, the 'fast-track' LCA method for estimating the embodied environmental impact of building structures is not considered adequate in accurately assessing the environmental impact of steelworks. The production of steel products is a highly complex, internationally oriented process and partial representation of quantitative data as represented in EPD certificates delivers misleading messages for policy- and decision makers. The following paragraphs will elaborate on the conclusions that can be made according to the analysis in the previous chapter on the use of structural steel EPDs and the 'fast-track' LCAs for of building structures.

5.8.1. The 'fast-track' LCA Method

As discussed in paragraph 4.4.1 the 'fast-track' LCA method is frequently used in the Netherlands as an obligatory part of the documentation necessary to apply for a building permit. According to the previous chapter it can however be concluded that this method has several downsides and shortcomings which will be discussed in the following paragraphs.

5.8.2. Choice of Assessment Method & Weighting Factors

The current certification requirements for building products and the commonly used building industry 'fast-track' LCA methods are resulting in underestimation of the actual environmental impact of the embodied environmental impact of steel structures. In paragraph 5.3 a comparative analysis was performed for a specific structural steel design on the basis of currently used NMD data (CML methodology) and the values derived from scientific literature (ReCiPe). From the outcomes of this study it can be concluded that the choice of assessment method & the used weighting factors can greatly influence the total environmental impact. Furthermore, it was found that using a different assessment method provides a different picture of the most harmful effects.

Firstly, according to the observations in paragraph 5 it can be concluded that the EPD certificates for steel construction products do not suffice with regard to accuracy as two important environmental impact categories namely human toxicity and particulate matter formation are not included on the certificate. These two categories have a significant impact on the overall environmental impact score and should therefore be included in an accurate evaluation.

Secondly, it seems that there is significant inconsistency in published GWP values for the various EPDs that have been examined. This can partly be explained by the average recovered content mentioned on the certificates. This content depends on the specific origin steel plant mentioned on the certificate. However, whenever a fast-track LCA is conducted in order to obtain a BREAAM or LEED certificate there is no way to verify that products used in a specific construction will actually originate from a specific plant. When for example a certificate is used for structural steel sections produced by the Differdange plant in Luxembourg but eventually the steel used to build a specific steel structure will originate from a BOF plant in South Korea this will lead to a gross underestimation of the GWP.

It can be concluded that the use of LCA data from scientific publication would lead to a more accurate estimation of the environmental impact profile of structural steel products.

5.8.3. Specific origin of steel products

To provide an accurate estimation of the environmental impact of the steel production process it is moreover important to know the origin of structural steel elements. It can be concluded that there are significant differences among the various EAF and BOF steel plants. Furthermore, the origin facility also determines the impact for LCA module ***A2***. In paragraph 5.5 it has been demonstrated that the impact due to transportation can be quite significant depending on the origin of structural steel products. Users performing fast-track LCAs do not have the time or knowledge to perform an extensive background check on the most probable origin steel plants of products and the subsequent necessary transportation needs. Therefore average values are included in the NMD rather than a variety of data for various origin facilities (MRPI, 2013). Although this significantly simplifies the ‘fast-track’ LCA calculation process, it is also inevitably leading to significant inaccuracies as illustrated in chapter 5. As steel is one of the major construction materials and often accounts for a significant share of the total embodied environmental impact, it can be concluded that this poses a serious problem for the reliability and accuracy of current assessment methods.

5.8.4. Inclusion of fabrication process and finishing methods

The fabrication process is another important consideration for environmental impact assessment. Steel products will arrive at the steel fabricator in specific standard lengths where they will have to be cut to length, drilled, welded, sandblasted and often a finishing will be applied in order to make them ready for installation. This will result in energy consumption and a waste material stream for both virgin and circular steel products. Both material and energy use as well as waste material will need to be taken into account in environmental impact evaluations.

As mentioned in paragraph 5.3 finishing methods influence both environmental impact as well as price. The impact from various finishing procedures such as hot dip galvanizing, powder coating, spray painting and fireproofing should be quantified and included in the impact evaluation tool. In case acquired circular steel still has a finishing which is deemed sufficiently effective this will imply savings in terms of cost and environmental impact since only partial surface treatment (or no surface treatment at all) would be needed in contrast to full surface treatment for virgin steel products. **Figure 45** illustrates how the quality of a structural steel surface treatment can still be quite adequate after more than 20 years of service. The steel was acquired from a demolition project at Schiphol where the steelfabricator chose to deconstruct the building rather than demolishing it because the quality of the steel was still excellent. In case this steel would be reused sandblasting and a new full surface treatment would seem unnecessary and wasteful. However, in order to ensure the surface treatment is sufficient, testing and inspection procedures will need to be developed and implemented.

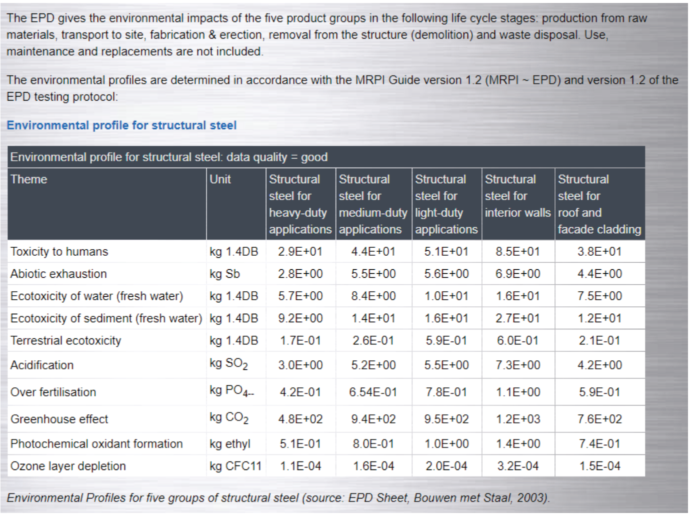
Figure 45: Circular steel inventory acquired through deconstruction of a warehouse - site visit Kampstaal 24/10/2018

5.8.5. Environmental Product Declarations

EPDs are an inextricable part of the 'fast-track' LCA method. For many building products the production modules ***A1-A3*** have the largest contribution to the total LCA environmental impact in an LCA. In order to perform an accurate 'fast-track' LCA it is therefore crucial that this data is reliable and verifiable. Conclusions with regard to the use and reliability of these product certificates are discussed in the following paragraphs.

5.8.6. Greenwashing

As the necessity to reduce the global anthropogenic environmental impact is becoming increasingly evident, many organisations are trying to contribute to positive change by providing supplementary information on the environmental impact of their products. In **Figure 46** below a screenshot is provided from the website of Bouwen met Staal (BmS), the branch organization for the steel industry in which the environmental impact for the 11 main categories according to the CML2 method is provided for various steel products. As mentioned above the table, the data is indeed in accordance with the MRPI. However, the values represented for 'structural steel for heavy-duty applications' are significantly smaller than would be expected based on the average values determined in paragraph 5.2.1. Taking a closer look at the denoted certificate by the MRPI (MRPI, 2013) illustrates that this difference can be explained due to the fact that module ***D*** appears to be subtracted from the aggregated results of modules ***A1-A3***. Although the lifecycle stages taken into account are noted above the table, and an observant LCA professional might conclude that reductions have been made due to category ***D***, this will unlikely be noticed by the general public. Representation of partial information on environmental impact in such a manner could thereby unintentionally lead to misinformation. As mentioned by Iacovidou inconclusive and partial LCA approaches will deliver misleading messages for policy- and decision makers (Iacovidou et al., 2017). It is therefore important to address the importance of data representation, transparency and accuracy. It is important to ensure that all actors in the building industry collaborate on improving the industry standards and procedures.



The EPD gives the environmental impacts of the five product groups in the following life cycle stages: production from raw materials, transport to site, fabrication & erection, removal from the structure (demolition) and waste disposal. Use, maintenance and replacements are not included.

The environmental profiles are determined in accordance with the MRPI Guide version 1.2 (MRPI ~ EPD) and version 1.2 of the EPD testing protocol:

Environmental profile for structural steel

Environmental profile for structural steel: data quality = good						
Theme	Unit	Structural steel for heavy-duty applications	Structural steel for medium-duty applications	Structural steel for light-duty applications	Structural steel for interior walls	Structural steel for roof and facade cladding
Toxicity to humans	kg 1.4DB	2.9E+01	4.4E+01	5.1E+01	8.5E+01	3.8E+01
Abiotic exhaustion	kg Sb	2.8E+00	5.5E+00	5.6E+00	6.9E+00	4.4E+00
Ecotoxicity of water (fresh water)	kg 1.4DB	5.7E+00	8.4E+00	1.0E+01	1.6E+01	7.5E+00
Ecotoxicity of sediment (fresh water)	kg 1.4DB	9.2E+00	1.4E+01	1.6E+01	2.7E+01	1.2E+01
Terrestrial ecotoxicity	kg 1.4DB	1.7E-01	2.6E-01	5.9E-01	6.0E-01	2.1E-01
Acidification	kg SO_2	3.0E+00	5.2E+00	5.5E+00	7.3E+00	4.2E+00
Over fertilisation	kg PO_4--	4.2E-01	6.54E-01	7.8E-01	1.1E+00	5.9E-01
Greenhouse effect	kg CO_2	4.8E+02	9.4E+02	9.5E+02	1.2E+03	7.6E+02
Photochemical oxidant formation	kg ethyl	5.1E-01	8.0E-01	1.0E+00	1.4E+00	7.4E-01
Ozone layer depletion	kg CFC11	1.1E-04	1.6E-04	2.0E-04	3.2E-04	1.5E-04

Environmental Profiles for five groups of structural steel (source: EPD Sheet, Bouwen met Staal, 2003).

Figure 46: Screenshot from the website of Bouwen met Staal which indicates environmental information for steel products

5.8.7. Variance between certificates

In **Appendix 1** a comparison was made between 13 different EPD certificates for structural steel products. From this comparative study it can be concluded that there is a significant spread of results as illustrated in **Figure 26** and **Figure 27** below. It is shown that among the various EAF and BOF certificates, there are differences in the order of the magnitude two or higher for almost every single category. Furthermore, some categories show a deviation of magnitudes of 10 or 100 times difference. Although some differences amongst various production facilities are two be expected, differences of this order of magnitude raise serious questions with regard to the reliability of certificates. As steel is one of the major construction materials, the proportion of primary load-bearing structures frequently contains a considerate amount of steel in the form of structural sections or rebar. As the environmental impact of steel is relatively high compared to other materials and the share of steel in the total weight of a construction can be quite considerable, the choice of a specific EPD can thereby greatly influence the LCA of a building structure. It is therefore important that the information contained in these certificates is accurate and verifiable. It can be concluded that the current practice does not fulfill either of these two requirements and that it is very likely that it is leading to underestimations in current ‘fast-track’ LCA calculations.

5.8.8. Data Reliability

The fact that manufacturers can publish their own EPDs raises serious questions with regard to the accuracy and verifiability of the certificates as mentioned in paragraph 5.1.2. In order to make accurate estimations on the environmental impact of materials, building products and constructions it is essential to have verifiable and unambiguous information. This requires manufacturers to be transparent with regard to emissions and waste streams which is currently not the case. Results from LCA studies on production processes should be published online and should always be verifiable by third parties, not only with regard to the assessment process but also the raw LCI data should be verifiable. This research has indicated that there is a clear discrepancy between scientific publications on environmental impact of steel production and information disclosed to the public by the industry. Information published in EPDs frequently provides a predominantly optimistic view of the environmental impact of products which will be elaborated on in the following chapters.

5.8.9. Category D

As discussed in paragraph 5.8.6 module ***D*** can cause confusion and including the end-of-life re-use, recovery and recycling potential in the overall environmental impact evaluation can send misleading messages. Module ***D*** is an advance on a future scenario which is still to a large extent uncertain. As illustrated in the certificate by the MRPI, the prescribed end-of-life potential of 51% recycling, 49% re-use (MRPI, 2013) is not consistent with the current C&D practice and causes a gross overestimation of the benefits. Moreover, taking into account the re-use, recovery and recycling potential as an advance hinders the incentive for actual reuse or recycling. In order to stimulate reuse and recycling for the C&D industry it is advised to allocate any environmental benefits at the moment products will actually be reused or recycled rather than including any future end-of-life potential to virgin products.

5.9. Recommendations

From the previous paragraphs on the methods and available data to assess the environmental impact of buildings the following conclusions and recommendations can be made:

- Literature indicates that reuse of heavy construction products is very uncommon and reuse rates of structural steel profiles are estimated to be between 5-10%. Although a building might be at its end-of-life, many of the structural steel components of which it is comprised are not. It is recommended that action is taken to increase the share of reuse and to invest in making this a viable alternative to recycling.
- The structural steel certificate by the MRPI registered in the NMD expired on the 8th of January 2018. It is an urgent matter to deal with this issue and it is recommended that swift and adequate action is taken to replace the current certificate as fast as possible.
- It should be noted that EPD certificates should strictly be used for products produced at the facilities listed on the certificate. Steel produced at plants that use the BOF route will have a significantly higher GWP and usage of EAF route certificates is therefore not acceptable.
- Next to the fact that this is a gross advance on future deconstruction scenarios, it also takes into account the recyclability of steel on both ends of the product lifecycle, both as an input and output advantage. The overall impact score indicated on the EPD often includes this reduction factor.
- It was found that HTP and PM are important environmental indicators for both BOF and EAF steel products. During the steel production process various compounds that pose

risks for human health are mitted. However, the HTP and PM categories are generally not included in EPD certificates. In order to make an accurate LCA for steel structures information on these categories is crucial.

- It is recommended to improve current recycling methods and sorting procedures for steel scrap in order to salvage various scarce metals that are added to steels to create high strength alloys. There are currently thousands of different alloys with small percentages of additive metals on the market. It can be questioned if this multitude of alloys is necessary. It is recommended to limit the amount of available alloys to improve recycling.
- It could be concluded that if the total shadowprice for EAF steel is calculated according to ReCiPe the external costs of steel production are estimated to be twice as high as estimated by the means of CML2 and data from the NMD. It is therefore recommended to use the more refined ReCiPe approach in the evaluation of steel structures.
- Furthermore it was concluded that including module ***D*** in the calculation will lead to a significant underestimation of the external costs as the total environmental costs are approximately only half as much as would be the case without its use. It is therefore recommended to omit module D for all LCA studies for the building industry.
- The environmental impact profile for steel products produced via the EAF route significantly differs from steel produced via the BOF route, the origin of products is thus an important essential influential factor for environmental impact assessment. It is therefore recommended that for an accurate LCA the origin location of steel products should always be taken into account.

Part III: Tool Development

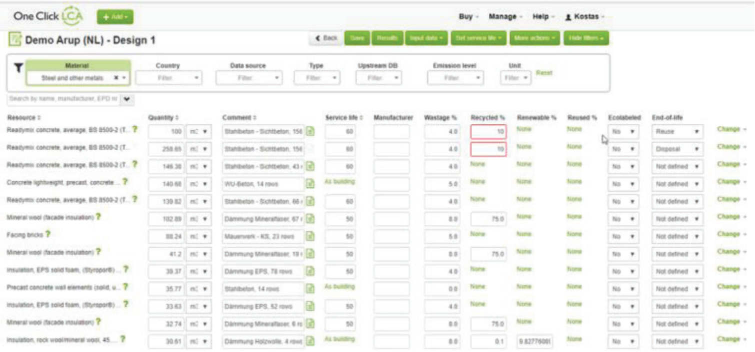
6 Circular Design Tool

This chapter will elaborate on the development of a digital assessment tool, which allows for evaluation of circular building designs, which has been created as part of this research in order to quantify the specific environmental benefits of circular building designs. Firstly, the design process will be discussed. It will be explained why the specific workflow was chosen, which software, parameters, data and calculation methods were used. Also, it will elaborate on the specific settings which should be used to generate a desired output. Secondly, the chapter will discuss the output data which can be generated by the tool. It will elaborate on the specific boundary conditions for which the tool applies, the reliability & variability of the output data and how the output could effectively aid structural engineers as well as policy & decision makers.

6.1. A tool to evaluate designs of circular steel structures

As research has pointed out in the previous chapters, there are several drawbacks with regard to the accuracy and transparency of current assessment methods used to evaluate the environmental impact of building structures in the Netherlands. Current methods are to a large extent ambiguous, non-transparent and tend to focus on the lifecycle energy efficiency of buildings rather than the ecological footprint of the structures themselves. Material efficiency and environmental impact reduction of building structures is only rudimentary considered in current assessment methods and is often subjected to various restrictions. This prevents building design professionals from effectively quantifying the environmental impact of their designs thereby impeding possible design improvements with regard to their environmental footprint.

Moreover, current methods do not allow for detailed evaluation of circular alternatives to traditional designs. Although some popular MPG calculation methods such as OneclickLCA and MPGCalc do allow for the allocation of percentages for circular materials, this only allows for design comparison on a very rudimentary level and the implied reductions come with a great amount of uncertainty, see **Figure 47**. In order to produce an accurate assessment of a design with circular steel profiles and to make an effective comparison between various design alternatives, current LCA assessment applications do not suffice.



Demo Arup (NL) - Design 1

Material: Steel and other metals
Country: Filter
Data source: Filter
Type: Filter
Upstream DB: Filter
Emission level: Filter
Unit: Filter

Search by name, manufacturer, EPD nr

Resource	Quantity		Comment	Service life	Manufacturer	Wastage %	Recycled %	Renewable %	Reused %	Ecolabeled	End-of-life	
Readymix concrete, average, BS 8500-2 (T...	100	m³	Stahlbeton - Sichtbeton, 156	60		4.0	10	None	None	No	Reuse	Change
Readymix concrete, average, BS 8500-2 (T...	258.65	m³	Stahlbeton - Sichtbeton, 156	60		4.0	10	None	None	No	Disposal	Change
Readymix concrete, average, BS 8500-2 (T...	146.38	m³	Stahlbeton - Sichtbeton, 43	60		4.0	None	None	None	No	Not defined	Change
Concrete lightweight, precast, concrete ...	140.68	m³	WU-Beton, 14 rows	As building		5.0	None	None	None	No	Not defined	Change
Readymix concrete, average, BS 8500-2 (T...	139.82	m³	Stahlbeton - Sichtbeton, 66	60		4.0	None	None	None	No	Not defined	Change
Mineral wool (facade insulation)	102.89	m³	Dämmung Mineralfaser, 67	50		8.0	75.0	None	None	No	Not defined	Change
Facing bricks	88.24	m³	Mauerwerk - KS, 23 rows	50		5.0	None	None	None	No	Not defined	Change
Mineral wool (facade insulation)	41.2	m³	Dämmung Mineralfaser, 19	50		8.0	75.0	None	None	No	Not defined	Change
Insulation, EPS solid foam, (Styropor®) ...	39.37	m³	Dämmung EPS, 78 rows	50		4.0	None	None	None	No	Not defined	Change
Precast concrete wall elements (solid, u...	35.77	m³	Stahlbeton, 14 rows	As building		0.0	None	None	None	No	Not defined	Change
Insulation, EPS solid foam, (Styropor®) ...	33.63	m³	Dämmung EPS, 52 rows	50		4.0	None	None	None	No	Not defined	Change
Mineral wool (facade insulation)	32.74	m³	Dämmung Mineralfaser, 6 ro	50		8.0	75.0	None	None	No	Not defined	Change
Insulation, rock wool/mineral wool, 45....	30.61	m³	Dämmung Holzwolle, 4 rows	As building		0.0	0.1	9.82776081	None	No	Not defined	Change

Figure 47: OneClickLCA – Allocating reuse and recycling percentages to certain construction materials (in red)

In order to improve the current environmental assessment capabilities for structural engineers, the evaluation and conclusions of current methods discussed in chapter 5 and 5.8 have been used to construct a detailed framework for environmental assessment and evaluation of load-bearing steel structures. The tool utilizes structural design data to determine material quantities and to provide an estimation of the environmental impact footprint of a given structural steel design. It is also possible to couple a database containing a wide variety of circular structural steel profiles in order to find possible substitutes which are suitable for re-use. The interface allows to user to make a quick visual assessment of the elements which could be replaced and provides feedback on the total environmental impact footprint of a certain design. Moreover, settings can be adjusted according to specific conditions as more information on the origin of structural steel products becomes available throughout the design process.

6.1.1. Goal

As explained earlier, the primary goal of this tool is to provide structural design & engineering professionals with a toolkit for quick, accurate and transparent quantification of the environmental impact of load-bearing structural steel building designs. Moreover, it allows for automated comparison between the design and a specific circular steel database to check if substitution of certain elements could be possible. Hereby it aims to improve structural steel building designs without compromising the standard structural engineering workflow. It should be noted that the developed tool is therefore not intended as a means to provide the engineer with design alternatives (which could be achieved by for example by optimizing the structural lay-out according to a given circular steel database). It should rather be conceived as a design check which provides suggestions for substitution of certain virgin elements with components from a reused marketplace. As these elements have a lower environmental impact, substitution will thereby improve the sustainability of a design.

The tool is first and foremost intended as a workable proof-of-concept to demonstrate the potential environmental benefits of structural steel reuse for the Dutch building industry. It should be regarded as a blueprint on how the improve the current practice rather than a finalized product. It aims to illustrate how the quantification of environmental benefits could provide engineers with an improved means to communicate with clients and collaborative partners on the subject of sustainability of construction works. Moreover, it would allow them to make suggestions on how designs could be improved by using circular components.

6.1.2. Scope

It should be noted that the tool only applies for certain conditions as defined by the specific domain and scope of this research discussed in paragraph 1.3.4. Therefore the tool has several restrictions and limitations of which the user should be aware:

- *Dutch building industry*: The tool is specifically intended for use within the Dutch building industry. Specific national data was used where possible and assumptions were made based on particular circumstances in the Netherlands. The tool should therefore not be used for the evaluation of construction works outside of the Netherlands without consulting the author.
- *Steel works*: It is specifically focused on the evaluation of steel works. Other structural materials are beyond the scope of this research and other common construction materials such as concrete and wood are disregarded by the script.
- *Load bearing structural framework:* It only evaluates the structural framework of load bearing structural steel works. All other parts of the superstructure, substructure and structure such as floors and walls are beyond the scope of this research.
- *Limited number of element typologies*: The tool only regards the most commonly available structural steel member families for H- and I- profiles available in the EU namely HEA, HEB, HEM and IPE. Other profiles are disregarded by the tool. It should however be noted that for simplification purposes the eventual analysis was performed for a construction only consisting of HEA and IPE profiles as will be explained further on.
- *Abstraction of connections and specific finishing methods*: In order to allow for the tool to be used in early design stages, when there is still uncertainty with regard to specific connection details and finishing requirements, an approximation is made based on an assumption of general conditions for manufacturing processes, average endplate thicknesses and surface finishings.

6.1.3. Functional unit

The specific total environmental impact performance of a design is provided by the functional unit *€ / m^2 / year*. The price is related to the financial costs which would be needed to mitigate the environmental impact incurred by a specific structural steel design, also known as shadowcosts (Ahdour et al., 2018). The area is expressed as the effective total built floor area contained within the building; the Gross Floor Area (GFA). Furthermore, in order to allow for comparison of the results with currently prescribed LCA methods such as MPG, it is important to ensure that the effect of building service life on the environmental impact of a structure is taken into account. Therefore the shadowcost per GFA are divided by the expected technical service life of the structure. In case of industrial warehouses the reference period is assumed to be 50 years.

6.1.4. Environmental impact categories considered

To provide an unambiguous and transparent representation of the total environmental impact, results are initially provided in an itemized manner for the individual impact categories and the various LCA modules. Subsequently results are weighted and aggregated in order to allow comparison between the various impact categories and life cycle stages. This particular assessment method considers the following 11 relevant environmental impact categories as defined by the CML2 method as used by the NMD in the national LCA database for building materials. This specific LCA method is discussed in paragraph 4.6.1 and the various environmental impact categories are expressed in the units listed below:

- **GWP** *Global Warming Potential* (kg CO_2 eq.)
- **ODP** *Ozone Layer Depletion* (kg CFC-11 eq.)
- **HTP** *Human Toxicity Potential* (kg 1,4-DB eq.)
- **POCP** *Photochemical Oxidant Formation Potential* (kg NMVOC eq.)
- **AP** *Acidification* (kg SO_2 eq.)
- **EP** *Eutrophication* (kg PO_4^{3-} eq.)
- **TAETP** *Terrestrial Ecotoxicity* (kg 1,4-DB eq.)
- **FAETP** *Freshwater Ecotoxicity* (kg 1,4-DB eq.)
- **MAETP** *Marine Ecotoxicity* (kg 1,4-DB eq.)
- **ADPe** *Abiotic Depletion Non-fuel* (kg Sb eq.)
- **ADPf** *Abiotic Depletion Fuel* (kg Sb eq.)

6.1.5. Software

Various software packages and plugins have been used to produce a functional tool which comfortably fits with the current workflow at structural design & engineering firms. Below is an overview of the software and tools which have been used along with a brief description:

- *Autodesk Revit Structure*: BIM software frequently used by various designing disciplines in the building industry. It is widely used by engineering firms to construct 3D models of designs and to produce construction drawings through integrated 2D drafting elements.
- *Dynamo*: Visual scripting language add-on for Revit. Used to extract necessary structural design data from Revit.
- *Microsoft Excel*: A spreadsheet developed by Microsoft which includes various features for data calculation, pivot tables and visual representation tools. It was used to compile various lists with information which serve as input for Grasshopper.
- *Rhinoceros 5.0*: A 3D free form surface modelling tool for engineers developed by Robert McNeel & Associates widely used for computer-aided design in the professional fields of architecture and structural engineering.
- *Grasshopper*: Visual scripting language add-on for Rhinoceros. It allows the user to create a program by placing components on a canvas and connecting them. It was used to create the script which evaluates the environmental impact, to construct a 3D geometry in Rhino and to produce the user interface.

- *Karamba3D*: Is a parametric structural engineering plugin for Grasshopper. It is used to create the geometry of a specific structural building design in Rhino.
- *HumanUI*: A Grasshopper plugin which includes elements that allow users to create a custom user interface. It is used to build the user interface for the tool.
- *Python*: A Grasshopper plugin which allows the user to define and execute python scripts for specified input and output channels.

6.1.6. Workflow

The proposed digital workflow for the evaluation of structural steel designs is based on the general structural design process for steel structures at Arup Amsterdam. It is assumed that this approach is to a large extent representative of the universal structural design & engineering practice and that this well ensure effective integration of the tool in the structural design process. Structural engineering professionals often use a variety of software for design development specifically focused on e.g. structural analysis, -calculations or the production of construction drawings. The exchange of information between different platforms is therefore becoming increasingly important in the structural engineering practice. In order to improve cross-platform exchange of information as well as potential collaboration with other disciplines and clients the platform neutral Industry Foundation Classes (IFC) open file format was chosen as a means to exchange information between platforms in combination with Microsoft Excel spreadsheets. Below is a brief description of the various phases of the proposed workflow

- *Data extraction*: Firstly a selection of BIM data is extracted from a specific structural design developed in Revit with the help of a custom built Dynamo script, **Appendix 2**. As Revit is extensively used throughout the various stages of design from conceptual design up to the construction documentation phase this seems a good source of data for the purpose of the tool. The dynamo script organizes and exports the acquired data to an Excel spreadsheet for which an example can be found in **Appendix 11**. For the intended purposes of this research data extraction by the current script is limited to the following information;
    - unique ID,
    - profile type
    - component startpoint (x,y,z coordinates)
    - component endpoints (x,y,z coordinates)

  However, additional information which could potentially improve the current assessment method such as e.g. steel strengths, connection details or other specific characteristics can easily be added to the script.
- *Re-use assessment*: Subsequently the grasshopper script imports the design data stored in the Excel file as a data tree and compares the information with a custom ‘circular steel database’, which is imported in the same manner by means of an Excel file. According to several customizable parameters the script will then determine if certain steel profiles can be replaced by their circular counterparts. The script provides feedback by means of generating a virtual building model in Rhino in which the components that could potentially be replaced are highlighted. Consecutively the

total tonnages of virgin steel, circular steel and waste material are determined for environmental evaluation.

- *Environmental evaluation*: This process uses LCA data on various processes, contained in Excel files, to determine the environmental impact of the structural steel design based on the quantities of virgin steel, circular steel and waste material. The various environmental impact categories are normalized according to the defined weighting factors and aggregated to produce an indication of the shadowcosts expressed in *€ / m² / year*.
- *Output generation*: With the help of the HumanUI plugin a user interface is created in which various parameters can be adjusted according to specific preferences. Customizing these settings will influence the environmental impact of the structure and will generate a specific total environmental impact score for a given design as well as a 3D representation of the structure in which the potential circular components are highlighted.

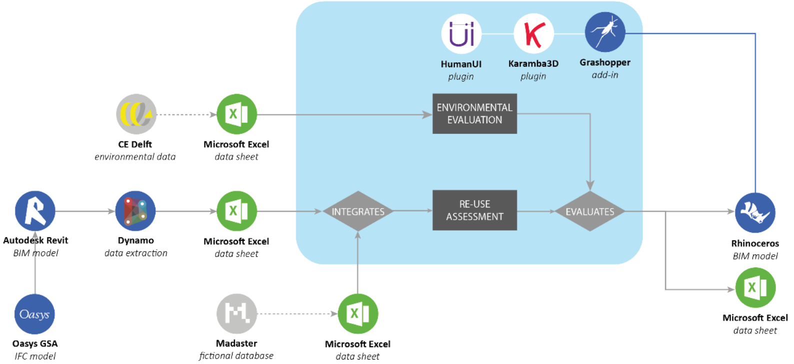


Figure 48: Schematic of the workflow for the environmental impact evaluation tool

6.1.7. System boundaries

The ‘fast-track’ LCA method for building structures considers the complete LCA *cradle-to-grave* scope as defined by EN15804 illustrated in **Figure 49**. In principle this includes all life-cycle stages A-D within the system boundaries. However, as mentioned in paragraph 5.1.1 the only consistently declared stages among the various structural steel EPDs are the *cradle-to-gate* stages A1-A3 as EN 15804 dictates that other modules may be omitted if deemed necessary. However, it is also stated that this should always be explicitly justified which is often not the case.

Although some of the stages will also be omitted in this particular assessment process, it is always explicitly stated which modules are omitted and why in order to ensure transparency of the assessment method and compliance with EN15804 as well as ISO14040. The tool will quantify the environmental impact for the 11 environmental impact categories as specified by the NMD (CML2-baseline) listed in paragraph 6.1.4 in order to calculate the total shadowcost. The specific influence of the various modules and their limitations are elaborated on below.

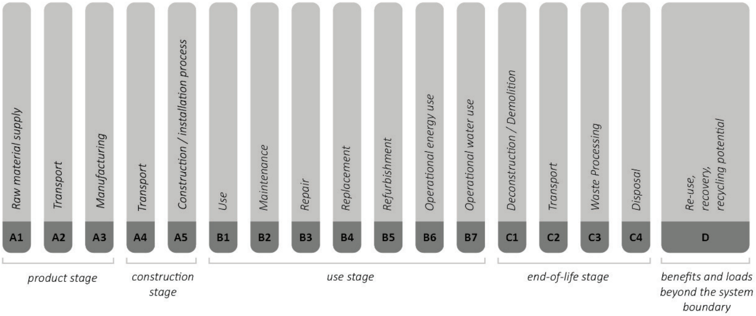


Figure 49: Various LCA Life-cycle stages specified in EN 15804:2012

- *Production stage (A1-3)*: The cradle-to-gate modules **A1-A3** cover raw material extraction and supply, transport to the production site, manufacturing and all associated processes. For structural steel members this includes all essential processes up until the ‘gate’ of the steelplant. These modules are relevant for virgin steel only i.e. products that are produced through the EAF or BOF production process.
- *Construction stage (A4 and A5)*: **A4 and A5** are also considered. Although these stages are often excluded in structural steel EPDs the transportation stage A4, the transport from the production site to the construction site, can actually be quite relevant dependent on the weight and size of products as well as their origin as discussed in paragraph 5.5. Also, as Hoeckman pointed out, although the installation process might be considered a grey area and it will have a low contribution to the total impact of a steel structure, it still can be approximated to a certain extent by considering the individual fabrication and installation processes (Hoeckman & Nelis, 2012).

- *Use stage (B1-7)*: Although the operational energy and water use requirements of buildings are quite significant and frequently tend to be larger than the impact of the construction itself, the use phase is beyond the scope of this particular research. The goal of this research is limited to quantifying the embodied environmental impact of the structure itself. The operational energy use module *B6* and water use module *B7* are therefore disregarded. Furthermore, as the load-bearing structure of the considered building solely consists of steel, the use, replacement, repair, refurbishment or maintenance stages *B1-B5* also don't need to be considered, as steel structures are highly durable by nature.
- *End-of-life phase (C1-4)*: The end-of-life phase is partially considered in this method. Module C3 and C4 are beyond the scope of this research but module **C1 and C2** can be considered as an 'alternative to module A1'. In these modules, structural steel components are 'extracted' from the obsolete building and transported to a specialized stockist for re-use. It should be noted that the sequence in which the various phases are considered differs from the standard procedure described in EN15804:2012.
- *Re-use, recovery and recycling potential (D)*: Module **D** plays an important role in this assessment method as the comparison between the use of virgin steel versus circular steel is a central part of this LCA. However, this stage is also used differently than prescribed by EN15804. Rather than considering it as a load or benefit beyond the system boundary thereby providing an environmental impact reduction based on an assumption of the end-of-life scenario. Category D is considered as an alternative module for the traditional production & construction stages. As it was explained in paragraph 5.8.9 the allocation of reductions to the final process

6.1.8. Supply chain modelling

In order to allow for effective evaluation and comparison between various design strategies, a general distinction is made between four primary supply chain models for structural steel profiles namely; direct reuse, indirect reuse (remanufacturing), recycled steel (EAF) and virgin steel (BOF). Every supply chain has its own particular primary activities, input materials and corresponding consequences with regard to the environmental impact categories, which should be considered for the various modules of **Figure 49**. The LCA method considered for both reuse scenarios is based on the ideology 'urban mining' in which buildings are considered to be 'material banks' from which materials can be harvested (Rau & Oberhuber, 2016). Therefore module C is considered as the starting point for these two re-use supply chains. The distinction between the various supply chains is elaborated on below.

- *Virgin steel - BOF*: For both BOF and EAF steel modules A1-5 will be considered according to **Figure 50**. The BOF supply chain encompasses the entire product system with interlinked activities from raw material extraction up unto the construction/installation module. It considers the production of the structural steel profile but also considers manufacturing and assembly processes such as cutting, drilling, welding and coating together with material losses.

- *Virgin steel - EAF*: Virgin steel also considers modules A1-5. However, as mentioned in paragraph 3.1.4 there are significant differences as the EAF steel requires steelscrap as a primary input material rather than raw materials. The various production processes as well as transportation requirements are considerably less resource intensive. Therefore the various environmental impact factors will be significantly lower compared to BOF steel.

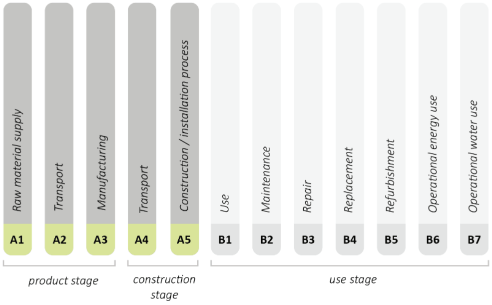


Figure 50: Considered LCA life-cycle stages in this assessment for virgin steel (EAF and BOF)

- *Indirect reuse (remanufacturing)*: This product system starts with module C1-C2 where the building is strategically deconstructed and elements are extracted from the obsolete building. Consecutively module D, which considers re-use, recovery and recycling, is considered. Thereby, this method differs from the standardized assessment process defined by NEN 15804:2012. Category D can be subdivided into a remanufacturing stage and construction stage. These stages are actually quite similar to the production and construction stage defined by module A1-5, illustrated in **Figure 50**. However, The specific assessment process is illustrated in **Figure 51**. The inventory analysis process tree can be found in **Appendix 3**.

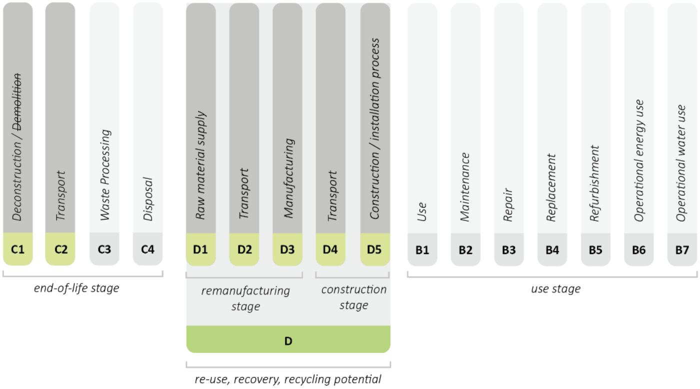


Figure 51: Considered LCA life-cycle stages in this assessment for indirect steel re-use.

- *Direct reuse*: This system is based on the fact that some elements can possibly be directly re-used after disassembly without any alterations. The system starts with end-of-life stages C1 and C2 in which the structure is deconstructed and elements are subsequently transported to a specialized stockist. Here structural steel members are temporarily stored and they can be tested to assess structural properties. Elements can be bought from an online marketplace for circular structural steel components. When they are ordered, elements can be directly transported to the construction site to be installed according to module D4 and D5. The inventory analysis process tree can be found in **Appendix 4**.

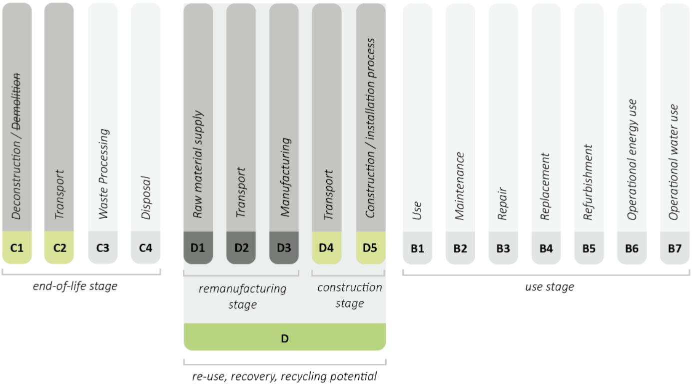


Figure 52: Considered LCA life-cycle stages in this assessment for direct steel re-use.

6.1.9. Assumptions

In order to improve the functionality of the tool several simplifications were made for the consecutive manufacturing and construction stages. There is general consensus that design professionals have the most influence on the final product during the initial design stages. In order to ensure that the proposed tool is usable in the early structural engineering design phases, when the most significant improvements can be accomplished, the following assumptions were made:

- *Connection details*: In this study an environmental impact assessment is made based on a preliminary design. In this design stage there is no definite information available on the specific detailing of connections. Moreover, detailing for steel constructions is often performed by the steel contractor and not part of the work of structural engineering firms. Therefore, specific manufacturing conditions are disregarded for the purpose of this study. Instead assumptions are made based on average requirements for the various manufacturing processes which are part of module A3 and D3 such as e.g. endplate requirements, cutting, drilling, welding and coating.
- *Steel strengths*: The specific steel strength is an important characteristic that determines the load-bearing capacity of steel profiles. The specified steel strength

specified by the structural engineer should therefore always be respected. In the re-use design process application of a lower steel strength is explicitly prohibited. However, it could potentially be considered to overdimension an element and to use a higher steel strength than specified. A potential future marketplace for structural steel elements should therefore always denote the characteristic steel strength of a profile. However for the purpose of this case study we will assume that all steel elements have a steel strength of S235.

- *Finishings*: In order to simplify the assessment method it is assumed that profiles considered for direct reuse do not need to have a protective coating re-applied. However, for virgin steels and indirect reuse a coating will have to be taken into account when assessing the environmental impact. A choice can be made between wet painting, powder coating and hot-dip galvanizing.
- *Origin locations*: As the specific origin of products is unknown at the design stage assumptions will be made according to the most probable origin facility based on import statistics and the production capacity of various international steel plants.

6.1.10. Output

The output of the tool consists of two three main components; a detailed overview of the environmental impact profile of a design, a table in which the matching profiles are provided and a virtual building data model containing the geometry of the structure and various characteristics of the individual components. Furthermore, additional information is provided by means of a map indicating origin locations of circular elements as well as a rudimentary cost calculation in order to provide an initial estimate of the associated costs. The content of these various output channels are discussed below:

- *Virtual BIM model*: The BIM model is a visual representation of the steel building construction in which circular profiles from the database are linked to elements in the design. Elements that could potentially be replaced are highlighted in order to give a quick indication of the potential replacements. The BIM model data can also be sent back to Revit in order to include information on the origin of circular components in the final construction documents.
- *Environmental impact assessment*: The environmental impact assessment quantifies the environmental impact for various production, construction and deconstruction modules. Consecutively, the total environmental impact in terms of the functional unit defined in paragraph 6.1.3 is provided. Moreover, the application provides feedback for the individual environmental impact categories on a separate tab. Here, a comparison can be made between a ‘regular’ design and a ‘circular’ design. By means of a visual representation for the various 11 impact categories it can easily be identified which components are the main contributing factors to the total impact. Furthermore, the tool indicates the benefits in terms of shadowcost savings, reduction of the GWP and the material savings. Altogether this provides the designer with instantaneous feedback on certain design alternatives and allows for quick comparison between various design properties.

- *Table with matching profiles:* Another important feature is the table in which all the structural profiles included in the model are listed. The modelled elements are linked to their database counterparts and necessary information with regard to acquisition and remanufacturing is provided such as unique database IDs, origin locations and cut lengths. This information is interchangeable with Revit and can subsequently be sent back in order to include these details in the final construction drawings.
- *A map with origin locations:* In order to provide the user with a quick indication of the logistics associated with reuse, a visual representation is provided in the form of a map which displays both the construction site and origin locations. Furthermore the amount of elements originating from a specific origin is also provided so the user can decide if it would be appropriate to acquire elements from that specific stockist.
- *Indication of financial costs:* A rudimentary costs calculation is provided as an initial indication of the financial consequences of using circular steel profiles. The calculation is primarily based on the work by Dunant et al. (Dunant et al., 2018) in combination with local data acquired from a structural steel manufacturer in the Netherlands. The purpose of this feature is to provide an indication of how the inclusion of environmental costs would influence the total sustainable selling price as illustrated in Figure 18. It should be noted that the calculation should therefore be considered as a rough first estimate of the economic feasibility in the design stage rather than an accurate indication of the eventual financial costs. The specific data used and its limitations will be elaborated on in paragraph 6.2.

6.2. Source data

This paragraph elaborates on the source data that was used to calculate the environmental impact profiles of the various product systems and their interlinked activities. For the most part information supplied by the NMD has been used for this purpose as this database contains national averages for a wide variety of products and processes for all necessary environmental impact categories prescribed by CML2-baseline. However, for the purpose of this study environmental impact data has also been derived from various EPD certificates which can be selected in order to allow for the evaluation of various scenarios.

6.2.1. Environmental base-line data: selection EPDs

In the early design stages there is generally no information on the specific building products that will be used in the eventual construction stage. It is not until the design is nearing completion before the client can put out a bid for the construction work and a specific general contractor can selected. In turn, the general contractor needs advanced construction documents and technical specifications to put them out to subcontractors for bids on sub-components. It is therefore generally not possible to make an accurate estimation of the specific origin of construction materials during the design stage. As the choice for a specific steel supplier is thus not made until the design is nearly finished, average characteristic values will have to be used for this assessment as specific conditions are to a large extent unknown at the design stage. Therefore, national averages are obtained from the NMD in order to provide an initial estimation of the environmental impact profile of design alternatives at an early design stage. Due to the fact that this method is opensource and the used data is easily accessible and adjustable, the input data can be finetuned at a later stage as more detailed information will become increasingly available providing an increasingly accurate estimation of the eventual environmental impact.

However, as it was concluded in paragraph 5 the specific certificate used for heavy steel products published by the MRPI in 2013 has several serious shortcomings. Therefore the tool enables the user to select a specific EPD certificate as the user seems fit. The application makes a distinction between structural steel profiles and steel plate material as, according to interviews conducted with several steel manufacturers, these often originate from different facilities. Individual certificates can be selected for the base-line cradle-to-gate ***A1*** module for both structural profiles as well as endplate material. The specific EPD data used for the reference study described in chapter 7 can be found in the overview in **Appendix 1**.

6.2.2. Transportation

The impact of the intermediate transportation processes are estimated according to the values for the various environmental impact categories provided in the latest version of the NMD (accessed: March 2019) for various modes of transport. The NMD contains average values which are characteristic for the Netherlands. This data can be used to determine the environmental impact for module ***A2*** as well as ***A4***. Various modes of transport are considered such as transport by truck, train and freight transport. In order to determine an average transport distance between countries, a specific origin facility within a country was selected based on the fact that it was listed as the largest facility within that specific country. To make an accurate approximation of the transport distance, based on origin and destination locations, the most logical chain of transport was considered e.a. prioritizing transport by water over land and transport by train over truck. Consecutively navigation software and information on shipping routes was used to determine the partial distances. Specific distances can be selected with the use of sliders on the dashboard which are linked to the Grasshopper script as illustrated below in **Figure 53**. The specific LCA data used for the purpose of this study can be found below in **Figure 54**. A more extensive overview of possible modes of transport as provided by the NMD can be found in **Appendix 7**.

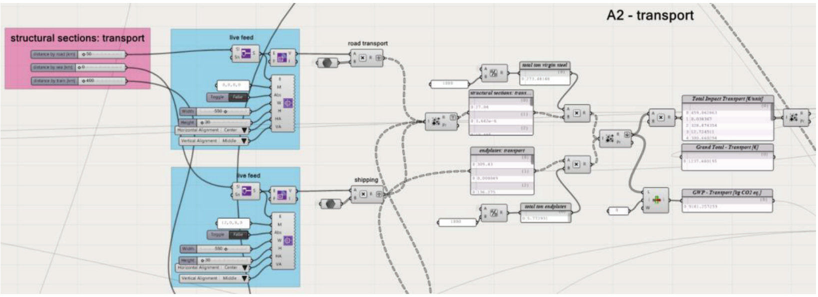
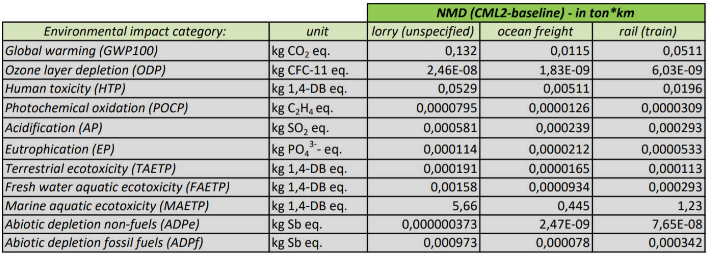


Figure 53: Snapshot of part of the GH script in which the total impact due to transport is calculated.



		*NMD (CML2-baseline) - in ton*km*		
Environmental impact category:	*unit*	*lorry (unspecified)*	*ocean freight*	*rail (train)*
Global warming (GWP100)	kg CO_2 eq.	0,132	0,0115	0,0511
Ozone layer depletion (ODP)	kg CFC-11 eq.	2,46E-08	1,83E-09	6,03E-09
Human toxicity (HTP)	kg 1,4-DB eq.	0,0529	0,00511	0,0196
Photochemical oxidation (POCP)	kg C_2H_4 eq.	0,0000795	0,0000126	0,0000309
Acidification (AP)	kg SO_2 eq.	0,000581	0,000239	0,000293
Eutrophication (EP)	kg PO_4^{3-} eq.	0,000114	0,0000212	0,0000533
Terrestrial ecotoxicity (TAETP)	kg 1,4-DB eq.	0,000191	0,0000165	0,000113
Fresh water aquatic ecotoxicity (FAETP)	kg 1,4-DB eq.	0,00158	0,0000934	0,000293
Marine aquatic ecotoxicity (MAETP)	kg 1,4-DB eq.	5,66	0,445	1,23
Abiotic depletion non-fuels (ADPe)	kg Sb eq.	0,000000373	2,47E-09	7,65E-08
Abiotic depletion fossil fuels (ADPf)	kg Sb eq.	0,000973	0,000078	0,000342

Figure 54: Environmental impact factors used for transportation from the NMD

6.2.3. Manufacturing

Data on the environmental impact of the manufacturing and remanufacturing processes, module ***A3***, are derived from values provided by the NMD for various energy sources such as the impact per kWh electricity used and the impact per m^3 of natural gas listed in **Appendix 7**. For the purpose of this study the factors for *electricity, renewable (average NL)* and *natural gas* were used in combination with information provided by a large steel manufacturer in the Netherlands to derive the average impact for the manufacturing module ***A3*** due to energy and gas consumption. For simplification purposes, the various environmental impact factors per ton of steel are provided for the manufacturing process as a whole rather than subdividing the manufacturing process into subprocesses such as example drilling, cutting, marking and overhead costs. Thereby the impact could easily be calculated by using the total annual energy and gas consumption data provided by the steel manufacturer as illustrated in **Figure 55**.

		NMD (CML2-baseline)			
Environmental impact category:	*unit*	*per kWh*	*per mt steel* [1]	*per m^3*	*per mt steel* [1]
Global warming (GWP100)	kg CO_2 eq.	0,101	10,49	2,09	14,79
Ozone layer depletion (ODP)	kg CFC-11 eq.	4,51E-09	4,68E-07	0,00000013	9,2E-07
Human toxicity (HTP)	kg 1,4-DB eq.	0,0613	6,3657	0,124	0,8775
Photochemical oxidation (POCP)	kg C_2H_4 eq.	0,0000558	0,00579	0,000138	0,00098
Acidification (AP)	kg SO_2 eq.	0,000576	0,05982	0,000994	0,00703
Eutrophication (EP)	kg PO_4^{3-}- eq.	0,000131	0,013604	0,000174	0,001231
Terrestrial ecotoxicity (TAETP)	kg 1,4-DB eq.	0,0091	0,9450	0,000655	0,0046
Fresh water aquatic ecotoxicity (FAETP)	kg 1,4-DB eq.	0,00155	0,16096	0,000807	0,00571
Marine aquatic ecotoxicity (MAETP)	kg 1,4-DB eq.	5,1	529,6	4,81	34,0
Abiotic depletion non-fuels (ADPe)	kg Sb eq.	0,00000198	0,0002056	0,000000139	0,0000010
Abiotic depletion fossil fuels (ADPf)	kg Sb eq.	0,000314	0,032608	0,0179	0,126677

Figure 55: Environmental impact derived for the manufacturing process based on data by a large steel manufacturer

Furthermore, it is important to take into account the specific surface finishing in order to make an accurate estimation of the impact due to module ***A3***. According to the steel manufacturer the average coating thickness for structural steel elements is around 80 μm and according to NEN-EN-ISO 1461:2009 hot-dip galvanizing requires a thickness of 85 μm of zinc (Galvanizers Association, n.d.; Zinkinfo Benelux, 2019). The environmental impact due to *wet paint protective coating*, *powder coating* and *galvanization* is determined by calculating the total kg of coating material based on the required coating thickness and the exposed surface of the steel (determined by profile types and element lengths according to the model considered and the steel tables in **Appendix 5**) as illustrated in part of the grasshopper script below in **Figure 56**. The environmental impact factors that are used were derived from the NMD and are provided in **Figure 57** below.

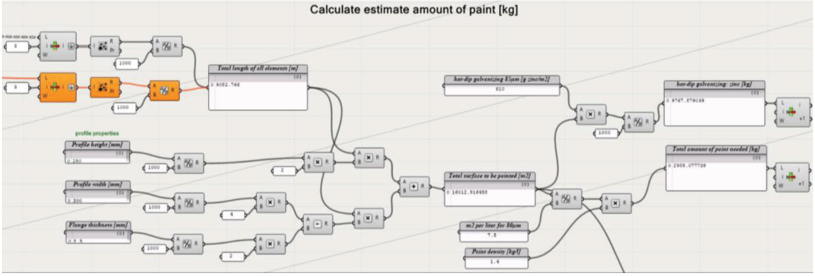
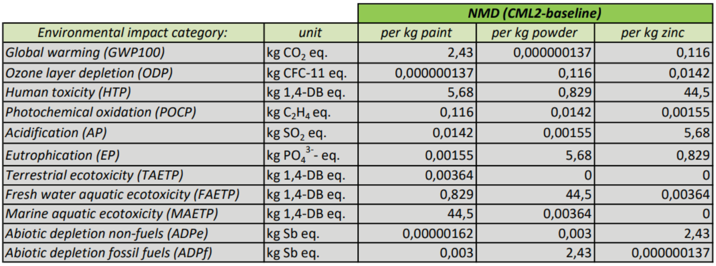


Figure 56: Snapshot of part of the GH script in which the total requirements for finishing methods are determined.

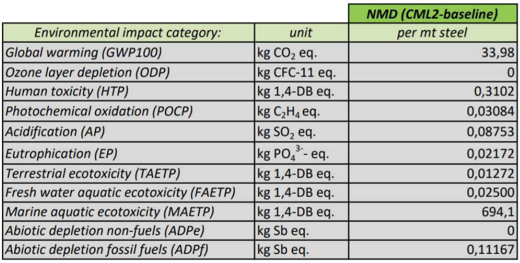


		NMD (CML2-baseline)		
Environmental impact category:	*unit*	*per kg paint*	*per kg powder*	*per kg zinc*
Global warming (GWP100)	kg CO_2 eq.	2,43	0,000000137	0,116
Ozone layer depletion (ODP)	kg CFC-11 eq.	0,000000137	0,116	0,0142
Human toxicity (HTP)	kg 1,4-DB eq.	5,68	0,829	44,5
Photochemical oxidation (POCP)	kg C_2H_4 eq.	0,116	0,0142	0,00155
Acidification (AP)	kg SO_2 eq.	0,0142	0,00155	5,68
Eutrophication (EP)	kg PO_4^{3-}- eq.	0,00155	5,68	0,829
Terrestrial ecotoxicity (TAETP)	kg 1,4-DB eq.	0,00364	0	0
Fresh water aquatic ecotoxicity (FAETP)	kg 1,4-DB eq.	0,829	44,5	0,00364
Marine aquatic ecotoxicity (MAETP)	kg 1,4-DB eq.	44,5	0,00364	0
Abiotic depletion non-fuels (ADPe)	kg Sb eq.	0,00000162	0,003	2,43
Abiotic depletion fossil fuels (ADPf)	kg Sb eq.	0,003	2,43	0,000000137

Figure 57: Environmental impact factors for various finishing methods derived from NMD (accessed March 2019)

6.2.4. Deconstruction

The average environmental impact due to the deconstruction process is calculated on the basis of the assessment method proposed in the work by Hoeckman et al. (Hoeckman, 2016; Hoeckman & Nelis, 2012) in combination with information obtained from interviews with several large steel construction companies in the Netherlands. It should be noted that these specific companies also had prior experience with the deconstruction of steelworks. It was indicated that the requirements in terms of labor and machinery necessary for deconstruction are to a large extent consistent with the requirements for the construction process. Furthermore, based on their individual experience with the disassembly of industrial steelworks, it was indicated that the effort to disassemble a steel frame construction, such as an industrial one-story warehouse, would take less time than to erect the structure. On the basis of these specific conditions it was estimated that the average amount of steel tonnage that could be disassembled per day was approximately 1,4 to 1,6 times as much as the amount that could be installed with the same effort. According to the reference study by Hoeckman on the construction process of various civil structures, average environmental impact values for the construction process of industrial warehouses could be determined. With the use of **Appendix 7** the individual values of the various impact categories could be determined and eventually aggregated. Subsequently the total environmental impacts were divided by the total tonnage of the construction in order to establish an average impact per ton of steel extracted from an obsolete building. The average values for the various categories are provided in **Appendix 9**.

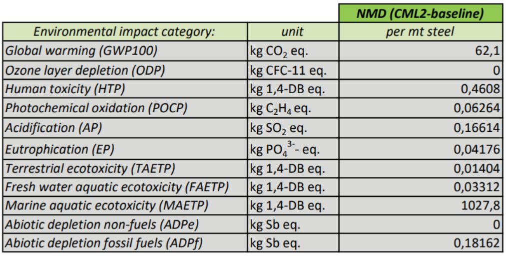


		NMD (CML2-baseline)
Environmental impact category:	*unit*	*per mt steel*
Global warming (GWP100)	kg CO_2 eq.	33,98
Ozone layer depletion (ODP)	kg CFC-11 eq.	0
Human toxicity (HTP)	kg 1,4-DB eq.	0,3102
Photochemical oxidation (POCP)	kg C_2H_4 eq.	0,03084
Acidification (AP)	kg SO_2 eq.	0,08753
Eutrophication (EP)	kg PO_4^{3-}- eq.	0,02172
Terrestrial ecotoxicity (TAETP)	kg 1,4-DB eq.	0,01272
Fresh water aquatic ecotoxicity (FAETP)	kg 1,4-DB eq.	0,02500
Marine aquatic ecotoxicity (MAETP)	kg 1,4-DB eq.	694,1
Abiotic depletion non-fuels (ADPe)	kg Sb eq.	0
Abiotic depletion fossil fuels (ADPf)	kg Sb eq.	0,11167

Figure 58: Used average environmental impact factors per mt steel extracted from an obsolete building

6.2.5. Erection

Furthermore, an approximation of the impact due to the construction phase ***A5*** can be made according to the work by Hoeckman & Nelis (Hoeckman, 2016; Hoeckman & Nelis, 2012). In the latest publication the environmental impact of the construction process was calculated for six different buildings and five bridges. The most relevant data for the purpose of this study was selected based on the similarities between the specific design considered in the case study of chapter 7 and the primary construction principle of industrial warehouses in Cuincy (F), Antwerp (B) and Eindhoven (NL) as described by Hoeckman (Hoeckman, 2016). The specific data used by the application for the construction process of module ***A5*** is provided in **Figure 59** . A summary of the various emission factors for the construction process as defined by Hoeckman and the derivation of the specific factors applicable for the purpose of this study can be found in **Appendix 12**.

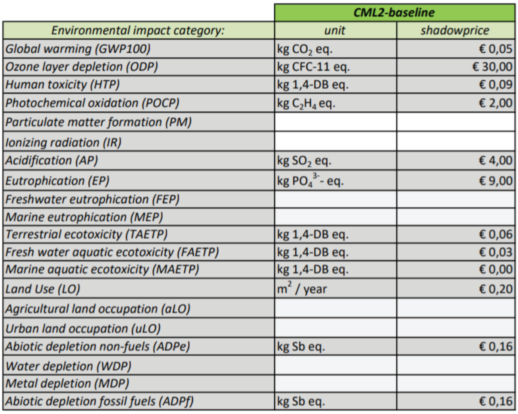


		NMD (CML2-baseline)
Environmental impact category:	*unit*	*per mt steel*
Global warming (GWP100)	kg CO_2 eq.	62,1
Ozone layer depletion (ODP)	kg CFC-11 eq.	0
Human toxicity (HTP)	kg 1,4-DB eq.	0,4608
Photochemical oxidation (POCP)	kg C_2H_4 eq.	0,06264
Acidification (AP)	kg SO_2 eq.	0,16614
Eutrophication (EP)	kg PO_4^{3-}- eq.	0,04176
Terrestrial ecotoxicity (TAETP)	kg 1,4-DB eq.	0,01404
Fresh water aquatic ecotoxicity (FAETP)	kg 1,4-DB eq.	0,03312
Marine aquatic ecotoxicity (MAETP)	kg 1,4-DB eq.	1027,8
Abiotic depletion non-fuels (ADPe)	kg Sb eq.	0
Abiotic depletion fossil fuels (ADPf)	kg Sb eq.	0,18162

Figure 59: Environmental impact factors per mt steel installed based on the study by Hoeckman (Hoeckman, 2016)

6.2.6. Weighting factors

The various impact categories are subsequently normalized according to the shadowcost method and weighting factors listed in **Figure 60.** These values are defined by the NMD and represent average values characteristic for the Netherlands as discussed in paragraph 4.5.8. These constructed prices are an indication of the environmental cost of pollution expressed in € / kg polluting material. By weighting the calculated environmental impact categories, comparisons can be made between the various categories and it can be determined which materials or processes cause the most overall average environmental impact.



	CML2-baseline	
Environmental impact category:	*unit*	*shadowprice*
Global warming (GWP100)	kg CO_2 eq.	€ 0,05
Ozone layer depletion (ODP)	kg CFC-11 eq.	€ 30,00
Human toxicity (HTP)	kg 1,4-DB eq.	€ 0,09
Photochemical oxidation (POCP)	kg C_2H_4 eq.	€ 2,00
Particulate matter formation (PM)		
Ionizing radiation (IR)		
Acidification (AP)	kg SO_2 eq.	€ 4,00
Eutrophication (EP)	kg PO_4^{3-}- eq.	€ 9,00
Freshwater eutrophication (FEP)		
Marine eutrophication (MEP)		
Terrestrial ecotoxicity (TAETP)	kg 1,4-DB eq.	€ 0,06
Fresh water aquatic ecotoxicity (FAETP)	kg 1,4-DB eq.	€ 0,03
Marine aquatic ecotoxicity (MAETP)	kg 1,4-DB eq.	€ 0,00
Land Use (LO)	m^2 / year	€ 0,20
Agricultural land occupation (aLO)		
Urban land occupation (uLO)		
Abiotic depletion non-fuels (ADPe)	kg Sb eq.	€ 0,16
Water depletion (WDP)		
Metal depletion (MDP)		
Abiotic depletion fossil fuels (ADPf)	kg Sb eq.	€ 0,16

Figure 60: Environmental price indices based on CML2-baseline methodology in €/unit as prescribed by the NMD

6.3. General settings

The following general settings are integrated in the Grasshopper script and can be finetuned by the means of various sliders, buttons and drop-down menus provided on the interface dashboard. This allows the user to change various production, manufacturing and transportation settings for the conditions that apply to a certain situation.

6.3.1. Choice of EPD for module A1

After the user has loaded a specific structural steel design model and has set the number of entries for the structural steel database that needs to be generated, as will be described more in depth in paragraph 7.1.2, the user can select a specific EPD which should be used for the structural steel profiles. The procedure for loading a specific design and selecting a certificate is highlighted in **Figure 64**. The selected EPD provides factors for the various environmental impact categories that should be used to calculate the impact due to the production process, module ***A1***. The selected EPD is characteristic for a certain production facility and the various origin facilities to which the EPD applies can be found under the *scope* of the corresponding certificate which is generally provided in the *general information* section of the certificate. Moreover, the user can also select a separate certificate for the endplate material on the second tab of the dashboard interface as can be seen in **Figure 67**.

6.3.2. Finishings

Subsequently, the user can select the desired protective coating which is assumed to be applied for the structural steel members in the design. He can choose between a *wet paint protective coating*, *powder coating* or *hot-dip galvanizing* as a protective measure as described in paragraph 6.2.3.

6.3.3. Endplates

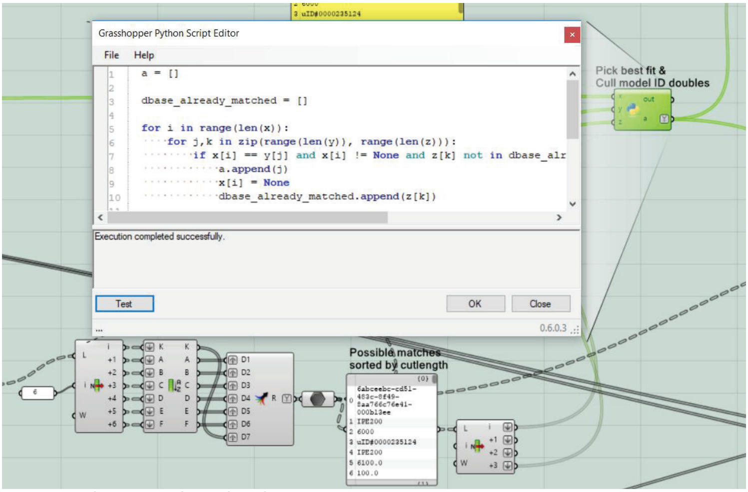
As the topic of CE is increasing in popularity, DfD is becoming an increasingly important design strategy for building structures as discussed in paragraph 3.2. Buildings which are designed according to the principles of DfD promote potential reuse of structural elements at the end of a building's lifetime by allowing for easy disassembly of elements. For steel construction works this will imply that bolted connections will become the preferred connection method which requires endplates to be welded to the structural members. As steel plate material often originates from China, as indicated during talks with several steel manufacturers, it is important to include this aspect in the environmental impact assessment. On the second tab of the dashboard window, the user can select several settings such as the average endplate thickness, the average amount of endplates per element and a specific EPD for quantifying the production process for module ***A1*** as illustrated in **Figure 67**. The total surface area of the plate material is determined according to the length and width properties of the specific elements which can be found in **Appendix 5**.

6.3.4. Transportation distances

As discussed in paragraph 5.5 the specific origin facility of structural steel elements or plate material can significantly influence LCA module ***A2***. In order to make an accurate assessment of the total impact due to transportation, specific requirements on this subject will have to be determined for both the most likely mode of transport which will be used as well as the estimated transportation distances. Subsequently when these values have been determined they can be set for the appropriate conditions on the third tab of the dashboard window for both the structural steel sections as well as the plate material. This is illustrated in Figure 67.

6.4. Selection of parameters

In this paragraph the variable parameters will be briefly discussed that determine which of the structural steel elements from the database are the most appropriate for the given situation. The application evaluates the model and tries to find all potential circular substitutes for virgin elements in the structural steel database based on the provided conditions. Subsequently it evaluates which of the selection of matching elements would lead to the least amount of total environmental impact based on the necessary transportation distance and the amount of waste material that would result from indirect reuse. Hereby the total environmental impact will be limited as much as possible by optimizing for waste material and transportation needs. For this purpose the Python plugin was used as it is more appropriate for *if*, *or* and *else* statements than the built in expression syntax. The integration of the Python plugin is illustrated in a screenshot of part of the script in **Figure 61** below. Python allows the tool to quickly loop over a list to see which items in a list are in agreement with certain defined conditions. The two primary parameters for determining the optimal use of circular steel elements are briefly elaborated on below.



```
a = []

dbase_already_matched = []

for i in range(len(x)):
    for j,k in zip(range(len(y)), range(len(z))):
        if x[i] == y[j] and x[i] != None and z[k] not in dbase_alr
            a.append(j)
            x[i] = None
            dbase_already_matched.append(z[k])
```

```
Execution completed successfully.
```

```
{0}
0 6abceebc-cd51-
  483c-8f49-
  8aa766c76e41-
  000b13ee
1 IPE200
2 6000
3 uID#0000235124
4 IPE200
5 6100.0
6 100.0
```

Figure 61: Screenshot of part of the Grasshopper script in which the Python plugin is used to loop over a list

6.4.1. Cut length

The cut length can be set to a maximum in order to limit the amount of waste material that results from remanufacturing elements in order to make them suitable for indirect reuse. Setting a maximum value will ensure that the amount of waste material generated during the remanufacturing phase will be limited. It is advised to keep the maximum cut length to a certain minimum as the ultimate goal is establishing an efficient re-use practice on a system level and not just on a project basis. Thereby, setting the cut length to example 2000mm is considered to be inappropriate, even though this would result in the usage of more circular material, as this would also result in unnecessary large waste streams. As a rule of thumb it is recommended to set the maximum cut length to approximately 200-500 mm. This is based on an average percentage of waste material of 3-6% for element lengths in the range of 3 to 8 meters. It is assumed that waste material losses in this range are still tolerable as the standard manufacturing process for virgin steel also implies losses of around 3%. According to correspondence with steel manufacturers these average losses for virgin steel elements are inevitable as standard elements purchased directly from steel plants only come in a range of specified lengths rounded to the nearest meter. However this range is merely a guideline and in the end it is up to the user of the application to set the specific cut length based on his personal preferences. It should be noted that the waste material is explicitly taken into account in the evaluation. Increasing the tolerances will thus result in a larger share of waste material and this will subsequently raise the environmental impact due to reprocessing of waste.

6.4.2. Transportation distance

The deconstruction module ***D1*** and the transportation module ***A2*** are considered to be the most important influential factors in the assessment of the environmental impact for reused elements in a circular steel design. Although other modules also significantly influence the total environmental impact of a specific element, these modules also apply for virgin elements and are generally of the same magnitude. For example, the impact due to transportation from the manufacturer to the site ***A4***, the manufacturing module ***A3*** and the construction module ***A5*** will most likely be consistent with the impact for virgin steel elements. As the transportation module ***A2*** is strongly dependent on the origin location and the specific mode of transport, the impact due to these specific conditions is taken into account as a driver for the optimization.

7 Reference study

Chapter 8 will evaluate the design of the primary load-bearing structure of an industrial distribution center by considering three different possible scenarios for the origin conditions of the structural steel members of which the building is comprised. Firstly, the scenarios will be described and it will be explained why these three specific scenarios are considered. Secondly, the chapter will elaborate on how the tool was used to generate the desired output and which settings were required. Lastly, the generated output for the various scenarios will be given.

7.1. Data generation

In order to perform a case-study analysis for the three scenarios, firstly input data will need to be acquired from a reference project to generate a virtual model of a relevant building with a structural steel load-bearing structure. Secondly, a database will need to be linked to the tool in which information is stored on a large amount of structural steel profiles. In this research it is assumed that reuse & recycling of building materials will become the dominant end-of-life scenarios for various components in the near future. However, as discussed in paragraph 3.2 currently several barriers are still in place preventing widespread adoption of structural steel reuse in the Netherlands. Although there are several developments which will likely stimulate the development of a market for used structural steel profiles, there currently is no such marketplace yet. For the purpose of this case-study a grasshopper script was made in order to generate a fictional database containing a large quantity of structural steel elements with several properties. Specific choices and considerations that were made to generate the required data are elaborated on below.

7.1.1. Reference project IFC data

For the purpose of this study the structural framework part of the design for a sorting and distribution center in Zaltbommel was used to perform a case-study. The load-bearing construction was designed and modelled by Arup. The construction consists of two levels and is comprised of various types of standard steel profiles. Only various types of I- and H- profiles for the primary construction were included and other typologies are disregarded. The Revit model for this particular building was used to extract all the necessary information on the building elements from the IFC file with the means of Dynamo according to the method specified in paragraph 6.1.6.

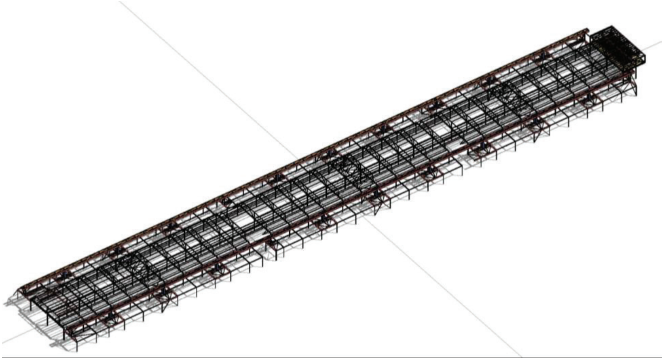
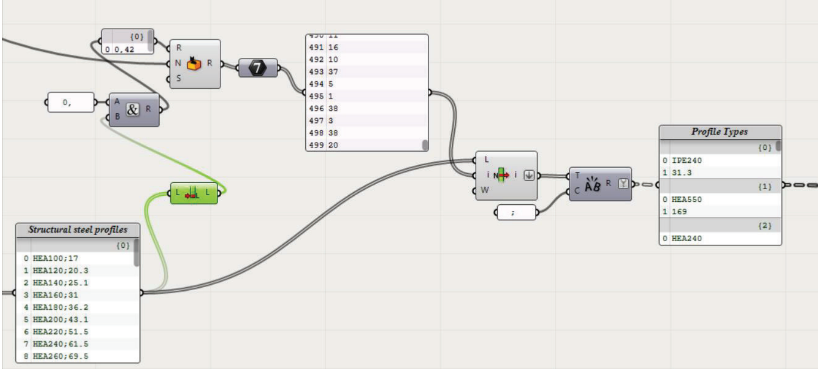


Figure 62: 3D BIM model of the distribution center for which a conveyor support structure was designed - from Revit

7.1.2. Generating a fictional circular steel database

In order to simulate a potential future marketplace for used building components, which is expected to gradually develop in the Netherlands in the coming years, a list of structural steel elements with realistic properties needed to be generated. Building a list with a large enough number of entries which are both realistic but also arbitrary to a certain extent can be done with the use of Grasshopper's built in Schrödinger's cat component as illustrated in **Figure 63** below. For a complete overview of the database generator please see **Appendix 13**.



```
{0}
0 0.42
```

```
0,
```

```
491 16
492 10
493 37
494 5
495 1
496 38
497 3
498 38
499 20
```

```
Structural steel profiles
{0}
0 HEA100;17
1 HEA120;20.3
2 HEA140;25.1
3 HEA160;31
4 HEA180;36.2
5 HEA200;43.1
6 HEA220;51.5
7 HEA240;61.5
8 HEA260;69.5
```

```
;
```

```
Profile Types
{0}
0 IPE240
1 31.3
{1}
0 HEA550
1 169
{2}
0 HEA240
```

Figure 63: Using Schrödinger's cat component to build a database with circular structural steel elements

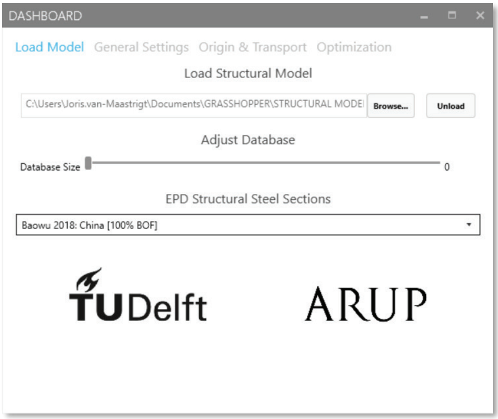
By having the database generator built into the Grasshopper script it provides the user with an option to set a predefined number of entries allowing for flexibility and the option to compare a design on the basis of variations in the total database size. This could prove to be helpful in predicting how mature the hypothetical 'reuse market' needs to become in order to achieve significant environmental impact reduction rates due to reuse. From varying the size of the database for this specific project, consisting of 1834 elements, it could be concluded that a database size of approximately 17.000 elements provided enough options to substitute 50% of the members.

7.2. Four scenarios

This paragraph will discuss the building design of part of an industrial distribution center situated in Zaltbommel with an intended lifetime of 50 years for which the environmental impact has been evaluated for four cases according to three distinct scenarios; a worst-case scenario, business as usual (BAU) and a circular optimization. For the purpose of this study it is assumed that the primary steel construction consists solely of standardized H- and I- profiles with a total estimated tonnage of the construction of 265,5 ton of steel and that the GFA for this specific project is approximately 4000 m^2. The total number of profiles used in this construction is 1834 and the total costs of the steelworks is estimated at roughly €800.000,- (based on standard approximations, excluding all other components and processes that are not related to the steelwork). Furthermore, is assumed that the steelwork will be manufactured 90 km to the Northeast of Amsterdam. The different scenarios and the specific application settings that were used to obtain the required results are described in the paragraphs below.

7.2.1. Case I: worst-case scenario

This scenario is based on the assumption that the preferred origin of steel elements is completely cost-driven and that the resulting environmental impact is completely disregarded. It assumes that due to environmental regulations in Europe the production of EAF steel in Europe is relatively expensive compared to BOF steel from Asia due to considerably less strict national environmental policies here as well as a relatively low price of raw materials. As indicated in paragraph 3.1.1 China produces more steel than any other country in the world and annual production rates of BOF steel continue to increase due to heavy government investment. Therefore, China is considered as the primary origin of structural steel products for this specific case. Considering these specific conditions, the Chinese EPD certificate held by Bauwo Steel Group Corp. Ltd. is deemed to be the most appropriate for the evaluation of this specific scenario.



Load Structural Model

C:\Users\Joris.van-Maastrigt\Documents\GRASSHOPPER\STRUCTURAL MODE

Adjust Database

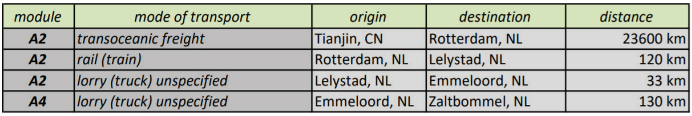
Database Size 0

EPD Structural Steel Sections

Baowu 2018: China [100% BOF]

Figure 64: Case I – Loading the structural design and selecting a specific steel EPD

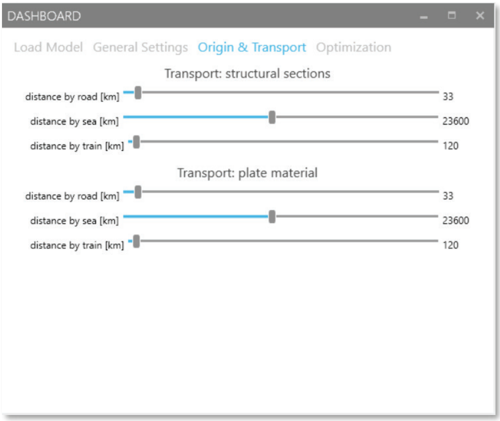
The biggest BOF steel production plant is situated in Tianjin, a port city in the northeast of China. For this case, Tianjin was therefore chosen as the origin point for structural steel products. Transport will primarily be carried out by transatlantic freight transport over sea from Tianjin to Rotterdam. The specific shipping route was calculated with the help of Ports.com and was estimated to be 14.665 nm or 23.600 km (Ports.com, 2019). From the port cities transport is assumed to be performed by train as much as possible and subsequently by lorry for the final stretch. Steel products are transported to Emmeloord by train and for the final stretch by lorry for further manufacturing and assembly and eventually transported by lorry to the construction site in Zaltbommel. The distances that have been used as input are provided below in **Figure 65**.



module	*mode of transport*	*origin*	*destination*	*distance*
A2	*transoceanic freight*	Tianjin, CN	Rotterdam, NL	23600 km
A2	*rail (train)*	Rotterdam, NL	Lelystad, NL	120 km
A2	*lorry (truck) unspecified*	Lelystad, NL	Emmeloord, NL	33 km
A4	*lorry (truck) unspecified*	Emmeloord, NL	Zaltbommel, NL	130 km

Figure 65: Specific distances used for the calculation of the impact of module ***A2*** and ***A4*** due to transportation

The settings for module ***A2*** related to transport from the origin steel plant to the steel manufacturer are manually adjusted on the third tab as illustrated in **Figure 66**.



Transport: structural sections

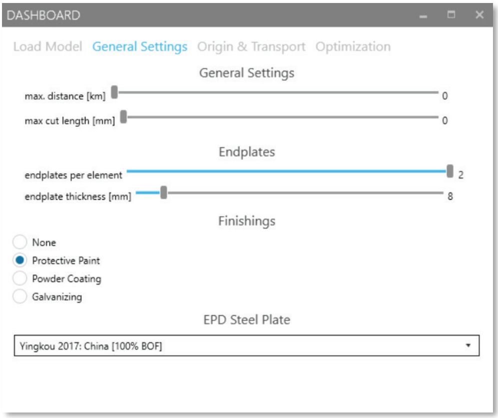
distance by road [km] 33
distance by sea [km] 23600
distance by train [km] 120

Transport: plate material

distance by road [km] 33
distance by sea [km] 23600
distance by train [km] 120

Figure 66: Case I – Specific settings used for transportation

Subsequently, additional settings are applied for the plate material. It is assumed that all elements will have endplates on both ends with an average thickness of 8mm and a protective wet paint coating will be applied to the steelwork of approximately 80µm. The specific EPD selected for the production module ***A1*** of the plate material is from a Chinese steel plate manufacturer Minmetals Yingkou Medium Plate Co. as illustrated in **Figure 67** (Minmetals Yingkou Medium Plate Co.Ltd., 2018). Yingkou is located along the same bay as Tianjin and according to (Ports.com, 2019) the shipping route length is nearly the same as the route via Tianjin (a difference of 4 nm, which has been disregarded). Lastly, it is important to note that the optimization option on the final tab is turned off for this scenario as the application of circular steel elements is disregarded.



General Settings

max. distance [km] 0

max cut length [mm] 0

Endplates

endplates per element 2

endplate thickness [mm] 8

Finishings

○ None
● Protective Paint
○ Powder Coating
○ Galvanizing

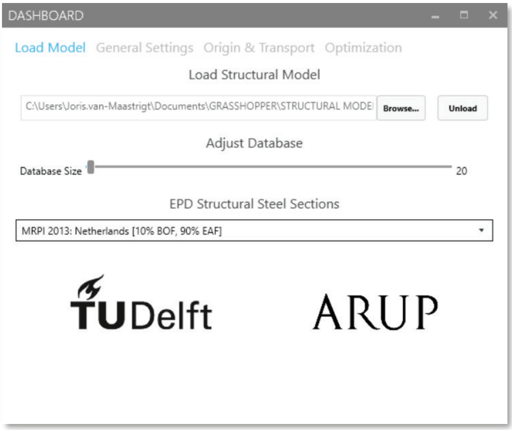
EPD Steel Plate

Yingkou 2017: China [100% BOF]

Figure 67: Case I – Specific settings used for endplates and surface finishing

7.2.2. Case II: BAU – based on MRPI certificate

In the subsequent scenario we will determine the total environmental impact based on the BAU for LCA assessment of building structures fully on the basis of data provided by the NMD and the predominantly used LCA software and procedures used in the Netherlands. For this reason it is assumed that the EPD by the MRPI from 2013 is used for both the structural steel section material as well as the endplates as the specific EPD states that it accounts for “ 900kg sections and 100kg plate material ”. Other settings related to manufacturing are consistent with the previously discussed scenario and settings are applied as defined in **Figure 68** and **Figure 69** below.



Load Structural Model

C:\Users\Joris.van-Maastrigt\Documents\GRASSHOPPER\STRUCTURAL MODE

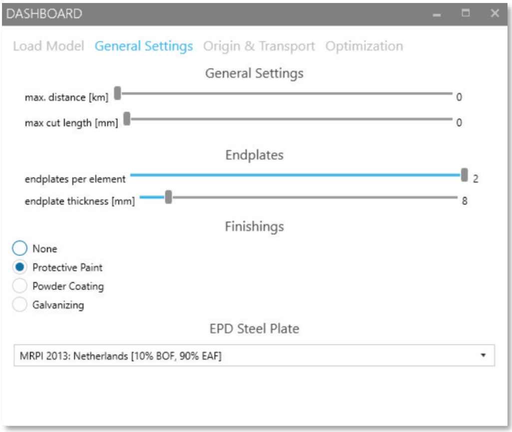
Adjust Database

Database Size 20

EPD Structural Steel Sections

MRPI 2013: Netherlands [10% BOF, 90% EAF]

Figure 68: Case II – Loading the structural design and selecting a specific steel EPD



General Settings

max. distance [km] 0

max cut length [mm] 0

Endplates

endplates per element 2

endplate thickness [mm] 8

Finishings

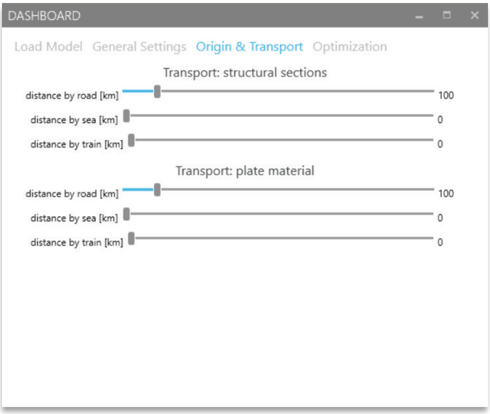
○ None
● Protective Paint
○ Powder Coating
○ Galvanizing

EPD Steel Plate

MRPI 2013: Netherlands [10% BOF, 90% EAF]

Figure 69: Case II – Specific settings used for endplates and surface finishing

According to the MRPI certificate “steel construction products are produced in Western-Europe and applied to the Dutch Market”. The NMD indicates that the transport distance for structural steel sections can be assumed to be 100km on average the used settings are provided in **Figure 70** below.



Transport: structural sections

distance by road [km] 100

distance by sea [km] 0

distance by train [km] 0

Transport: plate material

distance by road [km] 100

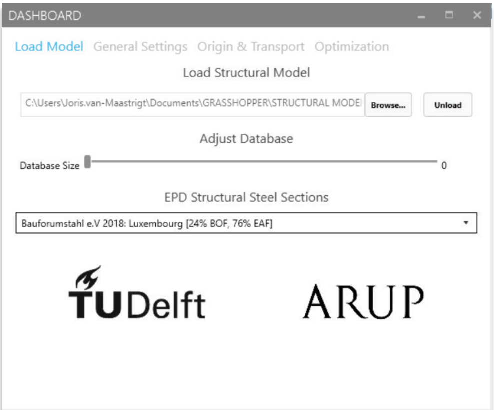
distance by sea [km] 0

distance by train [km] 0

Figure 70: Case II – Specific settings used for transportation

7.2.3. Case III: BAU – according to steel manufacturer

The third case assumes the BAU scenario but uses information provided by a large steel manufacturer as to determine the most accurate settings that reflect the BAU scenario. Therefore, structural steel beams and columns are considered to originate from Differdange in Luxembourg. It is assumed that the elements are primarily produced from recycled material as the specific plant in Differdange operated by ArcelorMittal mainly produces structural steel elements by means of the EAF process. The certificate *EPD-BFS-20180116-IBG2* by Bauforumstahl from 2018 can be found on their website (ArcelorMittal, 2018) and states that it applies to ArcelorMittal hot-rolled sections produced on the site in Differdange, **Figure 71**. Plate material generally originates from China according to the manufacturer. Therefore, the origin location for plate material is set to be Yingkou, China. For this purpose the EPD 078 by Minmetals Yingkou Medium Plate Co. Ltd. has been used (Minmetals Yingkou Medium Plate Co.Ltd., 2018).



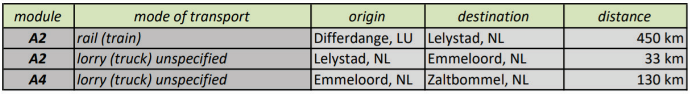
C:\Users\Joris.van-Maastrigt\Documents\GRASSHOPPER\STRUCTURAL MODEl

Database Size 0

Bauforumstahl e.V 2018: Luxembourg [24% BOF, 76% EAF]

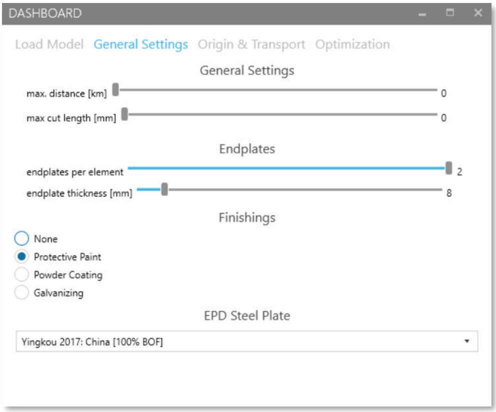
Figure 71: Case III – Loading the structural design and selecting a specific steel EPD

Further settings with regard to finishing are consistent with case II as illustrated in **Figure 73**. The transport settings are determined with the help of Google maps. It is assumed that structural sections will be transported from the Differdange steel plant to Emmeloord for the most part over the rail network and for the last stretch by means of a lorry. The data that was used and the specific settings can be found in **Figure 72** and **Figure 74** respectively.



module	*mode of transport*	*origin*	*destination*	*distance*
A2	*rail (train)*	Differdange, LU	Lelystad, NL	450 km
A2	*lorry (truck) unspecified*	Lelystad, NL	Emmeloord, NL	33 km
A4	*lorry (truck) unspecified*	Emmeloord, NL	Zaltbommel, NL	130 km

Figure 72: Calculated distances for LCA modules ***A2*** and ***A4***



General Settings

max. distance [km] 0

max cut length [mm] 0

Endplates

endplates per element 2

endplate thickness [mm] 8

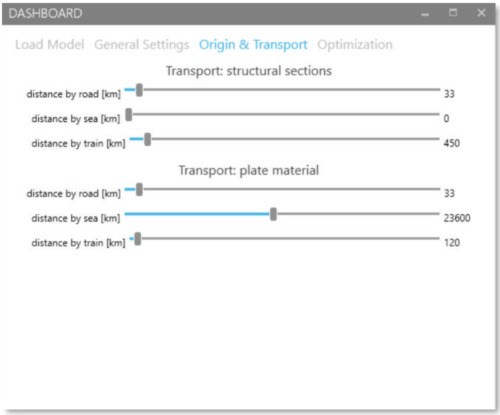
Finishings

○ None
● Protective Paint
○ Powder Coating
○ Galvanizing

EPD Steel Plate

Yingkou 2017: China [100% BOF]

Figure 73: Case III – Specific settings used for endplates and surface finishing



Transport: structural sections

distance by road [km] 33

distance by sea [km] 0

distance by train [km] 450

Transport: plate material

distance by road [km] 33

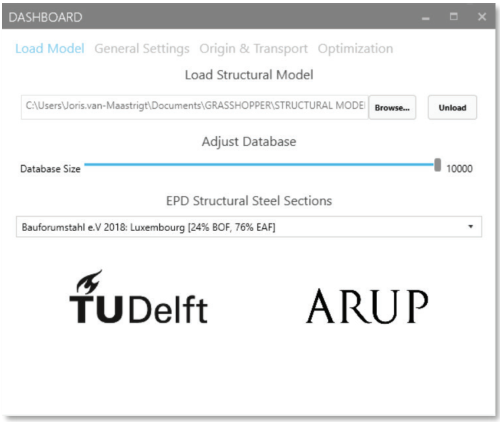
distance by sea [km] 23600

distance by train [km] 120

Figure 74: Case III – Specific settings used for transportation

7.2.4. Case IV: circular steel design

Lastly, an optimization will be performed with the aim of reducing the total environmental footprint of the design of the distribution center. The steel construction will be compared to a generated database with 10.000 entries of structural steel elements of various lengths and profile types (but limited to H- and I- profiles as discussed in paragraph 7.1.2). These profiles are sourced from several storage locations across the EU. The application will determine the best possible matches based on a minimum amount of waste material and a set maximum transport distance from the deconstruction site as discussed in paragraph 6.4.



Load Structural Model

C:\Users\Joris.van-Maastrigt\Documents\GRASSHOPPER\STRUCTURAL MODEl

Adjust Database

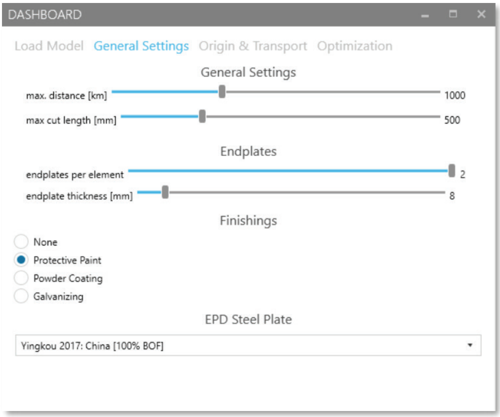
Database Size 10000

EPD Structural Steel Sections

Bauforumstahl e.V 2018: Luxembourg [24% BOF, 76% EAF]

Figure 75: Case IV – Loading the structural design and selecting a specific steel EPD

The maximum cut length is set to 500mm and the maximum transport distance to 1000 km. The script will determine which element is most appropriate for substitution based on both the minimum cut length and the minimum transportation distance. Transportation will be assumed to be by lorry for all circular steel profiles as distances are relatively small quantities of elements originating from a specific location are limited. The calculations are performed for every element individually and are integrated in the script. The transportation settings for virgin steel are consistent with the settings for *case III* as illustrated in **Figure 77**.



General Settings

max. distance [km] 1000

max cut length [mm] 500

Endplates

endplates per element 2

endplate thickness [mm] 8

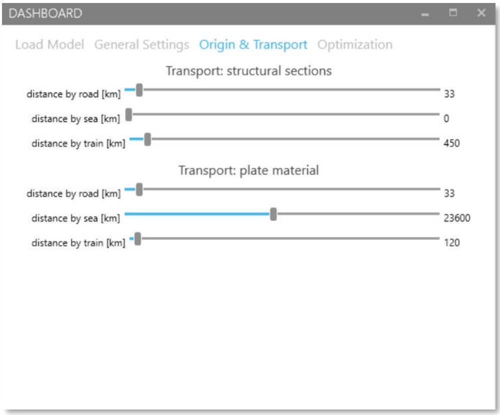
Finishings

○ None
● Protective Paint
○ Powder Coating
○ Galvanizing

EPD Steel Plate

Yingkou 2017: China [100% BOF]

Figure 76: Case IV – Specific settings used for endplates and surface finishing



Transport: structural sections

distance by road [km] 33

distance by sea [km] 0

distance by train [km] 450

Transport: plate material

distance by road [km] 33

distance by sea [km] 23600

distance by train [km] 120

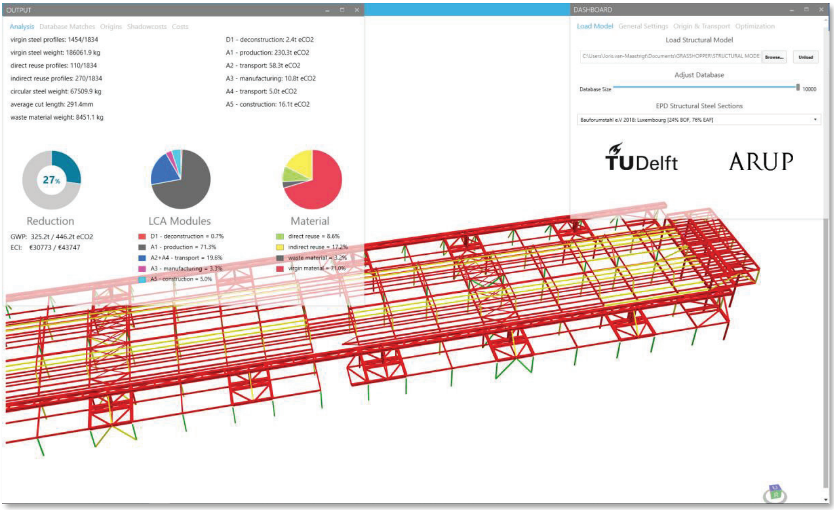
Figure 77: Case III – Specific settings used for transportation

8 Results

This chapter provides an overview of the results for the environmental impact study performed for the four beforementioned scenarios ***Case I - IV*** with the use of the application that was developed as part of this thesis as discussed in the previous paragraphs.

8.1.1. Output and interpretation of results

The particular interface of the tool consist of three components; the *dashboard*, an *output* window and a *3D model* of the structural steel design. This is illustrated in **Figure 78** below. The dashboard is used to change the settings according the specific preferences for a project as discussed in paragraph 7.2. The output of the analysis is provided by the means of a visual 3D presentation in which steel elements are highlighted according to the degree of circularity; red elements are similar to a standard design but the yellow and green elements are circular components. As illustrated in **Figure 79**, red thereby represents *virgin* steel, yellow indicates *indirect* reuse and green *direct* reuse.



```
virgin steel profiles: 1454/1834
virgin steel weight: 186061.9 kg
direct reuse profiles: 110/1834
indirect reuse profiles: 270/1834
circular steel weight: 67509.9 kg
average cut length: 291.4mm
waste material weight: 8451.1 kg

D1 - deconstruction: 2.4t eCO2
A1 - production: 230.3t eCO2
A2 - transport: 58.3t eCO2
A3 - manufacturing: 10.8t eCO2
A4 - transport: 5.0t eCO2
A5 - construction: 16.1t eCO2

GWP:  325.2t / 446.2t eCO2
ECI:   €30773 / €43747

D1 - deconstruction = 0.7%
A1 - production = 71.3%
A2+A4 - transport = 19.6%
A3 - manufacturing = 3.3%
A5 - construction = 5.0%

direct reuse = 8.6%
indirect reuse = 17.2%
waste material = 3.2%
virgin material = 71.0%
```

Load Structural Model

C:\Users\Joris.van-Maastrigt\Documents\GRASSHOPPER\STRUCTURAL MODE

Adjust Database

Database Size 10000

EPD Structural Steel Sections

Bauforumstahl e.V 2018: Luxembourg [24% BOF, 76% EAF]

Figure 78: General interface of the developed tool

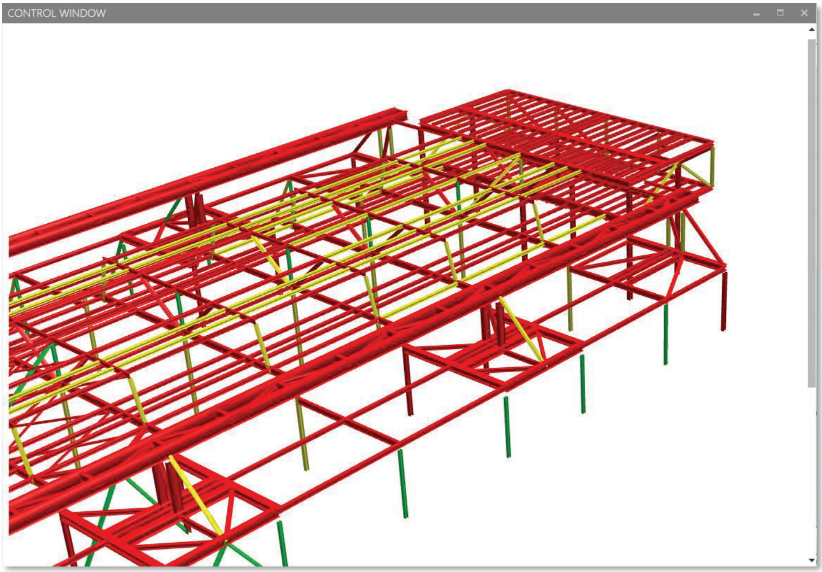
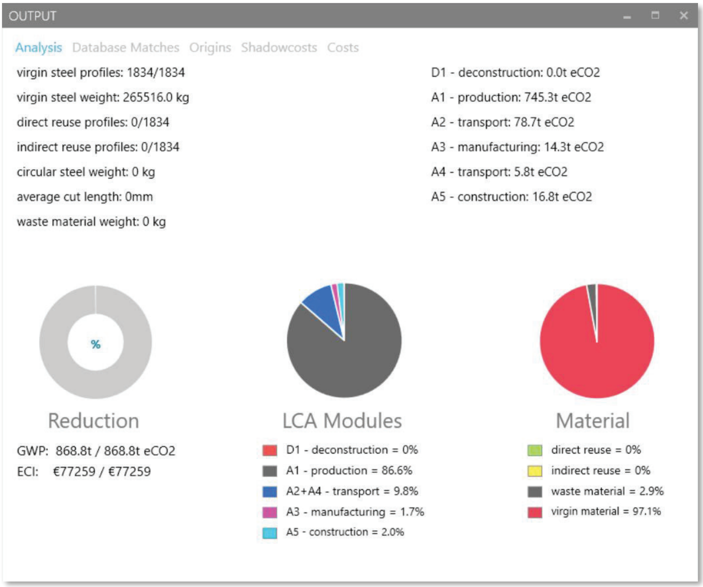


Figure 79: 3D model in which structural element are highlighted according to their use

The specific results of the a performed analysis are provided in the *output* window. There are various tabs with various results available to the user. In the next paragraphs we will specifically discuss the results of the LCA analysis. The general outcomes are displayed on the first tab. Results are provided in terms of quantities of elements, tonnages and percentages for the three element categories; *virgin*, *direct reuse* and *indirect reuse*. Moreover the total GWP and shadowprice reduction is given. Furthermore, the user gets an immediate indication of the impact for the various modules in terms of percentages of the total impact as well as the GWP per module. The second tab displays a list with all the matching profiles in which the user can find corresponding model and database IDs. The engineer can forward this information to the stockist to make a reservation for certain elements and can for example incorporate the database IDs in his Revit model to ensure that the contractor knows where the circular components should be installed. The fourth tab displays an overview of the shadowprices per impact category for the entirety of the structure. By weighting the various categories the user gets an immediate idea of what the most important environmental impact factors are. The following paragraphs will elaborate on the specific results of the four case studies discussed in 7.2.

8.1.2. Case I: worst-case scenario



virgin steel profiles: 1834/1834
virgin steel weight: 265516.0 kg
direct reuse profiles: 0/1834
indirect reuse profiles: 0/1834
circular steel weight: 0 kg
average cut length: 0mm
waste material weight: 0 kg

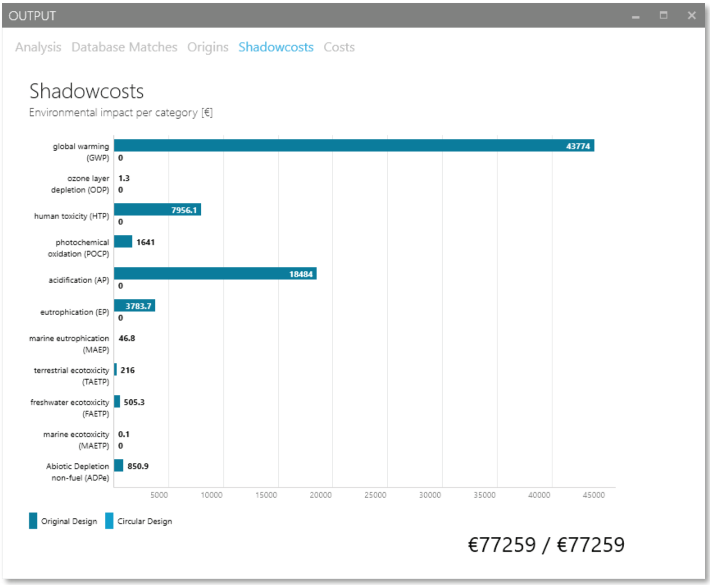
D1 - deconstruction: 0.0t eCO2
A1 - production: 745.3t eCO2
A2 - transport: 78.7t eCO2
A3 - manufacturing: 14.3t eCO2
A4 - transport: 5.8t eCO2
A5 - construction: 16.8t eCO2

GWP: 868.8t / 868.8t eCO2
ECI: €77259 / €77259

🟥 D1 - deconstruction = 0%
■ A1 - production = 86.6%
■ A2+A4 - transport = 9.8%
■ A3 - manufacturing = 1.7%
■ A5 - construction = 2.0%

🟩 direct reuse = 0%
🟨 indirect reuse = 0%
■ waste material = 2.9%
🟥 virgin material = 97.1%

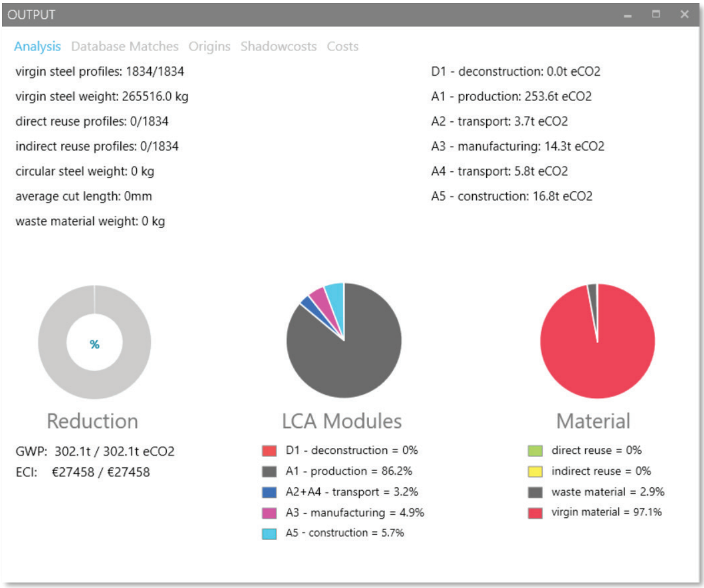
Figure 80: Case I – General results of the LCA analysis



€77259 / €77259

Figure 81: Case I – LCA analysis results for the shadowprices per impact category

8.1.3. Case II: based on MRPI certificate (EAF)



virgin steel profiles: 1834/1834
virgin steel weight: 265516.0 kg
direct reuse profiles: 0/1834
indirect reuse profiles: 0/1834
circular steel weight: 0 kg
average cut length: 0mm
waste material weight: 0 kg

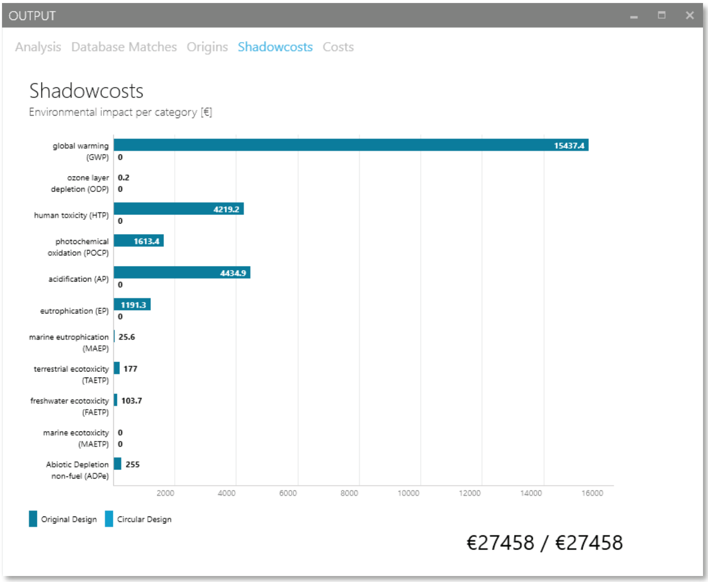
D1 - deconstruction: 0.0t eCO2
A1 - production: 253.6t eCO2
A2 - transport: 3.7t eCO2
A3 - manufacturing: 14.3t eCO2
A4 - transport: 5.8t eCO2
A5 - construction: 16.8t eCO2

GWP: 302.1t / 302.1t eCO2
ECI: €27458 / €27458

🟥 D1 - deconstruction = 0%
⬛ A1 - production = 86.2%
🟦 A2+A4 - transport = 3.2%
🟪 A3 - manufacturing = 4.9%
🟦 A5 - construction = 5.7%

🟩 direct reuse = 0%
🟨 indirect reuse = 0%
⬛ waste material = 2.9%
🟥 virgin material = 97.1%

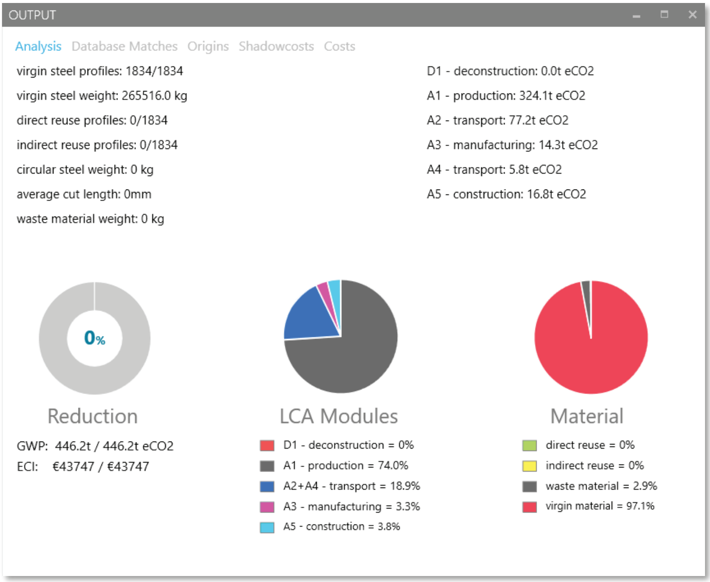
Figure 82: Case II – General results of the LCA analysis



€27458 / €27458

Figure 83: Case II – LCA analysis results for the shadowprices per impact category

8.1.4. Case III: according to steel manufacturer



virgin steel profiles: 1834/1834
virgin steel weight: 265516.0 kg
direct reuse profiles: 0/1834
indirect reuse profiles: 0/1834
circular steel weight: 0 kg
average cut length: 0mm
waste material weight: 0 kg

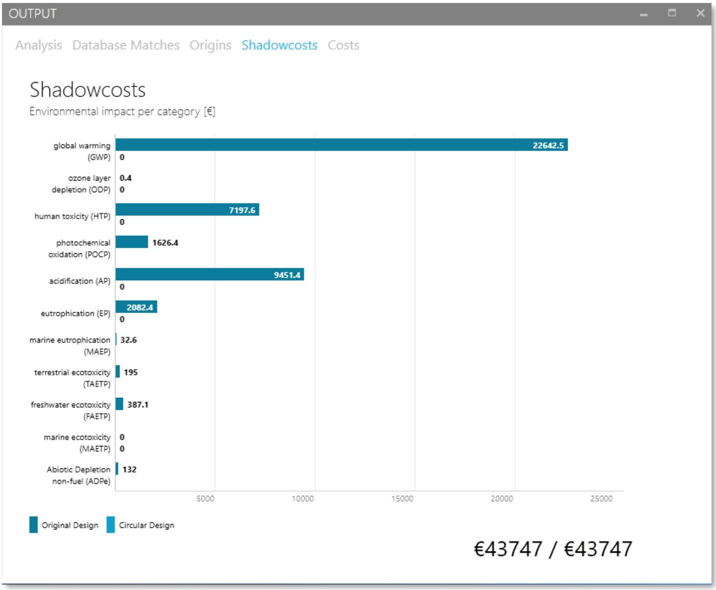
D1 - deconstruction: 0.0t eCO2
A1 - production: 324.1t eCO2
A2 - transport: 77.2t eCO2
A3 - manufacturing: 14.3t eCO2
A4 - transport: 5.8t eCO2
A5 - construction: 16.8t eCO2

GWP: 446.2t / 446.2t eCO2
ECI: €43747 / €43747

D1 - deconstruction = 0%
A1 - production = 74.0%
A2+A4 - transport = 18.9%
A3 - manufacturing = 3.3%
A5 - construction = 3.8%

direct reuse = 0%
indirect reuse = 0%
waste material = 2.9%
virgin material = 97.1%

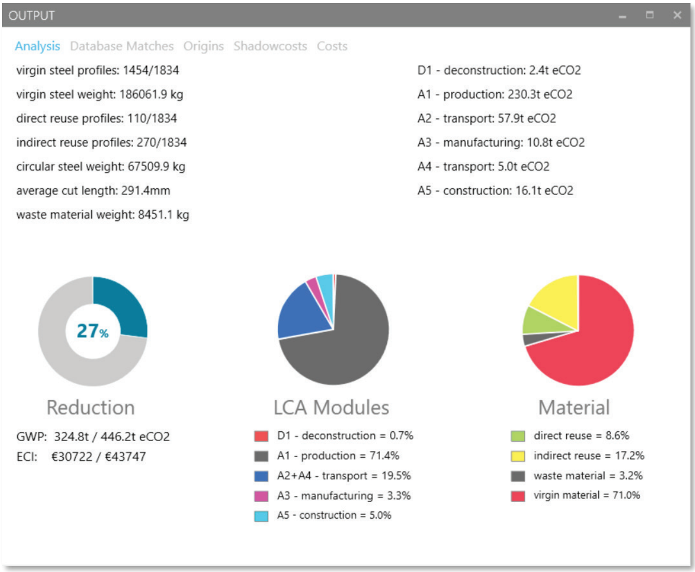
Figure 84: Case III – General results of the LCA analysis



€43747 / €43747

Figure 85: Case II – LCA analysis results for the shadowprices per impact category

8.1.5. Case IV: circular steel design



virgin steel profiles: 1454/1834
virgin steel weight: 186061.9 kg
direct reuse profiles: 110/1834
indirect reuse profiles: 270/1834
circular steel weight: 67509.9 kg
average cut length: 291.4mm
waste material weight: 8451.1 kg

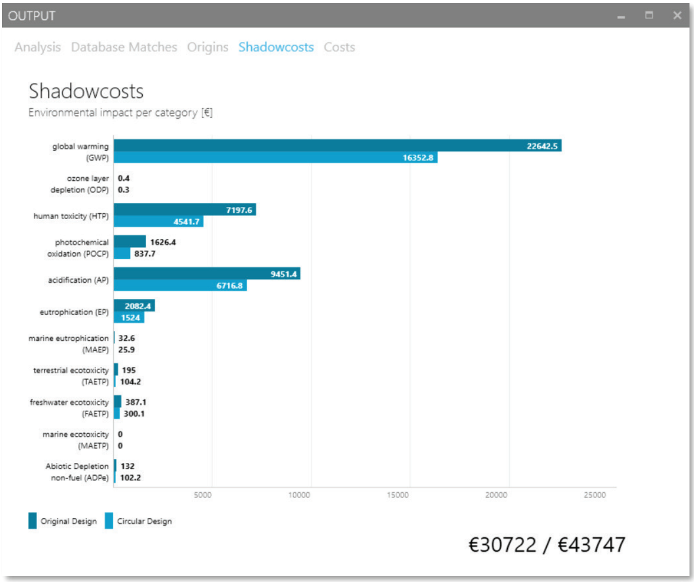
D1 - deconstruction: 2.4t eCO2
A1 - production: 230.3t eCO2
A2 - transport: 57.9t eCO2
A3 - manufacturing: 10.8t eCO2
A4 - transport: 5.0t eCO2
A5 - construction: 16.1t eCO2

GWP: 324.8t / 446.2t eCO2
ECI: €30722 / €43747

🟥 D1 - deconstruction = 0.7%
⬛ A1 - production = 71.4%
🟦 A2+A4 - transport = 19.5%
🟪 A3 - manufacturing = 3.3%
🟦 A5 - construction = 5.0%

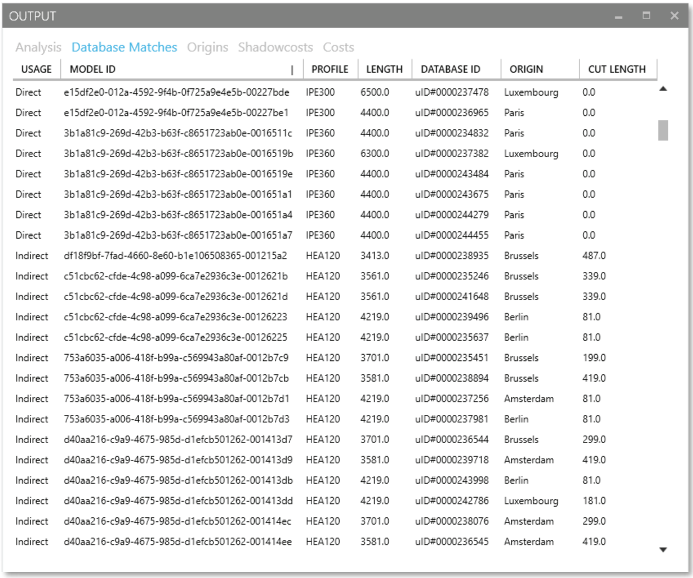
🟩 direct reuse = 8.6%
🟨 indirect reuse = 17.2%
⬛ waste material = 3.2%
🟥 virgin material = 71.0%

Figure 86: Case IV – General results of the analysis



€30722 / €43747

Figure 87: Case IV – LCA analysis results for the shadowprices per impact category

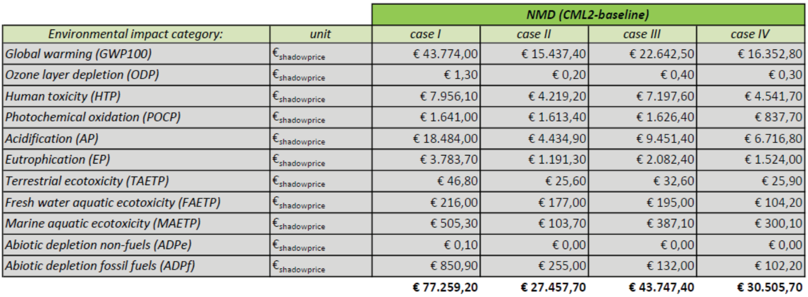


USAGE	MODEL ID	PROFILE	LENGTH	DATABASE ID	ORIGIN	CUT LENGTH
Direct	e15df2e0-012a-4592-9f4b-0f725a9e4e5b-00227bde	IPE300	6500.0	uID#0000237478	Luxembourg	0.0
Direct	e15df2e0-012a-4592-9f4b-0f725a9e4e5b-00227be1	IPE300	4400.0	uID#0000236965	Paris	0.0
Direct	3b1a81c9-269d-42b3-b63f-c8651723ab0e-0016511c	IPE360	4400.0	uID#0000234832	Paris	0.0
Direct	3b1a81c9-269d-42b3-b63f-c8651723ab0e-0016519b	IPE360	6300.0	uID#0000237382	Luxembourg	0.0
Direct	3b1a81c9-269d-42b3-b63f-c8651723ab0e-0016519e	IPE360	4400.0	uID#0000243484	Paris	0.0
Direct	3b1a81c9-269d-42b3-b63f-c8651723ab0e-001651a1	IPE360	4400.0	uID#0000243675	Paris	0.0
Direct	3b1a81c9-269d-42b3-b63f-c8651723ab0e-001651a4	IPE360	4400.0	uID#0000244279	Paris	0.0
Direct	3b1a81c9-269d-42b3-b63f-c8651723ab0e-001651a7	IPE360	4400.0	uID#0000244455	Paris	0.0
Indirect	df18f9bf-7fad-4660-8e60-b1e106508365-001215a2	HEA120	3413.0	uID#0000238935	Brussels	487.0
Indirect	c51cbc62-cfde-4c98-a099-6ca7e2936c3e-0012621b	HEA120	3561.0	uID#0000235246	Brussels	339.0
Indirect	c51cbc62-cfde-4c98-a099-6ca7e2936c3e-0012621d	HEA120	3561.0	uID#0000241648	Brussels	339.0
Indirect	c51cbc62-cfde-4c98-a099-6ca7e2936c3e-00126223	HEA120	4219.0	uID#0000239496	Berlin	81.0
Indirect	c51cbc62-cfde-4c98-a099-6ca7e2936c3e-00126225	HEA120	4219.0	uID#0000235637	Berlin	81.0
Indirect	753a6035-a006-418f-b99a-c569943a80af-0012b7c9	HEA120	3701.0	uID#0000235451	Brussels	199.0
Indirect	753a6035-a006-418f-b99a-c569943a80af-0012b7cb	HEA120	3581.0	uID#0000238894	Brussels	419.0
Indirect	753a6035-a006-418f-b99a-c569943a80af-0012b7d1	HEA120	4219.0	uID#0000237256	Amsterdam	81.0
Indirect	753a6035-a006-418f-b99a-c569943a80af-0012b7d3	HEA120	4219.0	uID#0000237981	Berlin	81.0
Indirect	d40aa216-c9a9-4675-985d-d1efcb501262-001413d7	HEA120	3701.0	uID#0000236544	Brussels	299.0
Indirect	d40aa216-c9a9-4675-985d-d1efcb501262-001413d9	HEA120	3581.0	uID#0000239718	Amsterdam	419.0
Indirect	d40aa216-c9a9-4675-985d-d1efcb501262-001413db	HEA120	4219.0	uID#0000243998	Berlin	81.0
Indirect	d40aa216-c9a9-4675-985d-d1efcb501262-001413dd	HEA120	4219.0	uID#0000242786	Luxembourg	181.0
Indirect	d40aa216-c9a9-4675-985d-d1efcb501262-001414ec	HEA120	3701.0	uID#0000238076	Amsterdam	299.0
Indirect	d40aa216-c9a9-4675-985d-d1efcb501262-001414ee	HEA120	3581.0	uID#0000236545	Amsterdam	419.0

Figure 88: Case IV – List with an overview of the matching profiles with their unique IDs

8.1.6. Summary

Below is an overview of the environmental impact expressed in €$_{\text{shadowcosts}}$ for the 11 basic CML2-baseline impact categories for the four different scenarios that have been studied.



		NMD (CML2-baseline)			
Environmental impact category:	*unit*	*case I*	*case II*	*case III*	*case IV*
Global warming (GWP100)	€$_{\text{shadowprice}}$	€ 43.774,00	€ 15.437,40	€ 22.642,50	€ 16.352,80
Ozone layer depletion (ODP)	€$_{\text{shadowprice}}$	€ 1,30	€ 0,20	€ 0,40	€ 0,30
Human toxicity (HTP)	€$_{\text{shadowprice}}$	€ 7.956,10	€ 4.219,20	€ 7.197,60	€ 4.541,70
Photochemical oxidation (POCP)	€$_{\text{shadowprice}}$	€ 1.641,00	€ 1.613,40	€ 1.626,40	€ 837,70
Acidification (AP)	€$_{\text{shadowprice}}$	€ 18.484,00	€ 4.434,90	€ 9.451,40	€ 6.716,80
Eutrophication (EP)	€$_{\text{shadowprice}}$	€ 3.783,70	€ 1.191,30	€ 2.082,40	€ 1.524,00
Terrestrial ecotoxicity (TAETP)	€$_{\text{shadowprice}}$	€ 46,80	€ 25,60	€ 32,60	€ 25,90
Fresh water aquatic ecotoxicity (FAETP)	€$_{\text{shadowprice}}$	€ 216,00	€ 177,00	€ 195,00	€ 104,20
Marine aquatic ecotoxicity (MAETP)	€$_{\text{shadowprice}}$	€ 505,30	€ 103,70	€ 387,10	€ 300,10
Abiotic depletion non-fuels (ADPe)	€$_{\text{shadowprice}}$	€ 0,10	€ 0,00	€ 0,00	€ 0,00
Abiotic depletion fossil fuels (ADPf)	€$_{\text{shadowprice}}$	€ 850,90	€ 255,00	€ 132,00	€ 102,20
		€ 77.259,20	**€ 27.457,70**	**€ 43.747,40**	**€ 30.505,70**

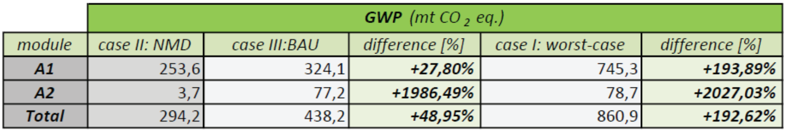
Figure 89: Environmental impact expressed in € shadowcost for the four scenario and specified per impact category

9 Conclusion

This chapter elaborates on the main findings and outcomes of this study and provides the final conclusions of this thesis. Furthermore the answer to the main research question is presented here and a brief summary of the results is provided.

9.1. Main Findings

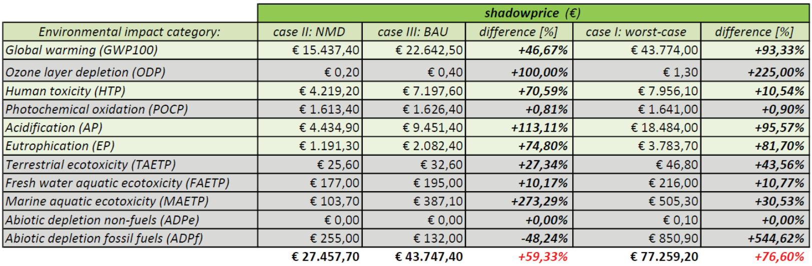
In part II, we concluded that there is a significant amount of uncertainty with regard to the accuracy of currently used methods and available source data for performing a ‘fast track’ LCA for steelworks. By means of the reference study described in paragraph 7 the findings in part II can be validated by calculating the environmental impact for various scenarios and comparison of the results. In **Figure 90** the current LCA data and prescribed transportation needs as defined by the NMD are used to calculate the total GWP of module ***A1*** and ***A2***. Results are compared with the BAU as indicated by a large steel manufacturer and a worst-case scenario in which it is assumed that all steel products originate from BOF plants in China. From the figure below it can be concluded that the reliability for calculating the GWP with the use of data from the NMD is questionable. The GWP of module ***A1*** is highly dependent on the production process. EAF steel has a significantly lower embodied GWP than BOF steel and the total GWP is therefore dependent on the specific ratio between EAF and BOF steel. Therefore it should always be ensured that LCA data from the specific origin facility is used in order to perform an accurate assessment.



	GWP *(mt CO_2 eq.)*				
module	*case II: NMD*	*case III:BAU*	*difference [%]*	*case I: worst-case*	*difference [%]*
A1	253,6	324,1	***+27,80%***	745,3	***+193,89%***
A2	3,7	77,2	***+1986,49%***	78,7	***+2027,03%***
Total	294,2	438,2	***+48,95%***	860,9	***+192,62%***

Figure 90: Comparison for the GWP as calculated according to principles NMD (case I) with two alternative scenario’s

Subsequently, by looking at the total shadowprice for the various environmental impact categories it can be concluded that four categories are of particular relevance in determining the environmental impact of steelworks; GWP, HTP, AP and EP. To a large extent these findings are consistent with the evaluation of scientific research on the steel production process, discussed in paragraph 5, in terms of identifying the dominant factors. However, as previously noted in the comparison between the ReCiPe and CML2 method in paragraph 5.1, it was pointed out that particulate matter formation is an important environmental factor which is not explicitly taken into account in the CML 2 method. This significantly affects the total calculated shadowcost of steel structures. Particulate matter formation is an important environmental impact factor of the steel production process which poses an important health risk to the general population. Including this aspect in an LCA significantly increases the total shadowprice as illustrated in 5.1. In **Figure 91** a comparison is made between the NMD, BAU and a worst-case scenario. From the figure it can be concluded that there are significant differences between the various scenarios. For the dominant factors general differences are observed in the range of roughly 10-110% with an average deviation of 73%. This validates the findings in phase II and indicates that a specific choice of EPD and origin location can greatly influence the outcomes of an environmental impact assessment.



	shadowprice (€)				
Environmental impact category:	*case II: NMD*	*case III: BAU*	*difference [%]*	*case I: worst-case*	*difference [%]*
Global warming (GWP100)	€ 15.437,40	€ 22.642,50	***+46,67%***	€ 43.774,00	***+93,33%***
Ozone layer depletion (ODP)	€ 0,20	€ 0,40	***+100,00%***	€ 1,30	***+225,00%***
Human toxicity (HTP)	€ 4.219,20	€ 7.197,60	***+70,59%***	€ 7.956,10	***+10,54%***
Photochemical oxidation (POCP)	€ 1.613,40	€ 1.626,40	***+0,81%***	€ 1.641,00	***+0,90%***
Acidification (AP)	€ 4.434,90	€ 9.451,40	***+113,11%***	€ 18.484,00	***+95,57%***
Eutrophication (EP)	€ 1.191,30	€ 2.082,40	***+74,80%***	€ 3.783,70	***+81,70%***
Terrestrial ecotoxicity (TAETP)	€ 25,60	€ 32,60	***+27,34%***	€ 46,80	***+43,56%***
Fresh water aquatic ecotoxicity (FAETP)	€ 177,00	€ 195,00	***+10,17%***	€ 216,00	***+10,77%***
Marine aquatic ecotoxicity (MAETP)	€ 103,70	€ 387,10	***+273,29%***	€ 505,30	***+30,53%***
Abiotic depletion non-fuels (ADPe)	€ 0,00	€ 0,00	***+0,00%***	€ 0,10	***+0,00%***
Abiotic depletion fossil fuels (ADPf)	€ 255,00	€ 132,00	***-48,24%***	€ 850,90	***+544,62%***
	€ 27.457,70	**€ 43.747,40**	***+59,33%***	**€ 77.259,20**	***+76,60%***

Figure 91: Comparison of shadowprices according to NMD with two alternative scenario's (CML2 method)

Figure 92 illustrates the partial contribution of the various LCA modules to the total ECI. It is notable that for case II, in which we used the data as prescribed by the NMD the influence of transportation is very insignificant. This can be explained due to the fact that the NMD indicates a transportation distance of 100 km. However, as previously indicated the closest steel plants producing structural steel sections are located in Peinen, Germany and Differdange, Luxemburg. The TATA steel plant in Ijmuiden, Netherlands only produces sheet metal. Setting the transport distance for ***A2*** to 100km is therefore incorrect and it the distance should always be based on the (most probable) origin facility.

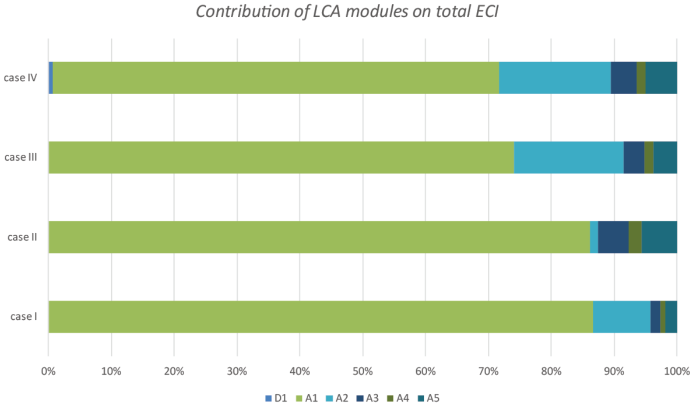
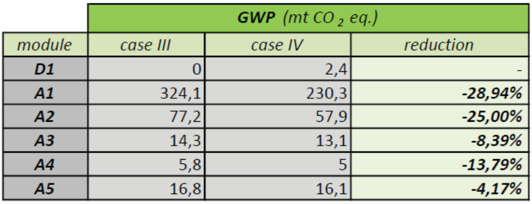


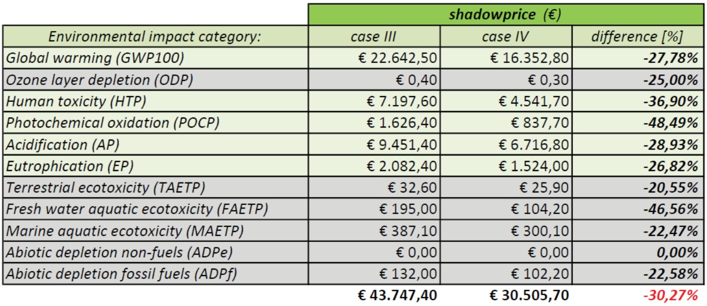
Figure 92: Comparison of shadowprices according to NMD with two alternative scenario's (CML2 method)

In case IV the circular optimization was used to determine if certain structural steel elements can be replaced with reused counterparts from the database that can either be directly reused or indirectly after remanufacturing. **Figure 86** indicates that 110 profiles were found which can directly be reused and 274 profiles that can be reused after remanufacturing. This accounts for 67,5 ton of virgin steel that can be replaced by circular counterparts. **Figure 93** highlights the reduction that could be achieved for the individual modules due to reuse. Furthermore **Figure 94** provides an overview of the shadowcost for the 11 environmental impact factors for case III and case IV. Notable are the relatively high reductions for HTP, POCP and FAETP. This could possibly be explained by the shift in transportation requirements. The use of circular profiles implies a significant increase in road transport from the storage facility to the construction site or steel manufacturer. Overall it can be concluded that the achieved reductions make a convincing case for structural steel reuse from the perspective of environmental impact reduction.



	GWP *(mt CO_2 eq.)*		
module	*case III*	*case IV*	*reduction*
D1	0	2,4	-
A1	324,1	230,3	***-28,94%***
A2	77,2	57,9	***-25,00%***
A3	14,3	13,1	***-8,39%***
A4	5,8	5	***-13,79%***
A5	16,8	16,1	***-4,17%***

Figure 93: Comparison for the GWP of the various LCA modules for case III and case IV



	shadowprice *(€)*		
Environmental impact category:	*case III*	*case IV*	*difference [%]*
Global warming (GWP100)	€ 22.642,50	€ 16.352,80	***-27,78%***
Ozone layer depletion (ODP)	€ 0,40	€ 0,30	***-25,00%***
Human toxicity (HTP)	€ 7.197,60	€ 4.541,70	***-36,90%***
Photochemical oxidation (POCP)	€ 1.626,40	€ 837,70	***-48,49%***
Acidification (AP)	€ 9.451,40	€ 6.716,80	***-28,93%***
Eutrophication (EP)	€ 2.082,40	€ 1.524,00	***-26,82%***
Terrestrial ecotoxicity (TAETP)	€ 32,60	€ 25,90	***-20,55%***
Fresh water aquatic ecotoxicity (FAETP)	€ 195,00	€ 104,20	***-46,56%***
Marine aquatic ecotoxicity (MAETP)	€ 387,10	€ 300,10	***-22,47%***
Abiotic depletion non-fuels (ADPe)	€ 0,00	€ 0,00	***0,00%***
Abiotic depletion fossil fuels (ADPf)	€ 132,00	€ 102,20	***-22,58%***
	€ 43.747,40	**€ 30.505,70**	***-30,27%***

Figure 94: Comparison for the shadowprices of the various LCA impact categories for case III and case IV

Furthermore, it was found that the final evaluation of a design for four different scenarios, with the tool developed in part III, could be performed fairly quick and without complications. The tool is explicitly not developed as a design aid. It is intended to improve structural steel designs by providing recommendations for substitution of certain elements with circular alternatives. The specific workflow of the tool thereby does not disrupt the current structural design practice. It can be expected that an engineer with basic knowledge of Revit and Grasshopper should be able to perform a similar analysis without prior knowledge by means of a brief set of instructions.

9.2. Conclusions

In this paragraph the main research question of this thesis will be answered and the final conclusions for the consecutive research phases will be discussed. Literature has indicated that a paradigm shift from our current linear economic model to a circular economy would offer significant benefits both in terms of curbing global warming as well as limiting the rate of global resource depletion and waste production. Steel has a lot of potential as a circular structural building material as it has excellent mechanical properties and it can be infinitely recycled. However, structural steel elements are currently only rarely being reused even though various studies have pointed out that reusing steel components could offer significant environmental benefits. From the literature review in phase I it can be concluded that several distinct barriers still exist which restrain the development of circular design strategies prevent the reuse of structural steel components in the current building industry. Value chain infrastructure and recertification are two of the major problems but there is also a significant amount of barriers that were classified as subjective. Improving current environmental impact assessment methods and accurately quantifying both the environmental and economic benefits of structural steel reuse could provide helpful in overcoming these subjective barriers.

The main research question of this thesis was:

“How can structural design & engineering firms accurately quantify the environmental benefits of using circular structural steel elements for primary load bearing constructions of building structures in the Netherlands?”

Therefore, in part II current assessment methods and environmental impact data were evaluated to see what the general deficiencies are and how the current practice could be improved. It was concluded that LCA is a highly developed and effective method to quantify the environmental impact of materials and products. However, it was concluded the ‘fast track’ LCA approach as used for the building industry is prone to large errors and inaccuracies. Current tools that serve the purpose of quantifying the environmental impact of building structures are to a large extent a ‘black box’ with very limited transparency and flexibility. Furthermore, it was noted that the EPD certificate system poses a lot of issues with regard to transparency and ambiguousness. Comparing various EPDs for structural steel products has brought to light that significant individual differences exist between certificates of magnitudes that are unacceptable for performing an accurate ‘fast track’ LCA analysis. Furthermore, the currently used environmental data integrated in the NMD on ‘heavy construction products’ is invalid as the certificate is currently more than a year past it’s due date. Moreover, comparison with other certificates and scientific publications raised several questions with regard to reliability of the data. As MPG calculations are obligatory to obtain a building permit in the Netherlands and the targets are becoming increasingly strict, it is crucial to ensure that the calculation methods and data are accurate and verifiable.

In part III an LCA tool for structural steel designs has been developed which is aimed at improving the current capabilities of engineers to accurately quantify the environmental benefits of using circular steel elements rather than virgin material. The tool offers the user a fast and flexible assessment method for steelworks which provides both increasing accuracy for determining the embodied environmental impact of building constructions as well as the option to effectively integrate structural elements in his design without any necessary changes to the current design practice. The performed case study verified previous conclusions that the choice of EPD certificate and the origin location of elements can greatly influence the outcomes of an analysis. Furthermore, it illustrated that the calculated environmental impact reductions in case of re-use make a convincing case for structural steel reuse. Even if elements need to be remanufactured and if they would be sourced across the European Union, implying transportation over long distances, the benefits would be very significant. The application could prove to be a valuable asset for engineers in convincing clients and decision makers of the benefits of reuse and persuading them into using circular components for (part of) a structural steel design.

10 Discussion

In this chapter the outcomes of this study are evaluated and the limitations are discussed. The used LCA framework, the considered boundary conditions, functional unit, impact factors and lifecycle stages will be elaborated on. Furthermore, the limitations with regard to the used data and the process of generating data will be critically evaluated. The main research question will be addressed and a brief summary will be provided of the outcomes of this study.

10.1. Used LCA data & calculation methods

With the provision of this tool an attempt is made to improve the current 'fast track' LCA procedure and to provide the user with increasing control and insight into LCA calculations. Current methods used for quantifying the environmental impact for building structures are to a large extent a black box. Users are generally unable to gain access to the underlying database and the used calculation methods as they occur in a closed environment. This makes it practically impossible for the user to evaluate the calculation process or to assess the accuracy of underlying data. In order to improve the current practice of quantifying the environmental impact of building structures this method offers complete transparency and users are able to adjust several settings taking into account specific conditions. Paragraph 6.2 thoroughly discusses the specific data that was used for the purpose of this case study and indicates where to find the appropriate resources. This allows users to evaluate to which extent the used data and method are actually applicable to their specific conditions and what the possible limitations could be.

The data used for determining the impact of the BOF and EAF production process, module ***A1***, is based on an LCA study performed for a specific plant in Poland (Dorota Burchart-Korol, 2013). This specific data was selected due to the fact that this research actually describes the specific assessment process and covers all relevant lifecycle cradle-to-gate processes. It thoroughly elaborates on the used weighting method, emissions, waste streams and assumptions made. It is therefore considered to be more transparent and reliable than information provided by EPDs and is deemed sufficient for the purpose of this study in providing average values for the European steel industry. However, seeing that the case study dates back to 2013 it makes the outcomes less reliable for current average conditions. Moreover, it is certain that individual differences between the various steel plants across Europe exist. It is therefore recommended to use facility specific data in case a verifiable and transparent LCA study is available. The information provided in EPDs is however not suitable for this purpose as was concluded in paragraph 4.4.6 and 5 as this data is non-transparent and the objectivity of these documents is questionable. In order for the EPD system to work plant operators should offer more openness with regard to their emissions and provide researchers and academics with unobstructed access to raw LCA data.

Although the tool is definitely an improvement with respect to transparency, there certainly is room for improvement as several assumptions had to be made due to lack of available data as described in paragraph 6.2. Environmental impact factors for modules ***A3*** are determined based on annual averages for total energy and resource usage. The assessment method of this module can be refined if additional and more extensive information could be obtained from various manufacturers to establish accurate average values for the subprocesses such as drilling, cutting, sandblasting, etc. The same holds for the construction and deconstruction modules ***A5*** and ***C1*** for which scientific literature was used to establish the environmental impact. Acquiring data from contractors and demolition contractors would be beneficial in establishing increasingly accurate estimates. However, this study has pointed out that the various actors in the supply chain are not keen on sharing information as this is often deemed ‘confidential’. It will therefore likely cost a lot of time and effort to obtain additional information which will complicate further research.

10.2.Generated Data

As there are currently no stockists active on the Dutch market specialized in the procurement and exchange of circular building materials yet, a fictional database of circular steel components had to be generated. It is important to keep in mind that the outcomes of the analysis are to a large extent dependent on the database and to understand the current limitations. This database is intended to reflect a matured marketplace in which various specialized stockists across Europe are actively involved in the trade of circular building materials. The database is generated randomly for a predefined range of profile types, lengths and origin locations as described in paragraph 7.1.2. Thereby the database entries show a fairly equal spread within the predefined boundaries with regard to profile types and element lengths. In practice it is expected that the spread will actually not be as equal as certain element types and sizes are more common than others. For example the use of an HEA800 is much more uncommon than an HEA300 in the building industry. The suitability of the generated data could therefore be significantly improved by analyzing a variety of buildings in the current building stock and creating a large scale inventory of profiles that could actually become available in the coming years. Moreover, the origin locations are set as the capital cities of various European countries. However, in practice it will be more likely that stockists facilities will be located in more rural areas as the price of land will be much lower here. This in turn will influence the transportation costs.

10.3.Sensitivity of results

The results and conclusions discussed in the previous paragraphs offer a first indication of the associated impact of primary steel constructions and the potential benefits of reusing circular steel elements. It should however be noted that these results are only valid for the specified domain and boundary conditions and specific circumstances that apply in the Netherlands. The results therefore can be interpreted only for this specific context. However, the used methodology and the framework of the tool could offer a basis for the development of a similar application for other regions. It was a conscious choice to develop this tool on a national level as part II of this study pointed out that local conditions have a significant impact on the outcomes of an LCA assessment. Therefore it is advised to use the same bottom up approach for developing similar applications. Although the results of the tool developed in part III offer improved insight into the magnitude of environmental impact of the different LCA production and construction modules ***A1-A5*** due to increased transparency and control of variables, the method could be further enhanced by future research. An important point for future studies would be the environmental impact of deconstruction. It is important to acquire data on previous deconstruction projects in order to improve estimates of the impact of the deconstruction process. Furthermore, as pointed out in part II there is a lot of uncertainty with regard to the reliability of EPDs. It would be very beneficial for this topic of research if all actors in the value chain support academic attempts to improve the quality of current data and if they would support similar studies by offering more transparency on their production processes and emissions.

10.4. Recommendations and future research

As mentioned in paragraph 6.1.1, the main purpose of the developed tool was to provide *“a workable proof-of-concept to demonstrate the potential environmental benefits of structural steel reuse”*. As this research is intended as a first exploration on how BIM and LCA could be combined to provide rapid feedback on the environmental impact of a design and to evaluate the potential for re-use there are still a lot of aspects to be improved and potential new features to be developed.

- *Assessment with the use of ReCiPe rather than CML2*: As the scientific field of LCA is rapidly developing, and the more recent ReCiPe method is being increasingly prescribed as the preferred method, it is recommended to make this method the new standard as this is expected to lead to increasingly accurate results.
- *Evaluation of designs at the Detailed Design stage* : There is a lot of room for improvement of the current tool for the later design stages when additional information is available with regard to the specific connections and requirements of a steel construction. Additional information can be added to the database with regard to the structural elements which can subsequently be taken into account during the evaluation processes. An increasingly accurate estimation of the required (re-)manufacturing and erection processes and requirements can be made at these stages and the assessment method can therefore be significantly be improved for module ***A3*** and ***A5***.
- *Allowing for overdimensioning*: The current method could be further improved by allowing for overdimensioning of certain elements such as freestanding columns or beams in places where the floor to ceiling height requirements are deemed fit to allow for an increased depth of horizontal elements.
- *Inclusion of additional materials*: The proposed method only evaluates the lifecycle impact of basic structural HEA- and -IPE steel elements. An interesting topic for further research would be to include other structural building materials and elements in the evaluation such as rebar, concrete and timber in order to provide an estimate of the actual total environmental impact of a wider variety of load-bearing constructions.
- *Financial costs estimation*: The financial costs indication uses a very rudimentary calculation model which is based on large assumptions and overall industry averages. For the purpose of providing a rough general indication of the influence of including shadowcosts on the total sustainable selling price it provides valuable insight for a decision making basis. However, the results should not be interpreted as a valid indication of the eventual costs of a structural steel design. In order to provide an

increasingly accurate estimation of the financial costs and the relationship between economics and environmental impact, further research is required with regard to specific details, processes and conditions. An example of how this could be integrated is illustrated in **Figure 96**.

- *Parametric optimization*: The current tool can be considered to be an optimization of the environmental impact of a standard virgin steel design by including circular components. An interesting topic for further research would consequently be the exploration of parametric optimization for various factors influencing the environmental impact of the circular components themselves. For example, it would be interesting to develop a feature which allows the user to find the best possible option for reuse by considering various factors such as; transportation distance from origin facility, the loss of material due to remanufacturing and the intended life expectancy of a building. A visual representation of origin facilities could prove to be beneficial in transferring information to the client. **Figure 95** gives an indication of how such a feature could look like.
- *Inclusion of external factors*: Another interesting topic would be identification and inclusion of external factors that are influenced by the reuse of circular steel components. If the demand for structural steel reuse will grow in coming years this will likely create new local business models and associated jobs. On the other side it will most likely incur increasing road transportation putting increasing strain on the local road network. How should such factors be taken into account in a CE evaluation model?

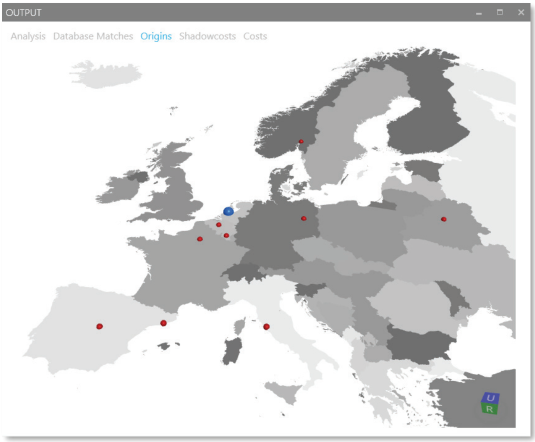
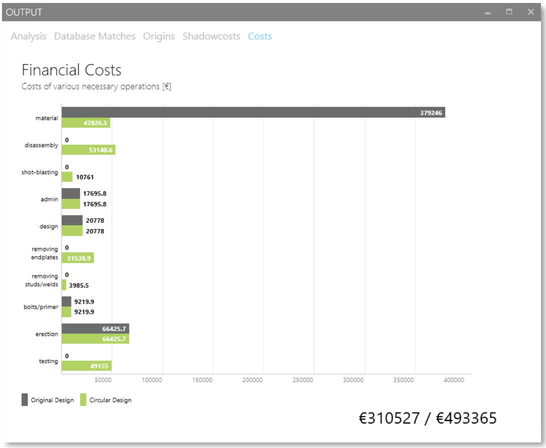


Figure 95: Adding a map with origin locations to the interface



Financial Costs

Costs of various necessary operations [€]

€310527 / €493365

Figure 96: Adding a financial cost model to the application & interface

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12 Appendices

Environmental Impact

		Netherlands	Germany		Italy	Australia		Luxembourg		Spain	U.S.	Finland	China	Bahrein
Parameter	Unit (per mt)	MRPI 2013	Bauforumstahl 2013	Bauforumstahl 2010	NUCOR 2018	Thinkstep 2016	Bluescope 2015	ArcelorMittal 2017	ArcelorMittal 2018	CELSA Group 2014	AISC 2016	Ruuki 2014	Yingkou 2018	SULB 2018
1 global warming potential	kg CO_2 eq./ton	908	1735	1680	981,48	3600	2850	524	1140	632	1160	2710	2610	2670
2 depletion potential of the stratospheric ozone layer	kg CFC-11 eq./ton	0,0000155	0,000000139	0,0000319	0	0,000017	0,000000118	0,000000614	2,55E-09	0,000000098	0,000000252	0,00000974	0,0000848	0,00011
3 Acidification potential of land and water	kg SO_2eq./ton	3,38	3,52	3,47	5,19	8,4	11,3	1,9	2,57	3,08	5,94	5,48	11,3	10,3
4 Eutrophication potential	kg $(PO_4)^3$ eq./ton	0,374	0,37	0,289	0,56	1,1	1,18	0,148	0,245	0,193	0,139	0,575	1,21	0,9
5 Formation potential of tropospheric ozone photochemical oxidants	kg C_2H_4 eq/ton	0,33	0,698	0,755	0,3	2,1	1,75	0,167	0,371	0,215	31,2	1,89	1,16	0,608
6 Abiotic depletion potential for non fossil resources	kg Sb eq/ton	-0,000134	0,000285	8,77	0	0,00089	0,000221	0,000263	0,00015	0,000159	0	0,0128	0,000364	0,0031
7 Abiotic depletion potential for fossil resources	kg Sb eq/ton	6,35	8,18	9,37	12,28	18,76	15,10	2,77	5,24	3,64	6,20	13,27	9,48	16,88
	Total shadowcost:	**€ 63,96**	**€ 106,86**	**€ 104,89**	**€ 77,44**	**€ 230,70**	**€ 204,24**	**€ 35,91**	**€ 71,07**	**€ 46,67**	**€ 146,40**	**€ 168,50**	**€ 190,43**	**€ 186,72**

Resource Use

		Netherlands	Germany		Italy	Australia		Luxembourg		Spain	U.S.	Finland	China	Bahrein
Parameter	Unit (per mt)	MRPI 2013	Bauforumstahl 2013	Bauforumstahl 2010	NUCOR 2018	Thinkstep 2016	Bluescope 2015	ArcelorMittal 2017	ArcelorMittal 2018	CELSA Group 2014	AISC 2016	Ruuki 2014	Yingkou 2018	SULB 2018
8 Renewable primary energy as energy carrier	MJ/ton	528	840	650	484,82	2300	362	824	1160	1160	509	2160	0,0146	91,1
9 Renewable primary energy resources as material utilization	MJ/ton	0	0	0	0	0	0	0	0	0	0	0	3	0
10 Total use of renewable primary energy resources	MJ/ton	528	840	650	484,82	2300	362	824	1160	1160	509	2160	3,01	91,1
11 Non renewable primary energy as energy carrier	MJ/ton	13200	17800	19840	26114,53	40000	31500	9170	12500	8430	14800	17780	18900	33400
12 Non renewable primary energy as material utilization	MJ/ton	0	0	0	604,79	0	0	0	0	0	0	12100	3	0
13 Total use of non renewable primary energy resources	MJ/ton	13200	17800	19480	26719,31	40000	31500	9170	12500	8430	14800	29890	18900	33400
14 Use of secondary material	kg/ton	-	618	-	1188,81	310	131	1080	827	1150	0	0	0	0
15 Use of renewable secondary fuels	MJ/ton	-	0,175	-	0	0	0	0	0	0	-	0	0	0
16 Use of non renewable secondary fuels	MJ/ton	-	1,7	-	0	9,3	0	0	0	0	0	0	0	0
17 Use of net fresh water	m^3/ton	2590	2,65	3,011	31,74	13	2,38	3,82	3,69	3,19	-	20	3,48	4,36

Output Flows and Waste Categories

		Netherlands	Germany		Italy	Australia		Luxembourg		Spain	U.S.	Finland	China	Bahrein
Parameter	Unit (per mt)	MRPI 2013	Bauforumstahl 2013	Bauforumstahl 2010	NUCOR 2018	Thinkstep 2016	Bluescope 2015	ArcelorMittal 2017	ArcelorMittal 2018	CELSA Group 2014	AISC 2016	Ruuki 2014	Yingkou 2018	SULB 2018
18 Hazardous waste disposed	kg	89,9	0,279	3	22,46	0,012	0,0378	0,00000611	0,00000692	0,0469	0,00256	53,7	0	0
19 Non hazardous waste disposed	kg	111	51,9	4510	174,55	0,0028	15,7	6,99	4,76	38,3	15,2	0,412	0	0
20 Radioactive waste disposed	kg	-	0,315	0,43	-	0,41	0,0142	1,35	0,618	0,359	0,735	0,297	0	0
21 Components for re-use	kg	0	0	0	0	0	0	0	0	0	0	0	0	0
22 Materials for recycling	kg	0	0	0	0	0	0	0	0	0	0	0	0	0
23 Materials for energy recovery	kg	0	0	0	0	0	0	0	0	0	0	0	0	0
24 Exported electrical energy	MJ	0	0	0	0	0	0	0	0	0	0	0	0	0
25 Exported thermal energy	MJ	0	0	0	0	0	0	0	0	0	0	0	0	0

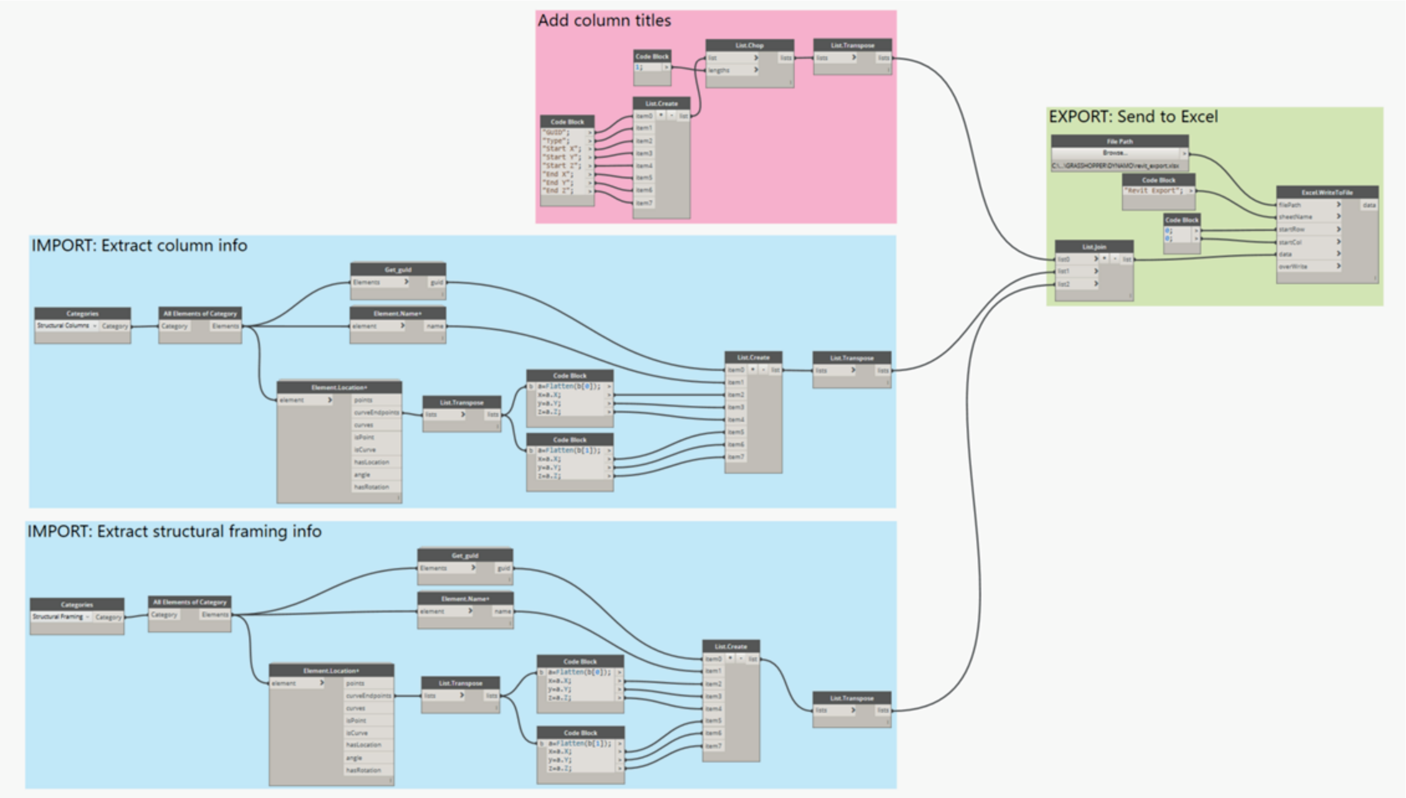
Recycling and Reuse

		Netherlands	Germany		Italy	Australia		Luxembourg		Spain	U.S.	Finland	China	Bahrein
Parameter	Unit	MRPI 2013	Bauforumstahl 2013	Bauforumstahl 2010	NUCOR 2018	Thinkstep 2016	Bluescope 2015	ArcelorMittal 2017	ArcelorMittal 2018	CELSA Group 2014	AISC 2016	Ruuki 2014	Yingkou 2018	SULB 2018
26 Average recovered content / scrap (EAF route)	%	90	35	35	100	25	25	100	82,7	100			-	-
27 Recycling Potential	%	51	88	88	-	89	89	88	88	88		95	-	-
28 Reuse Potential	%	49	11	11	-	0	0	11	11	11		0	-	-
29 Landfilling	%	0	1	1	-	11	11	1	1	1		5	-	-

Norms and Standards

		Netherlands	Germany		Italy	Australia		Luxembourg		Spain	U.S.	Finland	China	Bahrein
Parameter	Unit	MRPI 2013	Bauforumstahl 2013	Bauforumstahl 2010	NUCOR 2018	Thinkstep 2016	Bluescope 2015	ArcelorMittal 2017	ArcelorMittal 2018	CELSA Group 2014	AISC 2016	Ruuki 2014	Yingkou 2018	SULB 2018
30 According to standard ISO 14025	-	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
31 CEN Norm EN15804 serves as the core PCR	-	no	yes	no	yes	yes	yes	yes	yes	yes	no	yes	yes	yes

Appendix 1: Comparison of various EPDs



```
"GUID";
"Type";
"Start X";
"Start Y";
"Start Z";
"End X";
"End Y";
"End Z";
```

```
1;
```

```
a=Flatten(b[0]);
x=a.X;
y=a.Y;
z=a.Z;
```

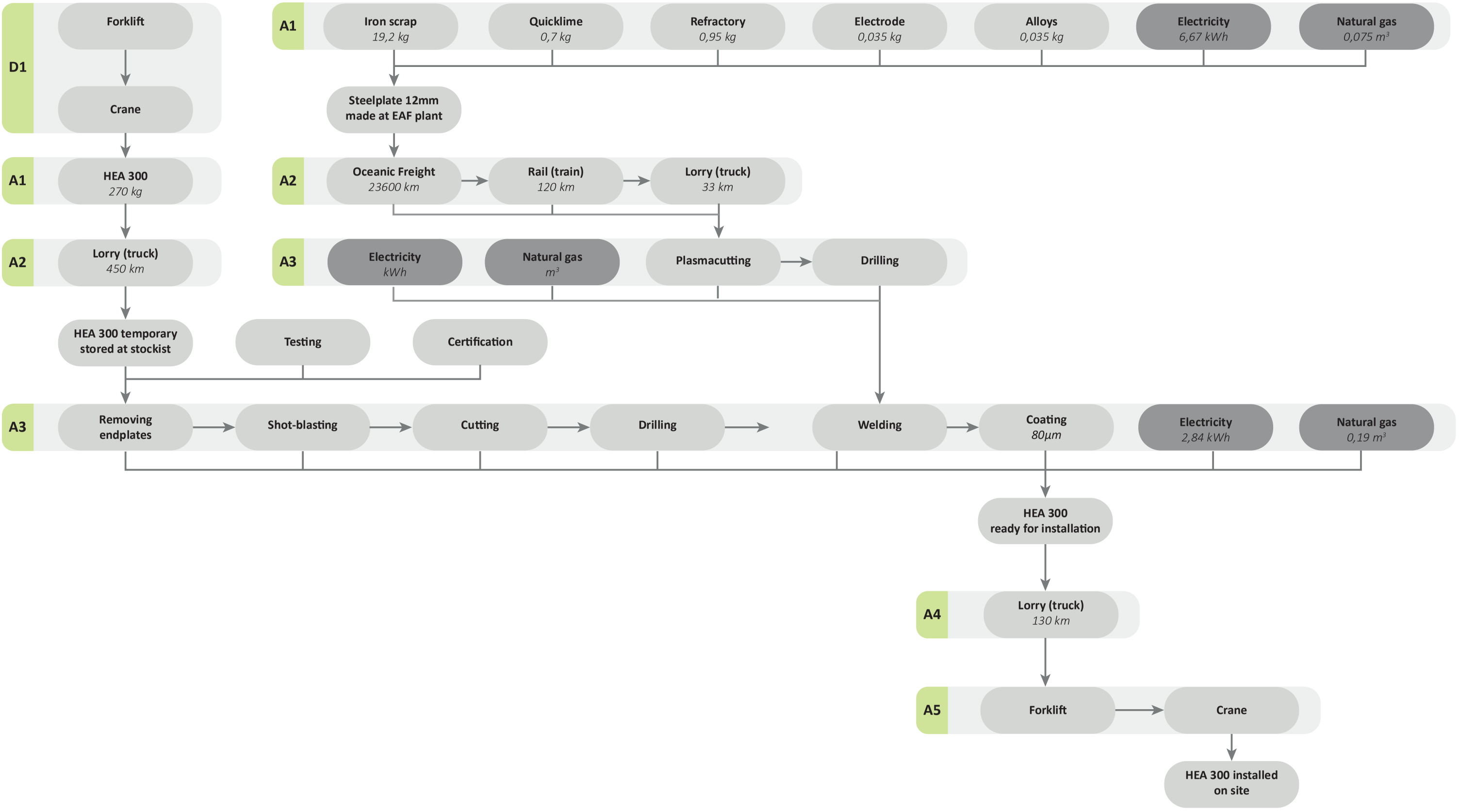
```
a=Flatten(b[1]);
x=a.X;
y=a.Y;
z=a.Z;
```

C:\...\GRASSHOPPER\DYNAMO\revit_export.xlsx

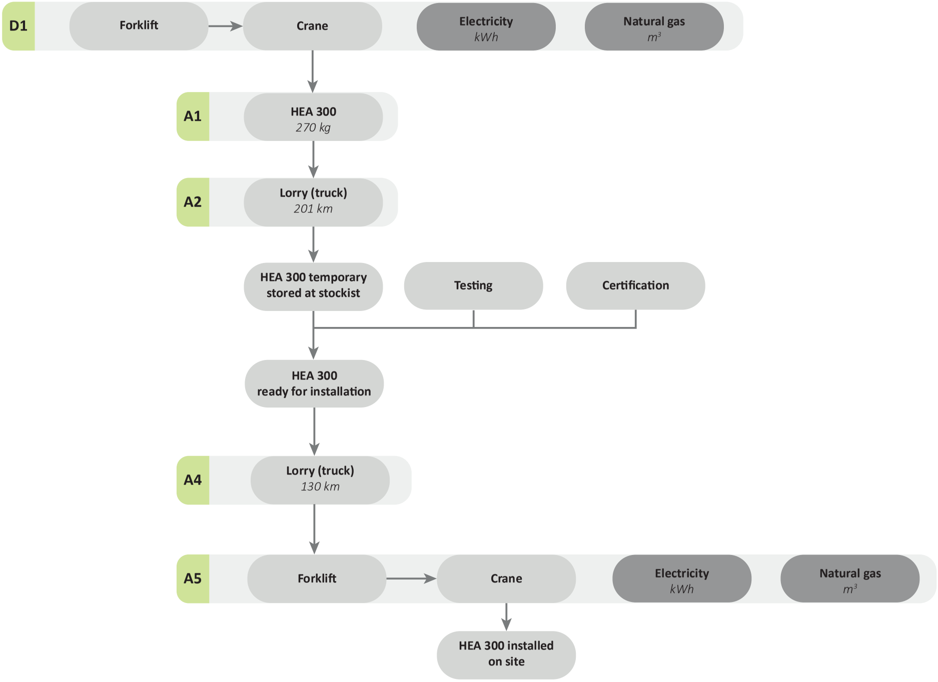
```
"Revit Export";
```

```
0;
0;
```

***Appendix 2**: Dynamo script, Extracting information from Revit*



***Appendix 3**: Inventory Analysis Process Tree: Indirect Reuse*



Appendix 4: *Inventory Analysis Process Tree: Direct Reuse*

profile	dimensions (mm)				weight	section area
	h	b	s	t	kg/m	cm^2
HEA 100	96	100	5	8	16,7	21,2
HEA 120	114	120	5	8	19,9	25,3
HEA 140	133	140	5,5	8,5	24,7	31,4
HEA 160	152	160	6	9	30,4	38,8
HEA 180	171	180	6	9,5	35,5	45,3
HEA 200	190	200	6,5	10	42,3	53,8
HEA 220	210	220	7	11	50,5	64,3
HEA 240	230	240	7,5	12	60,3	76,8
HEA 260	250	260	7,5	12,5	68,2	86,8
HEA 280	270	280	8	13	76,4	97,3
HEA 300	290	300	8,5	14	88,3	112
HEA 320	310	300	9	15,5	97,6	124
HEA 340	330	300	9,5	16,5	105	133
HEA 360	350	300	10	17,5	112	143
HEA 400	390	300	11	19	125	159
HEA 450	440	300	11,5	21	140	178
HEA 500	490	300	12	23	155	198
HEA 550	540	300	12,5	24	166	212
HEA 600	590	300	13	25	178	226
HEA 650	640	300	13,5	26	190	242
HEA 700	690	300	14,5	27	204	260
HEA 800	790	300	15	28	224	286
HEA 900	890	300	16	30	252	320
HEA 1000	990	300	16,5	31	272	347

profile	dimensions (mm)				weight	section area
	h	b	s	t	kg/m	cm^2
IPE 80	80	46	3,8	5,2	6	7,64
IPE 100	100	55	4,1	5,7	8,1	10,3
IPE 120	120	64	4,4	6,3	10,4	13,2
IPE 140	140	73	4,7	6,9	12,9	16,4
IPE 160	160	82	5	7,4	15,8	20,1
IPE 180	180	91	5,3	8	18,8	23,9
IPE 200	200	100	5,6	8,5	22,4	28,5
IPE 220	220	110	5,9	9,2	26,2	33,4
IPE 240	240	120	6,2	9,8	30,7	39,1
IPE 270	270	135	6,6	10,2	36,1	45,9
IPE 300	300	150	7,1	10,7	42,2	53,8
IPE 330	330	160	7,5	11,5	49,1	62,6
IPE 360	360	170	8	12,7	57,1	72,7
IPE 400	400	180	8,6	13,5	66,3	84,5
IPE 450	450	190	9,4	14,6	77,6	98,82
IPE 500	500	200	10,2	16	90,7	115,5
IPE 550	550	210	11,1	17,2	106	134,4
IPE 600	600	220	12	19	122	156

Appendix 5: *Properties for structural steel HEA and IPE profiles*

Tool Name	author	study field	output	indicators	focus	limitations
Material Circularity Index (MCI)	*EMF / Granta*	*CE*	*MCI-score (%)*	*1*	*Lifecycle Thinking*	*No distinction between regenerative and non-regenerative materials, Only allows for comparison of components*
Cradle 2 Cradle Certificates (C2C)	*Ecolabel Index*	*C2C*	*C2C-certificate (5 cat.)*	*5*	*Materials, use, social & output*	*No consideration of time; low transparancy; no incentive for longer use or reuse*
Once Click LCA (LCA)	*BioNova Ltd*	*LCA*	*Shadowcost*	*29*	*Materials, use, waste & output*	*No assessment of functional degradation of materials; High degree of complexity*
Milieu Relevante Product Informatie (MRPI)	*MRPI*	*LCA*	*Shadowcost*	*15*	*Materials & use*	*No output flow indicators*
GPR-gebouw (GPR)	*W/E Adviseurs*	*LCA*	*GPR-score (5 cat.)*	*24*	*Materials, use & output*	*Too much emphasis on emissions (CO2); High level of abstraction of influential factors*
Milieu Prestatie van Gebouwen (MPGCalc)	*DGMR Software B.V.*	*LCA*	*Shadowcost*	*12*	*Materials*	*No resource use and output flow indicators*
mass, time, performance, environment, business (MTPEB)	*Hemmen (2017)*	*CE*	*Material flow rate (%)*	*5*	*Economics, materials & use*	*Multiple dimensions makes it less comprehensible; only indication of environmental impact not precise*
Eco-costs / Value Ratio (EVR)	*Vögtlander (2012)*	*LCA*	*Ecocosts & Carbonfoot*	*2*	*Economics*	*Focus on material, Financials are conventional LCC and this doesn't disclose reuse values*
Circular Economy Index (CEI)	*Di Maio (2015)*	*CE*	*CEI-index*	*1*	*Economics*	*One dimensional, focus on recycling only*
Economic Value Ratio	*Linder (2017)*	*CE*	*Numerical*	*1*	*Economics*	*One dimensional, focus on recirculation only*

Appendix 6: *Comparison of various CE & LCA assessment tools and theoretical frameworks*

Impact Transportation

		Abiotic depletion non-fuels	*Abiotic depletion fossil fuels*	*Global warming (GWP100)*	*Ozone layer depletion (ODP)*	*Photochemical oxidation*	*Acidification*	*Eutrophication*	*Human toxicity*	*Fresh water aquatic ecotox.*	*Marine aquatic ecotoxicity*	*Terrestrial ecotoxicity*
Transport type	***unit***	kg Sb eq	kg Sb eq	kg CO_2 eq	kg CFC-11 eq	kg C_2H_4	kg SO_2 eq	kg PO_4^{3-} eq.	kg 1,4-DB eq	kg 1,4-DB eq	kg 1,4-DB eq	kg 1,4-DB eq
Lorry (truck) unspecified	ton· km	0,000000373	0,000973	0,132	2,46E-08	0,0000795	0,000581	0,000114	0,0529	0,00158	5,66	0,000191
Lorry (truck); 3.5 - 7.5t; EURO3	ton· km	0,00000276	0,00373	0,521	9,04E-08	0,000292	0,00255	0,000504	0,17	0,00539	17,3	0,000797
Lorry (truck); 7.5 - 16t; EURO3	ton· km	0,000000846	0,00157	0,217	0,000000039	0,000126	0,00108	0,00022	0,0755	0,00247	7,92	0,000312
Lorry (truck); 16 - 32t; EURO4	ton· km	0,000000494	0,00121	0,166	3,07E-08	0,0000852	0,000663	0,000127	0,0624	0,00174	6,71	0,000225
Lorry (truck); > 32t; EURO4	ton· km	0,000000169	0,000677	0,0899	1,73E-08	0,0000574	0,000359	0,0000686	0,0409	0,00112	4,42	0,000132
Light commercial vehicle, Van	ton· km	0,00000709	0,0137	1,94	0,00000032	0,0018	0,00871	0,00162	0,614	0,0152	54,5	0,00315
Rail (train)	ton· km	7,65E-08	0,000342	0,0511	6,03E-09	0,0000309	0,000293	0,0000533	0,0196	0,000293	1,23	0,000113
Barge (inland waterways)	ton· km	2,69E-08	0,000304	0,0481	7,17E-09	0,0000289	0,00035	0,0000765	0,0107	0,000286	0,877	0,0000554
Barge tanker (inland waterways)	ton· km	2,99E-08	0,00028	0,0444	6,66E-09	0,0000299	0,000324	0,0000712	0,0107	0,00028	0,809	0,000057
Transoceanic freight ship	ton· km	2,47E-09	0,000078	0,0115	1,83E-09	0,0000126	0,000239	0,0000212	0,00511	0,0000934	0,445	0,0000165
Transoceanic tanker	ton· km	1,53E-09	0,0000415	0,00606	9,58E-10	0,00000693	0,00014	0,0000188	0,00543	0,0000513	0,236	0,00000934
Concrete truck mixer NL, 6 m^3	ton· km	1,17E-08	0,000725	0,117	0,00000002	0,0000664	0,000682	0,000167	0,0141	0,000764	1,81	0,0000579
Concrete truck mixer NL, 10 m^3	ton· km	9,02E-09	0,000559	0,0903	1,54E-08	0,0000512	0,000525	0,000129	0,0108	0,000589	1,4	0,0000446
Concrete truck mixer NL - 13.5 m^3	ton· km	8,78E-09	0,000544	0,0878	0,000000015	0,0000498	0,000511	0,000125	0,0105	0,000573	1,36	0,0000434
Asphalt truck 16t, 270 kW, 6x4	ton· km	0,000000533	0,00139	0,189	3,51E-08	0,000114	0,000831	0,000163	0,0756	0,00225	8,09	0,000272
Asphalt truck 25t, 240 kW, 8x4	ton· km	0,000000242	0,000632	0,0858	0,000000016	0,0000517	0,000378	0,0000743	0,0344	0,00102	3,68	0,000124
Tractor and trailer, agricultural	ton· km	0,00000202	0,0026	0,399	4,22E-08	0,000362	0,00248	0,000389	0,293	0,00357	19,7	0,00115

Steel Manufacturing

		Abiotic depletion non-fuels	*Abiotic depletion fossil fuels*	*Global warming (GWP100)*	*Ozone layer depletion (ODP)*	*Photochemical oxidation*	*Acidification*	*Eutrophication*	*Human toxicity*	*Fresh water aquatic ecotox.*	*Marine aquatic ecotoxicity*	*Terrestrial ecotoxicity*
Manufacturing:	***unit***	kg Sb eq	kg Sb eq	kg CO2 eq	kg CFC-11 eq	kg C2H4	kg SO2 eq	kg PO_4^{3-} eq.	kg 1,4-DB eq	kg 1,4-DB eq	kg 1,4-DB eq	kg 1,4-DB eq
Wet painting steel	kg	0,00000162	0,003	2,43	0,000000137	0,116	0,0142	0,00155	5,68	0,829	44,5	0,00364
Powder coating	kg	0,0000139	0,132	15,8	0,0000018	0,00559	0,0456	0,00592	4,59	0,0781	677	0,00382
Galvanizing	kg	0,000645	0,0343	4,69	0,000000417	0,00335	0,00494	0,00963	7,44	0,12	482	0,198

Impact Energy Use

		Abiotic depletion non-fuels	*Abiotic depletion fossil fuels*	*Global warming (GWP100)*	*Ozone layer depletion (ODP)*	*Photochemical oxidation*	*Acidification*	*Eutrophication*	*Human toxicity*	*Fresh water aquatic ecotox.*	*Marine aquatic ecotoxicity*	*Terrestrial ecotoxicity*
Energy:	***unit***	kg Sb eq.	kg Sb eq.	kg CO_2 eq.	kg CFC-11 eq.	kg C_2H_4 eq.	kg SO_2 eq.	kg PO_4^{3-} eq.	kg 1,4-DB eq	kg 1,4-DB eq	kg 1,4-DB eq	kg 1,4-DB eq
Diesel - fossil	l	0,00000077	0,022	3,3	0,00000041	0,0033	0,025	0,0057	2,5	0,041	220	0,0041
Bio-diesel	l	0,0000039	0,0076	2	0,0000002	0,00089	0,032	0,017	0,73	2,4	90	1,1
Electricity - fossil	kWh	0,00000091	0,0056	0,69	0,000000028	0,000081	0,0011	0,00028	0,16	0,0024	45	0,0094
Electricity - Renewable source (average NL,	kWh	0,00000198	0,000314	0,101	4,51E-09	0,0000558	0,000576	0,000131	0,0613	0,00155	5,1	0,0091
Methane gas - fossil	m3	0,000000139	0,0179	2,09	0,00000013	0,000138	0,000994	0,000174	0,124	0,000807	4,81	0,000655

Appendix 7: *Environmental impact factors for transport & energy according to the NMD*

Energy Use

				Global warming (GWP100)	Acidification Potential	Nitrogen oxides	Particulate matter formation	Shadowcost
			unit	kg eCO_2 eq.	kg $SO_{2\ eq.}$	kg NO_x eq.	kg ePM_{10} eq.	€
energy	electricity	grijze stroom	kWh	0,526	0,00039	0,00071	0,00003	0,0664
		stroom (onbekend)	kWh	0,355	0,00026	0,00049	0,00002	0,045092
		windkracht	kWh	0	0	0	0	0
		waterkracht	kWh	0	0	0	0	0
		zonne-energie	kWh	0	0	0	0	0
		biomassa	kWh	0,189	0,0002	0,0004	0,00003	0,031703
	fuel	diesel (NL)	l	3,23	0,0026492	0,0011456	0,0001074	0,297238
		biodiesel B100 (NL)	l	3,154	0,0022554	0,00179	0,0002864	0,31781206
		marine gas oil	l	3,49	0,00342	0,0010944	0,0001026	0,32914308
		natural gas	m^3	1,89	0,001953889	0,003907778	0,000293083	0,312204463

Transportation

				Global warming (GWP100)	Acidification Potential	Nitrogen oxides	Particulate matter formation	Shadowcost
			unit	kg eCO_2 eq.	kg $SO_{2\ eq.}$	kg NO_x eq.	kg ePM_{10} eq.	€
road	truck	delivery van	ton km	1,585	0,0016	0,0065	0,000473	0,388372
		truck small (<10 ton)	ton km	0,432	0,0004	0,0037	0,000053	0,166631
		truck medium (10-20 ton)	ton km	0,259	0,0003	0,00018	0,000026	0,030273
		truck large (>20 ton)	ton km	0,11	0,0001	0,0006	0,000011	0,030339
		trekker met oplegger zwaar	ton km	0,082	0,0001	0,0003	0,000007	0,018057
		LZV	ton km	0,079	0,0001	0,0003	0,000006	0,017817
shipping	inland	small (300-600 ton)	ton km	0,041	0,000041	0,00051	0,00002	0,0224349
		medium (1500-3000 ton)	ton km	0,03	0,000028	0,00033	0,000013	0,0147552
		large (5000-110000 ton)	ton km	0,021	0,000021	0,00023	0,000009	0,0103219
	sea	small (0-5 dwkt)	ton km	0,027	0,000041	0,00047	0,000011	0,0196279
		medium (5-10 dwkt)	ton km	0,021	0,000032	0,00036	0,000009	0,0151068
		large (10-20 dwkt)	ton km	0,015	0,000023	0,00026	0,000006	0,0108637
rail	train	electric, short	ton km	0,031	0,000017	0,000029	0,000001	0,0032656
		electric, average	ton km	0,024	0,000013	0,000023	0,000001	0,0025588
		electric, long	ton km	0,02	0,000011	0,000019	0,000001	0,0021422

Appendix 8: *Environmental impact factors according to STREAM (CE Delft, 2017)*

NMD

	CML2-baseline		MRPI - NL 2013 *(90% EAF, 10% BOF)*			MRPI - NL 2013 + module D *(90% EAF, 10% BOF)*		
Environmental impact category:	unit	shadowprice	impact (unit/mt)	total (unit)	shadowprice (€)	impact (unit/mt)	total (unit)	shadowprice (€)
Abiotic depletion non-fuels (ADPe)	kg Sb eq.	€ 0,16	-0,000134	-0,026453181	€ 0,00	-0,0000385	-0,007600354	€ 0,00
Abiotic depletion fossil fuels (ADPf)	kg Sb eq.	€ 0,16	5,21	1028,515478	€ 164,56	3,07359	606,7629344	€ 97,08
Global warming (GWP100)	kg CO_2 eq.	€ 0,05	908	179249,9144	€ 8.962,50	396	78175,0728	€ 3.908,75
Ozone layer depletion (ODP)	kg CFC-11 eq.	€ 30	0,0000155	0,003059883	€ 0,09	0,00001178	0,002325511	€ 0,07
Photochemical oxidation (POCP)	kg C_2H_4	€ 2	0,33	65,145894	€ 130,29	0,146	28,8221228	€ 57,64
Acidification (AP)	kg SO_2 eq.	€ 4	3,38	667,251884	€ 2.669,01	1,87	369,160066	€ 1.476,64
Eutrophication (EP)	kg PO_4^{3-} eq.	€ 9	0,374	73,8320132	€ 664,49	0,221	43,6280078	€ 392,65
Human toxicity (HTP)	kg 1,4-DB eq.	€ 0,09	33,3	6573,81294	€ 591,64	24,45	4826,71851	€ 434,40
Fresh water aquatic ecotoxicity (FAETP)	kg 1,4-DB eq.	€ 0,03	3,02	596,183636	€ 17,89	1,15	227,02357	€ 6,81
Marine aquatic ecotoxicity (MAETP)	kg 1,4-DB eq.	€ 0,0001	6340	1251590,812	€ 125,16	4560	900197,808	€ 90,02
Terrestrial ecotoxicity (TAETP)	kg 1,4-DB eq.	€ 0,06	0,468	92,3887224	€ 5,54	0,328	64,7510704	€ 3,89
					€ 13.331,16			**€ 6.467,96**

BAU

	CML2-baseline		Yingkou Medium Plate Co. Ltd. - CN 2017 *(100% BOF)*			Bauforumstahl e.V. - LU 2018 *(76% EAF, 24% BOF)*			TOTAL
Environmental impact category:	unit	shadowprice	impact (unit/mt)	total (unit)	shadowprice (€)	impact (unit/mt)	total profiles (unit)	shadowprice (€)	shadowprice (€)
Abiotic depletion non-fuels (ADPe)	kg Sb eq.	€ 0,16	0,000364	0,00210028	€ 0,00	0,000492	0,094287766	€ 0,02	€ 0,02
Abiotic depletion fossil fuels (ADPf)	kg Sb eq.	€ 0,16	9,4757	54,674789	€ 8,75	0,49062	94,02329992	€ 15,04	€ 23,79
Global warming (GWP100)	kg CO_2 eq.	€ 0,05	2610	15059,7	€ 752,99	1130	216555,234	€ 10.827,76	€ 11.580,75
Ozone layer depletion (ODP)	kg CFC-11 eq.	€ 30	0,0000848	0,000489296	€ 0,01	1,96E-09	3,75618E-07	€ 0,00	€ 0,01
Photochemical oxidation (POCP)	kg C_2H_4	€ 2	1,16	6,6932	€ 13,39	0,0402	7,70400036	€ 15,41	€ 28,79
Acidification (AP)	kg SO_2 eq.	€ 4	11,3	65,201	€ 260,80	2,16	413,946288	€ 1.655,79	€ 1.916,59
Eutrophication (EP)	kg PO_4^{3-} eq.	€ 9	1,21	6,9817	€ 62,84	0,219	41,9695542	€ 377,73	€ 440,56
Human toxicity (HTP)	kg 1,4-DB eq.	€ 0,09	104	600,08	€ 54,01	46,3	8870,523997	€ 798,35	€ 852,35
Fresh water aquatic ecotoxicity (FAETP)	kg 1,4-DB eq.	€ 0,03	5,98	34,5046	€ 1,04	4,20	804,473948	€ 24,13	€ 25,17
Marine aquatic ecotoxicity (MAETP)	kg 1,4-DB eq.	€ 0,0001	4744	27372,88	€ 2,74	881	168886,2527	€ 16,89	€ 19,63
Terrestrial ecotoxicity (TAETP)	kg 1,4-DB eq.	€ 0,06	2,08	12,0016	€ 0,72	0,651	124,6668237	€ 7,48	€ 8,20
									€ 14.895,86

Literature

	ReCiPe midpoint (H)		Burchart-Korol 2013 *(BOF)*			Burchart-Korol 2013 *(EAF)*			
Environmental impact category:	unit	shadowprice	impact (unit/mt)	total plates (unit)	shadowprice (€)	impact (unit/mt)	total profiles (unit)	shadowprice (€)	TOTAL
Global warming (GWP100)	kg CO_2 eq.	€ 0,057	2459	14188,43	€ 808,74	913	174968,9634	€ 9.973,23	€ 10.781,97
Ozone layer depletion (ODP)	kg CFC-11 eq.	€ 30,40	0	0	€ 0,00	0	0	€ 0,00	€ 0,00
Human toxicity (HTP)	kg 1,4-DB eq.	€ 0,0206	929	5360,33	€ 110,42	412	78956,4216	€ 1.626,50	€ 1.736,93
Photochemical oxidation (POCP)	kg NMVOC	€ 2,10	7,06	40,7362	€ 85,55	1,66	318,125388	€ 668,06	€ 753,61
Particulate matter formation (PM)	kg PM_{10} eq.	€ 51,50	6,66	38,4282	€ 1.979,05	0,93	178,226874	€ 9.178,68	€ 11.157,74
Ionizing radiation (IR)	kg U^{235} eq.	€ 0,0425	119,63	690,2651	€ 29,34	28,77	5513,534586	€ 234,33	€ 263,66
Acidification (AP)	kg SO_2 eq.	€ 0,638	6,95	40,1015	€ 25,58	2,96	567,259728	€ 361,91	€ 387,50
Freshwater eutrophication (FEP)	kg P eq.	€ 1,78	1,17	6,7509	€ 12,02	0,55	105,40299	€ 187,62	€ 199,63
Marine eutrophication (MEP)	kg N eq.	€ 12,50	0,43	2,4811	€ 31,01	0,17	32,579106	€ 407,24	€ 438,25
Terrestrial ecotoxicity (TAETP)	kg 1,4-DB eq.	€ 1,28	6,95	40,1015	€ 51,33	0,07	13,414926	€ 17,17	€ 68,50
Fresh water aquatic ecotoxicity (FAETP)	kg 1,4-DB eq.	€ 0,04	17,63	101,7251	€ 4,07	8,3	1590,62694	€ 63,63	€ 67,69
Marine aquatic ecotoxicity (MAETP)	kg 1,4-DB eq.	€ 0,00	19,24	111,0148	€ 0,00	8,46	1621,289628	€ 0,00	€ 0,00
Agricultural land occupation (aLO)	m^2 / year	€ 0,094	65,79	379,6083	€ 35,68	16,18	3100,764324	€ 291,47	€ 327,16
Urban land occupation (uLO)	m^2 / year	€ 0,094	17,63	101,7251	€ 9,56	4,92	942,877656	€ 88,63	€ 98,19
Water depletion (WDP)	m^3	€ 1,00	126,29	728,6933	€ 728,69	2,24	429,277632	€ 429,28	€ 1.157,97
Metal depletion (MDP)	kg Fe eq.	€ 0,00	1228	7085,56	€ 0,00	15	2874,627	€ 0,00	€ 0,00
Abiotic depletion fossil fuels (ADPf)	kg oil eq.	€ 0,00	764	4408,28	€ 0,00	218	41777,9124	€ 0,00	€ 0,00
									€ 27.438,80

Appendix 9: *Case study: determining the environmental impact of module* ***A1*** *according to the four predefined scenarios*

Import & Export I-profielen Nederland 2016

		h= 80-220mm		h > 220mm		total import	percentage	total export	percentage
#	Countries	import (kg)	export (kg)	import (kg)	export (kg)	kg	%	kg	%
1	Azerbeidzjan	3113	30256	8855	6543	11968	0,01%	36799	0,11%
2	België	411435	4094270	1035251	16961375	1446686	0,90%	21055645	65,17%
3	Bulgarije	707	0	3185	2	3892	0,00%	2	0,00%
4	Ceuta	0	178	0	0	0	0,00%	178	0,00%
5	Cyprus	0	16	0	57	0	0,00%	73	0,00%
6	Denemarken	42669	24874	102294	63110	144963	0,09%	87984	0,27%
7	Duitsland	16290970	387259	61103325	5409102	77394295	48,08%	5796361	17,94%
8	Finland	5	0	9867	2348	9872	0,01%	2348	0,01%
9	Frankrijk	1972409	82965	3762	418302	1976171	1,23%	501267	1,55%
10	Griekenland	18	0	75	0	93	0,00%	0	0,00%
11	Hongarije	21	0	416	0	437	0,00%	0	0,00%
12	Ierland	2303	0	8492	0	10795	0,01%	0	0,00%
13	IJsland	2346	6909	0	0	2346	0,00%	6909	0,02%
14	Italië	487763	3107	252046	0	739809	0,46%	3107	0,01%
15	Kazachstan	0	273	0	0	0	0,00%	273	0,00%
16	Kosovo	0	3	0	2	0	0,00%	5	0,00%
17	Kroatië	70	215	974	805	1044	0,00%	1020	0,00%
18	Letland	0	0	1323	0	1323	0,00%	0	0,00%
19	Litouwen	196749	0	36932	0	233681	0,15%	0	0,00%
20	Luxemburg	12907383	141090	39512620	7101	52420003	32,56%	148191	0,46%
21	Macedonië	0	88	0	1	0	0,00%	89	0,00%
22	Malta	0	36	1	138	1	0,00%	174	0,00%
23	Noorwegen	4096	4975	0	0	4096	0,00%	4975	0,02%
24	Oostenrijk	26145	4350	168	8	26313	0,02%	4358	0,01%
25	Polen	1165995	880	169462	9194	1335457	0,83%	10074	0,03%
26	Portugal	1	2590	20305	74081	20306	0,01%	76671	0,24%
27	Roemenië	39	1676	549	24757	588	0,00%	26433	0,08%
28	Russische Federatie	0	0	0	697	0	0,00%	697	0,00%
29	Servië	0	952	0	2576	0	0,00%	3528	0,01%
30	Slovenië	252	0	2137	0	2389	0,00%	0	0,00%
31	Slowakije	27380	0	5000	0	32380	0,02%	0	0,00%
32	Spanje	2376030	15011	3138728	27951	5514758	3,43%	42962	0,13%
33	Tsjechië (Republiek	18404	36129	2138	0	20542	0,01%	36129	0,11%
34	Turkije	302783	0	0	0	302783	0,19%	0	0,00%
35	Turkmenistan	0	274	0	12603	0	0,00%	12877	0,04%
36	Vaticaanstad	24119	425355	0	0	24119	0,01%	425355	1,32%
37	Verenigd Koninkrijk	407517	50761	5062208	2893466	5469725	3,40%	2944227	9,11%
38	Zweden	10	0	1480	0	1490	0,00%	0	0,00%
	Totaal Europa	36670732	5314492	110481593	25914219	147152325	91,41%	31228711	96,66%
39	Bahrein	0	0	4854907	0	4854907	3,02%	0	0,00%
40	India	0	0	64835	0	64835	0,04%	0	0,00%
41	Indonesië	0	1597	0	2280	0	0,00%	3877	0,01%
42	Japan	0	0	0	6571	0	0,00%	6571	0,02%
43	Korea (Republiek)	237748	2895	8579029	0	8816777	5,48%	2895	0,01%
44	Maleisië	0	9061	0	46956	0	0,00%	56017	0,17%
45	Oman	0	0	0	8816	0	0,00%	8816	0,03%
46	Qatar	0	0	0	7890	0	0,00%	7890	0,02%
47	Saoedi-Arabië	0	0	0	9820	0	0,00%	9820	0,03%
48	Singapore	0	131958	0	187475	0	0,00%	319433	0,99%
49	Verenigde Arabisch	0	74490	0	316624	0	0,00%	391114	1,21%
	Totaal Azie	237748	220001	13498771	586432	13736519	8,53%	806433	2,50%
50	Canada	83946	0	0	0	83946	0,05%	0	0,00%
51	Colombia	0	8638	0	0	0	0,00%	8638	0,03%
52	Cuba	0	0	0	18	0	0,00%	18	0,00%
53	Suriname	0	32115	0	114847	0	0,00%	146962	0,45%
	Totaal Amerika	83946	40753	0	114865	83946	0,05%	155618	0,48%
54	Egypte	0	585	0	27986	0	0,00%	28571	0,09%
55	Nigeria	0	44175	0	42923	0	0,00%	87098	0,27%
	Totaal Afrika	0	44760	0	70909	0	0,00%	115669	0,36%
						160972790		**32306431**	

Appendix 10: *Statistics on the import and export of structural steel I- profiles for the Netherlands (CBS)*

Import & Export H-profielen Nederland 2016

		h= 80-180mm		*h=> 180mm*		*total import*	*percentage*	*total export*	*percentage*
#	*Countries*	*import (kg)*	*export (kg)*	*import (kg)*	*export (kg)*	kg	%	kg	%
1	*Azerbeidzjan*	*0*	*11513*	*0*	*118710*	0	0,00%	130223	0,15%
2	*België*	*1294567*	*10968002*	*1672789*	*36942612*	2967356	0,86%	47910614	55,01%
3	*Bulgarije*	*1450*	*7*	*1834*	*5*	3284	0,00%	12	0,00%
4	*Cyprus*	*0*	*84*	*0*	*141*	0	0,00%	225	0,00%
5	*Denemarken*	*3395*	*8773*	*27814*	*424195*	31209	0,01%	432968	0,50%
6	*Duitsland*	*42507615*	*3148932*	*106418698*	*22516400*	148926313	43,28%	25665332	29,47%
7	*Estland*	*0*	*0*	*0*	*7016*	0	0,00%	7016	0,01%
8	*Finland*	*4*	*0*	*44371*	*5069*	44375	0,01%	5069	0,01%
9	*Frankrijk*	*85607*	*30385*	*150242*	*1361783*	235849	0,07%	1392168	1,60%
10	*Griekenland*	*1061*	*0*	*345*	*0*	1406	0,00%	0	0,00%
11	*Hongarije*	*197*	*0*	*61*	*0*	258	0,00%	0	0,00%
12	*Ierland*	*45053*	*0*	*41904*	*0*	86957	0,03%	0	0,00%
13	*Italië*	*744092*	*7699*	*638201*	*70570*	1382293	0,40%	78269	0,09%
14	*Kazachstan*	*0*	*37820*	*0*	*279*	0	0,00%	38099	0,04%
15	*Kroatië*	*960*	*144*	*534*	*14238*	1494	0,00%	14382	0,02%
16	*Letland*	*54*	*0*	*0*	*0*	54	0,00%	0	0,00%
17	*Litouwen*	*201*	*0*	*818*	*38696*	1019	0,00%	38696	0,04%
18	*Luxemburg*	*31807436*	*45*	*93256296*	*204065*	125063732	36,34%	204110	0,23%
19	*Macedonië*	*0*	*0*	*0*	*0*	0	0,00%	0	0,00%
20	*Malta*	*0*	*73*	*10*	*336*	10	0,00%	409	0,00%
21	*Noorwegen*	*0*	*24616*	*0*	*48444*	0	0,00%	73060	0,08%
22	*Oekraïne*	*105878*	*0*	*0*	*14124*	105878	0,03%	14124	0,02%
23	*Oostenrijk*	*0*	*0*	*10*	*349217*	10	0,00%	349217	0,40%
24	*Polen*	*405932*	*14294*	*39212*	*144057*	445144	0,13%	158351	0,18%
25	*Portugal*	*18103*	*0*	*129*	*28807*	18232	0,01%	28807	0,03%
26	*Roemenië*	*249*	*4737*	*370*	*24838*	619	0,00%	29575	0,03%
27	*Servië*	*0*	*5768*	*0*	*0*	0	0,00%	5768	0,01%
28	*Slovenië*	*508*	*0*	*683*	*0*	1191	0,00%	0	0,00%
29	*Slowakije*	*2748*	*0*	*8945*	*0*	11693	0,00%	0	0,00%
30	*Spanje*	*5371788*	*6643*	*6785346*	*85122*	12157134	3,53%	91765	0,11%
31	*Tsjechië (Republiek)*	*5285*	*0*	*17304*	*0*	22589	0,01%	0	0,00%
32	*Turkije*	*0*	*1684*	*0*	*0*	0	0,00%	1684	0,00%
33	*Turkmenistan*	*0*	*0*	*0*	*6520*	0	0,00%	6520	0,01%
34	*Verenigd Koninkrijk*	*1188798*	*317489*	*15471809*	*1513364*	16660607	4,84%	1830853	2,10%
35	*Zwitserland*	*0*	*0*	*0*	*102532*	0	0,00%	102532	0,12%
	Totaal Europa	*83590981*	*14588708*	*224577725*	*64021140*	308168706	89,55%	78609848	90,26%
36	*Bahrein*	*0*	*0*	*18058345*	*0*	18058345	5,25%	0	0,00%
37	*China (Volksrepubliek)*	*368*	*2458*	*0*	*24163*	368	0,00%	26621	3,06%
38	*India*	*0*	*23362*	*0*	*45382*	0	0,00%	68744	7,89%
39	*Indonesië*	*0*	*1321568*	*0*	*6370*	0	0,00%	1327938	152,48%
40	*Israël*	*0*	*0*	*0*	*3086470*	0	0,00%	3086470	354,40%
41	*Korea (Republiek)*	*0*	*22390*	*17437667*	*16905*	17437667	5,07%	39295	4,51%
42	*Maleisië*	*0*	*4366*	*0*	*582632*	0	0,00%	586998	67,40%
43	*Oman*	*0*	*0*	*0*	*7080*	0	0,00%	7080	0,81%
44	*Saoedi-Arabië*	*0*	*250343*	*0*	*0*	0	0,00%	250343	28,75%
45	*Singapore*	*0*	*410774*	*0*	*1144743*	0	0,00%	1555517	178,61%
46	*Verenigde Arabische Emiraten*	*0*	*66130*	*465645*	*406167*	465645	0,14%	472297	54,23%
	Totaal Azie	*368*	*2101391*	*35961657*	*5319912*	35962025	10,45%	7421303	8,52%
47	*Aruba*	*0*	*0*	*0*	*176461*	0	0,00%	176461	0,20%
48	*Bahamas*	*0*	*2529*	*0*	*7623*	0	0,00%	10152	0,01%
49	*Brazilië*	*0*	*744*	*0*	*3933*	0	0,00%	4677	0,01%
50	*Canada*	*0*	*0*	*0*	*199440*	0	0,00%	199440	0,23%
51	*Colombia*	*0*	*15802*	*0*	*0*	0	0,00%	15802	0,02%
52	*Suriname*	*0*	*4557*	*0*	*181483*	0	0,00%	186040	0,21%
53	*Verenigde Staten van Amerika*	*0*	*0*	*0*	*48780*	0	0,00%	48780	0,06%
	Totaal Amerika	*0*	*23632*	*0*	*617720*	0	0,00%	641352	0,74%
55	*Angola*	*0*	*8500*	*0*	*0*	0	0,00%	8500	0,01%
56	*Egypte*	*0*	*6827*	*0*	*256055*	0	0,00%	262882	0,30%
57	*Ghana*	*0*	*15407*	*0*	*0*	0	0,00%	15407	0,02%
58	*Marokko*	*0*	*0*	*0*	*1850*	0	0,00%	1850	0,00%
59	*Nigeria*	*0*	*42716*	*0*	*14929*	0	0,00%	57645	0,07%
60	*Oeganda*	*0*	*0*	*0*	*70096*	0	0,00%	70096	0,08%
	Totaal Afrika	*0*	*73450*	*0*	*342930*	0	0,00%	416380	0,48%
						344130731		**87088883**	

Appendix 11: *Statistics on the import and export of structural steel H- profiles for the Netherlands (CBS)*

Import & Export C-profielen Nederland 2016

		h= 80-220mm		h=> 220mm		total import	percentage	total export	percentage
#	countries	import (kg)	export (kg)	import (kg)	export (kg)	kg	%	kg	%
1	Azerbeidzjan	0	6156	0	618	0	0,00%	6774	0,05%
2	België	893990	4490105	1251904	1705715	2145894	3,16%	6195820	43,92%
3	Bulgarije	3789	1010	1972	0	5761	0,01%	1010	0,01%
4	Cyprus	0	440	0	3	0	0,00%	443	0,00%
5	Denemarken	1806	30918	555	0	2361	0,00%	30918	0,22%
6	Duitsland	20175938	4422118	12415342	60991	32591280	48,05%	4483109	31,78%
7	Estland	0	38732	2952	0	2952	0,00%	38732	0,27%
8	Finland	126	12352	2964	0	3090	0,00%	12352	0,09%
9	Frankrijk	4487543	50105	5076	43178	4492619	6,62%	93283	0,66%
10	Griekenland	1006	3097	401	0	1407	0,00%	3097	0,02%
11	Hongarije	97	10832	5788	0	5885	0,01%	10832	0,08%
12	Ierland	28761	6579	5626	0	34387	0,05%	6579	0,05%
13	IJsland	0	9185	0	0	0	0,00%	9185	0,07%
14	Italië	341844	50705	153968	1206	495812	0,73%	51911	0,37%
15	Kazachstan	0	15764	0	65	0	0,00%	15829	0,11%
16	Kirgizische Republiek	0	32711	0	0	0	0,00%	32711	0,23%
17	Kosovo	0	280	0	0	0	0,00%	280	0,00%
18	Kroatië	259	6576	972	90	1231	0,00%	6666	0,05%
19	Letland	0	2897	248	0	248	0,00%	2897	0,02%
20	Litouwen	394	34782	2456	0	2850	0,00%	34782	0,25%
21	Luxemburg	10632586	122841	2698864	100	13331450	19,65%	122941	0,87%
22	Malta	40	2861	0	12	40	0,00%	2873	0,02%
23	Noorwegen	0	43992	5537	89	5537	0,01%	44081	0,31%
24	Oekraïne	3804668	0	454970	0	4259638	6,28%	0	0,00%
25	Oostenrijk	57893	2267	0	471	57893	0,09%	2738	0,02%
26	Polen	2732080	9850	293786	647	3025866	4,46%	10497	0,07%
27	Portugal	24327	504314	4314	0	28641	0,04%	504314	3,57%
28	Roemenië	483	30261	2483	2475	2966	0,00%	32736	0,23%
29	Russische Federatie	0	25481	0	0	0	0,00%	25481	0,18%
30	Servië	0	426	0	0	0	0,00%	426	0,00%
31	Slovenië	699	1387	15591	0	16290	0,02%	1387	0,01%
32	Slowakije	3077	93420	16614	0	19691	0,03%	93420	0,66%
33	Spanje	4035748	44597	1746387	45357	5782135	8,52%	89954	0,64%
34	Tsjechië (Republiek)	18487	4648	24629	9	43116	0,06%	4657	0,03%
35	Turkmenistan	0	0	0	893	0	0,00%	893	0,01%
36	Verenigd Koninkrijk	985600	124893	477540	600565	1463140	2,16%	725458	5,14%
37	Zweden	1120	228	8927	341	10047	0,01%	569	0,00%
	Totaal Europa	48232361	10236810	19599866	2462825	67832227	100,00%	12699635	90,02%
38	China (Volksrepubliek)	0	59837	0	37308	0	0,00%	97145	0,69%
39	India	0	103	0	7864	0	0,00%	7967	0,06%
40	Indonesië	0	319127	0	37717	0	0,00%	356844	2,53%
41	Israël	0	0	0	47841	0	0,00%	47841	0,34%
42	Korea (Republiek)	0	4739	0	0	0	0,00%	4739	0,03%
43	Maleisië	0	2097	0	4840	0	0,00%	6937	0,05%
44	Singapore	0	283327	0	19308	0	0,00%	302635	2,15%
45	Verenigde Arabische Emiraten	0	165971	0	5038	0	0,00%	171009	1,21%
46	Vietnam	0	4503	0	7320	0	0,00%	11823	0,08%
	Totaal Azie	0	839704	0	167236	0	0,00%	1006940	7,14%
47	Bahamas	0	8522	0	0	0	0,00%	8522	0,06%
48	Bolivia	0	0	0	647	0	0,00%	647	0,00%
49	Brazilië	0	20400	0	0	0	0,00%	20400	0,14%
50	Britse Maagdeneilanden	0	0	0	4459	0	0,00%	4459	0,03%
51	Canada	0	14703	0	0	0	0,00%	14703	0,10%
52	Chili	0	0	0	546	0	0,00%	546	0,00%
53	Colombia	0	3646	0	0	0	0,00%	3646	0,03%
54	Costa Rica	0	0	0	84723	0	0,00%	84723	0,60%
55	Sint Maarten	0	0	0	708	0	0,00%	708	0,01%
56	Suriname	0	93561	0	0	0	0,00%	93561	0,66%
57	Venezuela	0	0	2284	75216	2284	0,00%	75216	0,53%
58	Verenigde Staten van Amerika	77	0	0	0	77	0,00%	0	0,00%
	Totaal Amerika	77	140832	2284	166299	2361	0,00%	307131	2,18%
59	Angola	0	5294	0	1162	0	0,00%	6456	0,05%
60	Egypte	0	8792	0	0	0	0,00%	8792	0,06%
61	Gabon	0	130	0	0	0	0,00%	130	0,00%
62	Tanzania (Verenigde Republiek)	0	107	0	78509	0	0,00%	78616	0,56%
	Totaal Afrika	0	14323	0	79671	0	0,00%	93994	0,67%
						67834588		**14107700**	

Appendix 12: *Statistics on the import and export of structural steel C- profiles for the Netherlands (CBS)*

Import & Export schroot Nederland 2016

		waste & disposed alloyed steel products		total import	percentage	total export	percentage
#	countries	import (kg)	export (kg)	kg	%	kg	%
1	België	18377627	45112161	18377627	14,33%	45112161	23,80%
2	Bulgarije	1062	1039	1062	0,00%	1039	0,00%
3	Cyprus	110537	6608	110537	0,09%	6608	0,00%
4	Denemarken	360114	2224	360114	0,28%	2224	0,00%
5	Duitsland	73092516	24736625	73092516	57,01%	24736625	13,05%
6	Estland	7647	206287	7647	0,01%	206287	0,11%
7	Finland	263192	213	263192	0,21%	213	0,00%
8	Frankrijk	8285792	0	8285792	6,46%	0	0,00%
9	Griekenland	46287	1092	46287	0,04%	1092	0,00%
10	Hongarije	323	740	323	0,00%	740	0,00%
11	Ierland	212453	2485	212453	0,17%	2485	0,00%
12	Italië	152676	287	152676	0,12%	287	0,00%
13	Kroatië	909	2187	909	0,00%	2187	0,00%
14	Letland	399	473	399	0,00%	473	0,00%
15	Litouwen	417598	388	417598	0,33%	388	0,00%
16	Luxemburg	145370	4073608	145370	0,11%	4073608	2,15%
17	Malta	0	267	0	0,00%	267	0,00%
18	Montenegro	48830	0	48830	0,04%	0	0,00%
19	Noorwegen	54380	0	54380	0,04%	0	0,00%
20	Oostenrijk	2811264	2830	2811264	2,19%	2830	0,00%
21	Polen	3444219	778656	3444219	2,69%	778656	0,41%
22	Portugal	113	13191	113	0,00%	13191	0,01%
23	Roemenië	1228	18837	1228	0,00%	18837	0,01%
24	Russische Federatie	891006	0	891006	0,69%	0	0,00%
25	Slovenië	27278	466	27278	0,02%	466	0,00%
26	Slowakije	79278	9740	79278	0,06%	9740	0,01%
27	Spanje	12685	0	12685	0,01%	0	0,00%
28	Tsjechië (Republiek)	842418	240891	842418	0,66%	240891	0,13%
29	Turkije	2426769	0	2426769	1,89%	0	0,00%
30	Verenigd Koninkrijk	3671635	28973	3671635	2,86%	28973	0,02%
31	Wit-Rusland	107008	0	107008	0,08%	0	0,00%
32	Zweden	765540	7816	765540	0,60%	7816	0,00%
33	Zwitserland	170654	1042	170654	0,13%	1042	0,00%
	Totaal Europa	116828807	75249126	116828807	91,12%	75249126	39,71%
34	Bangladesh	0	1185080	0	0,00%	1185080	0,63%
35	China (Volksrepubliek)	0	51142175	0	0,00%	51142175	26,99%
36	Hongkong	17510	42288	17510	0,01%	42288	0,02%
37	India	26600	45431485	26600	0,02%	45431485	23,97%
38	Indonesië	49046	0	49046	0,04%	0	0,00%
39	Israël	155574	0	155574	0,12%	0	0,00%
40	Japan	0	343395	0	0,00%	343395	0,18%
41	Korea (Republiek)	252782	0	252782	0,20%	0	0,00%
42	Maleisië	165924	0	165924	0,13%	0	0,00%
43	Pakistan	0	13225972	0	0,00%	13225972	6,98%
44	Singapore	217458	0	217458	0,17%	0	0,00%
45	Taiwan	988139	256320	988139	0,77%	256320	0,14%
46	Thailand	59404	0	59404	0,05%	0	0,00%
	Totaal Azie	1932437	111626715	1932437	1,51%	111626715	58,90%
47	Brazilië	1604960	0	1604960	1,25%	0	0,00%
48	Canada	90292	0	90292	0,07%	0	0,00%
49	Colombia	174253	0	174253	0,14%	0	0,00%
50	Cuba	47770	0	47770	0,04%	0	0,00%
51	Guatemala	137445	0	137445	0,11%	0	0,00%
52	Mexico	2397058	0	2397058	1,87%	0	0,00%
53	Peru	2167	0	2167	0,00%	0	0,00%
54	Trinidad en Tobago	132903	0	132903	0,10%	0	0,00%
55	Uruguay	59752	0	59752	0,05%	0	0,00%
56	Verenigde Staten van Amerika	854911	0	854911	0,67%	0	0,00%
	Totaal Amerika	5501511	0	5501511	4,29%	0	0,00%
57	Egypte	846015	0	846015	0,66%	0	0,00%
58	Libië (Arabische Republiek)	1936310	0	1936310	1,51%	0	0,00%
59	Marokko	81215	2642045	81215	0,06%	2642045	1,39%
60	Tunesië	69267	0	69267	0,05%	0	0,00%
61	Zuid-Afrika	126740	0	126740	0,10%	0	0,00%
	Totaal Afrika	3059547	2642045	3059547	2,39%	2642045	1,39%
60	Australië	808126	0	808126	0,63%	0	0,00%
61	Nieuw-Zeeland	81346	0	81346	0,06%	0	0,00%
	Totaal Oceanië	889472	0	889472	0,69%	0	0,00%
				128211774		**189517886**	

Appendix 13: *Statistics on the import and export of steel scrap for the Netherlands (CBS)*

Import & Export ijzererts Nederland 2016

		iron ore		total import	percentage	total export	percentage
#	countries	import (kg)	export (kg)	kg	%	kg	%
1	Albanië	0	40000	0	0,00%	40000	0,06%
2	België	3022860	218	3022860	0,03%	218	0,00%
3	Bulgarije	568	2217	568	0,00%	2217	0,00%
4	Cyprus	8	312	8	0,00%	312	0,00%
5	Denemarken	22674	159991	22674	0,00%	159991	0,25%
6	Duitsland	408471	0	408471	0,00%	0	0,00%
7	Estland	91	65	91	0,00%	65	0,00%
8	Finland	63625396	23439	63625396	0,70%	23439	0,04%
9	Frankrijk	1914937	44423697	1914937	0,02%	44423697	69,43%
10	Griekenland	90	39297	90	0,00%	39297	0,06%
11	Hongarije	3	133774	3	0,00%	133774	0,21%
12	Ierland	1251	14530	1251	0,00%	14530	0,02%
13	Italië	10519	81341	10519	0,00%	81341	0,13%
14	Kroatië	38	0	38	0,00%	0	0,00%
15	Letland	424806860	20200	424806860	4,67%	20200	0,03%
16	Litouwen	105	11001	105	0,00%	11001	0,02%
17	Luxemburg	1164	156746	1164	0,00%	156746	0,24%
18	Macedonië	0	47920	0	0,00%	47920	0,07%
19	Malta	128	586	128	0,00%	586	0,00%
20	Noorwegen	1166826528	3061381	1166826528	12,81%	3061381	4,78%
21	Oostenrijk	2563261	79669	2563261	0,03%	79669	0,12%
22	Polen	16100	0	16100	0,00%	0	0,00%
23	Portugal	119	215918	119	0,00%	215918	0,34%
24	Roemenië	114	325	114	0,00%	325	0,00%
25	Russische Federatie	4400	645600	4400	0,00%	645600	1,01%
26	Slovenië	2484	337953	2484	0,00%	337953	0,53%
27	Slowakije	2195	104	2195	0,00%	104	0,00%
28	Spanje	8827	0	8827	0,00%	0	0,00%
29	Tsjechië (Republiek)	20009	133931	20009	0,00%	133931	0,21%
30	Turkije	5623232	0	5623232	0,06%	0	0,00%
31	Verenigd Koninkrijk	3798785	1189096	3798785	0,04%	1189096	1,86%
32	Wit-Rusland	0	12000	0	0,00%	12000	0,02%
33	Zweden	2371231119	5942350	2371231119	26,04%	5942350	9,29%
34	Zwitserland	0	1461680	0	0,00%	1461680	2,28%
	Totaal Europa	4043912336	58235341	4043912336	44,41%	58235341	91,02%
35	China (Volksrepubliek)	35552	29000	35552	0,00%	29000	0,05%
36	Filipijnen	0	200000	0	0,00%	200000	0,31%
37	India	0	42000	0	0,00%	42000	0,07%
38	Indonesië	0	584000	0	0,00%	584000	0,91%
39	Israël	0	358800	0	0,00%	358800	0,56%
40	Japan	0	54000	0	0,00%	54000	0,08%
41	Korea (Republiek)	0	21300	0	0,00%	21300	0,03%
42	Maleisië	0	121600	0	0,00%	121600	0,19%
43	Qatar	0	24000	0	0,00%	24000	0,04%
44	Saoedi-Arabië	0	46000	0	0,00%	46000	0,07%
45	Singapore	3013	0	3013	0,00%	0	0,00%
46	Taiwan	0	440800	0	0,00%	440800	0,69%
47	Thailand	0	2901200	0	0,00%	2901200	4,53%
48	Verenigde Arabische Emiraten	0	676000	0	0,00%	676000	1,06%
	Totaal Azie	38565	5498700	38565	0,00%	4822700	7,54%
49	Argentinië	77076179	0	77076179	0,85%	0	0,00%
50	Brazilië	4522363104	0	4522363104	49,67%	0	0,00%
51	Canada	423065201	0	423065201	4,65%	0	0,00%
52	Costa Rica	0	102000	0	0,00%	102000	0,16%
53	Trinidad en Tobago	0	54000	0	0,00%	54000	0,08%
54	Uruguay	11420	0	11420	0,00%	0	0,00%
55	Verenigde Staten van Amerika	61308	184766	61308	0,00%	184766	0,29%
	Totaal Amerika	5022577212	340766	5022577212	55,16%	340766	0,53%
56	Algerije	0	247200	0	0,00%	247200	0,39%
57	Egypte	0	20000	0	0,00%	20000	0,03%
58	Liberia	4425	0	4425	0,00%	0	0,00%
59	Marokko	22606512	20400	22606512	0,25%	20400	0,03%
60	Mauritanië	16500000	0	16500000	0,18%	0	0,00%
61	Tunesië	99122	0	99122	0,00%	0	0,00%
62	Zuid-Afrika	6378	0	6378	0,00%	0	0,00%
	Totaal Afrika	39110937	287600	39110937	0,43%	287600	0,45%
63	Australië	0	297800	0	0,00%	297800	0,47%
	Totaal Oceanië	0	297800	0	0,00%	297800	0,47%
				9105639050		**63984207**	

Appendix 14: *Statistics on the import and export of iron ore for the Netherlands (CBS)*

Import & Export kolen Nederland 2016

		coal		total import	percentage	total export	percentage
#	countries	import (kg)	export (kg)	kg	%	kg	%
1	Azerbeidzjan	0	14700	0	0,00%	14700	0,00%
2	België	26022134	124942600	26022134	0,14%	124942600	1,44%
3	Bulgarije	124613	61	124613	0,00%	61	0,00%
4	Cyprus	7	20803	7	0,00%	20803	0,00%
5	Denemarken	510754	38103032	510754	0,00%	38103032	0,44%
6	Duitsland	23694081	7165330303	23694081	0,12%	7165330303	82,84%
7	Estland	6442	1	6442	0,00%	1	0,00%
8	Finland	230295	0	230295	0,00%	0	0,00%
9	Frankrijk	1261857	382198143	1261857	0,01%	382198143	4,42%
10	Griekenland	138049	58	138049	0,00%	58	0,00%
11	Hongarije	51541	8	51541	0,00%	8	0,00%
12	Ierland	243450	76859750	243450	0,00%	76859750	0,89%
13	IJsland	0	116787239	0	0,00%	116787239	1,35%
14	Italië	1337009	0	1337009	0,01%	0	0,00%
15	Kosovo	0	1500	0	0,00%	1500	0,00%
16	Kroatië	10041	0	10041	0,00%	0	0,00%
17	Letland	50832228	4305501	50832228	0,27%	4305501	0,05%
18	Litouwen	261142	38	261142	0,00%	38	0,00%
19	Luxemburg	65231	38881569	65231	0,00%	38881569	0,45%
20	Malta	3576	2179	3576	0,00%	2179	0,00%
21	Noorwegen	518285	324561604	518285	0,00%	324561604	3,75%
22	Oostenrijk	418273	10131926	418273	0,00%	10131926	0,12%
23	Polen	97992732	0	97992732	0,52%	0	0,00%
24	Portugal	53872	16	53872	0,00%	16	0,00%
25	Roemenië	480428	97	480428	0,00%	97	0,00%
26	Russische Federatie	5949843202	66718447	5949843202	31,28%	66718447	0,77%
27	Slovenië	50944	0	50944	0,00%	0	0,00%
28	Slowakije	12220	6956799	12220	0,00%	6956799	0,08%
29	Spanje	428252	47453288	428252	0,00%	47453288	0,55%
30	Tsjechië (Republiek)	490385	0	490385	0,00%	0	0,00%
31	Verenigd Koninkrijk	4439903	197325703	4439903	0,02%	197325703	2,28%
32	Zweden	767939	0	767939	0,00%	0	0,00%
33	Zwitserland	0	24524923	0	0,00%	24524923	0,28%
	Totaal Europa	6160288885	8625120288	6160288885	32,38%	8625120288	99,71%
35	India	2359	656725	2359	0,00%	656725	0,76%
36	Indonesië	3012	0	3012	0,00%	0	0,00%
37	Maleisië	261240	0	261240	0,00%	0	0,00%
38	Thailand	463950	433462	463950	0,00%	433462	0,50%
	Totaal Azie	730561	1090187	730561	0,00%	1090187	1,26%
49	Chili	22936429	0	22936429	0,12%	0	0,00%
50	Colombia	8635216518	0	8635216518	45,39%	0	0,00%
51	Verenigde Staten van Amerika	2484995019	7000	2484995019	13,06%	7000	0,01%
	Totaal Amerika	11143147966	7000	11143147966	58,57%	7000	0,01%
56	Egypte	0	10157754	0	0,00%	10157754	11,74%
57	Kenia	1337	0	1337	0,00%	0	0,00%
58	Mozambique	392612397	0	392612397	2,06%	0	0,00%
59	Zuid-Afrika	923677138	0	923677138	4,86%	0	0,00%
	Totaal Afrika	1316290872	10157754	1316290872	6,92%	10157754	11,74%
63	Australië	403650660	13406684	403650660	2,12%	13406684	15,50%
	Totaal Oceanië	403650660	13406684	403650660	2,12%	13406684	15,50%
				19024108944		**8649781913**	

Appendix 15: *Statistics on the import and export of coal for the Netherlands (CBS)*

Import & Export Kalksteen Nederland 2016

		limestone		total import	percentage	total export	percentage
#	countries	import (kg)	export (kg)	kg	%	kg	%
1	België	679326511	2252617	679326511	81,70%	2252617	96,12%
2	Bulgarije	1466	131	1466	0,00%	131	0,01%
3	Cyprus	0	15	0	0,00%	15	0,00%
4	Denemarken	301956	0	301956	0,04%	0	0,00%
5	Duitsland	86876242	30902	86876242	10,45%	30902	1,32%
6	Estland	16639508	83	16639508	2,00%	83	0,00%
7	Finland	175237	16	175237	0,02%	16	0,00%
8	Frankrijk	13633590	0	13633590	1,64%	0	0,00%
9	Griekenland	20877	70	20877	0,00%	70	0,00%
10	Hongarije	7487	0	7487	0,00%	0	0,00%
11	Ierland	3975735	25	3975735	0,48%	25	0,00%
12	IJsland	0	9380	0	0,00%	9380	0,40%
13	Italië	3787751	0	3787751	0,46%	0	0,00%
14	Kroatië	461	88	461	0,00%	88	0,00%
15	Letland	1531	9	1531	0,00%	9	0,00%
16	Litouwen	381632	551	381632	0,05%	551	0,02%
17	Luxemburg	61814	2097	61814	0,01%	2097	0,09%
18	Malta	0	13	0	0,00%	13	0,00%
19	Noorwegen	0	24000	0	0,00%	24000	1,02%
20	Oostenrijk	5379	8	5379	0,00%	8	0,00%
21	Polen	68546	3807	68546	0,01%	3807	0,16%
22	Portugal	4089446	1568	4089446	0,49%	1568	0,07%
23	Roemenië	3679	444	3679	0,00%	444	0,02%
24	Slovenië	2510	8	2510	0,00%	8	0,00%
25	Slowakije	23836	0	23836	0,00%	0	0,00%
26	Spanje	20957556	0	20957556	2,52%	0	0,00%
27	Tsjechië (Republiek)	39094	0	39094	0,00%	0	0,00%
28	Verenigd Koninkrijk	44790	402	44790	0,01%	402	0,02%
29	Zweden	750314	0	750314	0,09%	0	0,00%
	Totaal Europa	831176948	2326234	831176948	99,96%	2326234	99,26%
30	India	27500	0	27500	0,00%	0	0,00%
31	Maleisië	0	1985	0	0,00%	1985	0,08%
	Totaal Azie	27500	1985	27500	0,00%	1985	0,08%
32	Curacao	0	5100	0	0,00%	5100	0,22%
33	Suriname	0	10000	0	0,00%	10000	0,43%
34	Verenigde Staten van Amerika	293660	0	293660	0,04%	0	0,00%
	Totaal Amerika	293660	15100	293660	0,04%	15100	0,64%
35	Somalië	0	245	0	0,00%	245	0,01%
	Totaal Afrika	0	245	0	0,00%	245	0,01%
36	Australië	0	0	0	0,00%	0	0,00%
	Totaal Oceanië	0	0	0	0,00%	0	0,00%
				831498108		**2343564**	

Appendix 16: *Statistics on the import and export of limestone for the Netherlands (CBS)*

Crude Steel Production by Process

Country	*Million tonnes*	*Oxygen (BOF) %*	*Electric (EAF) %*
Austria	8,1	91,1	8,9
Belgium	7,8	68,8	31,2
Bulgaria	0,7	0	100
Croatia	0		100
Czech Republic	4,6	94,6	5,4
Finland	4	67,5	32,5
France	15,5	68,8	31,2
Germany	43,4	71,2	28,8
Greece	1,4	0	100
Hungary	1,9	84,3	15,7
Italy	24,1	19,7	80,3
Luxembourg	2,2	0	100
Netherlands	6,8	100	0
Poland	10,3	55,2	44,8
Portugal	2,1	0	99
Romania	3,4	69,3	30,7
Slovak Republic	5	92,9	7,1
Slovenia	0,6	0	100
Spain	14,5	33,5	66,5
Sweden	4,7	65,3	34,7
United Kingdom	7,5	80,1	19,9
Turkey	37,5	30,8	69,2
Canada	13,6	53,4	46,6
United States	81,6	31,6	68,4
Brazil	34,4	77,6	21
China	831,7	91	9

* World Steel in figures 2018 - Worldsteel Association, 2018

Appendix 17: *Global crude steel production by process (Worldsteel, 2018)*

This research is aimed at exploring the possibilities to reduce the environmental impact of buildings with a primary steel load-bearing structure in the Netherlands, by incorporating previously used & remanufactured structural steel elements in newly designed buildings. The study elaborates on the critical environmental issues of the 21st century and adresses the urgency for a global paradigm shift towards a circular economy. It provides an up-to-date overview of the current state of the steel industry, elaborates on the potential for steel as a circular building material, and highlights the most important barriers that are currently in place prohibiting the re-use of structural steel. This publication provides a critical review of the current LCA practice for building structures in the Netherlands and discusses the reliability of environmental data on steel products available from national and international databases. In conclusion, a tool is proposed which could aid structural engineers in improving the sustainability of their designs. By performing an analysis of a steel framework design the engineer can check whether certain steel elements can potentially be replaced by circular alternatives listed in re-used steel databases. Environmental benefits are calculated and presented in a well-structured overview which can help policy and decision makers in implementing sustainable decisions.

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