The geographical scale of a circular economy

Introducing a framework to determine a relevant geographical scale for the recycling of materials, based on a case study of concrete and copper for the Municipality of Leiden.

Thesis research

MSc. Industrial Ecology

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Summary

Circular economy (CE) is regarded as a solution to the two sided problem we are facing today: on the one hand resources are rapidly depleted, while on the other hand waste is piling up (MacArthur, 2013). The implications of a CE and the transition towards it are widely researched. This gives a broad understanding of the concept, but different assumptions of relevant scales are made throughout different studies. There is a lack of research into the relevant geographical scales of CE. Literature on the debate about the sustainability of local versus global production also does not offer a solution to this. Thus, this research aims to present a framework that identifies relevant scales for the resupply materials.

The proposed framework aims to determine an optimised geographical scale for the recycling of materials based on various factors. The framework is tested against a case study of recycled concrete and copper for the municipality of Leiden. For concrete two recycling processes are assessed: wet processing and advanced dry recycling. For copper recycling through remelting and electrolysis is assessed. The municipality of Leiden wants to adopt a CE to increase resilience and minimise environmental impact related to material use. In addition, it is assumed that economic viability plays an important role in decision making. Therefore, this research focusses on both the economic and environmental factors of CE, in line with Jenssen et al. (2011). For the economic factor, a crude cost benefit analysis is carried out. In this analysis only the production cost, transport cost and proceeds from the sales of the recycled material are taken into account. For the environmental factor, a life cycle assessment (LCA) of both concrete and copper recycling is conducted. The goal of this LCA is to assess and compare the environmental impact of primary sourced concrete and copper and recycled concrete and copper. This LCA will also provide the impact of transport of the concrete and copper waste to the recycling plant. Based on these results a geographical scale of the transport of waste for recycling will be determined. For both factors the maximum distance for transport of waste materials to the recycling facility is calculated. However, it is important to note that the research is thus limited to the first part of the resupply chain, and therefore does not assess the impact of the transport of recycled material to the location where it is used.

Based on the results of the analyses, the framework indicates that concrete rubble can be transported up to 70km by truck and 110km by barge for wet processing. Under present circumstances, economic cost is not a limiting factor, with an upper limit of 170km for advanced dry recycled concrete and 160km for wet processed concrete. Within this distance from Leiden, a lot of transport, sorting and concrete production facilities are available. The results for copper seem to indicate that environmental impact and economic cost are not the determining factors for geographic scale. Based on environmental impact scrap copper can be transported 4330km by truck or 11500km by barge. Based on economic cost the copper scrap can be transported as far as 12300km.

The framework provides a positive outlook for both concrete and copper: both recycled materials are now outperforming their primary sourced counterpart in terms of environmental impact and can be transported further based on economic cost. In general, the application of the framework in this research results in a clear indication of the maximum distance that waste materials can be transported over to be recycled, based on global warming potential and cost. Even though the framework proves to be robust to small changes in emissions from transport, it is sensitive to small changes in composition of the recycled material. Therefore, the results are not easily generalisable to all types of recycled concrete or copper. Moreover, this implies that the results for concrete are not generalisable for other stony materials and for copper not generalisable for other non-ferrous metals.

The framework has the potential to help decision making on the geographical scale of the recycling process for specific materials. The results of the framework could be used by government agencies to aid in decision making around new policies or spatial planning. Companies could use the framework as a tool to determine from where to source their recycled materials and recyclers could use the framework to determine where to locate new facilities. Within academic research the framework can add practical knowledge and give insight into the scale at which CE should be conducted. This in turn will add to the understanding of how CE can contribute to minimising our environmental impact.

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Over the last months I have learned a lot. Not only on the subject matter of my research, but also about myself and the research process. Even though this is an individual assignment, I have not been alone throughout the process. For this, and for everything they have taught me I want to thank everyone who has been involved, active or passive, in this journey.

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Table of Contents

List of figures

List of tables

List of abbreviations and acronyms

ADR	Advanced dry recycling
CE	Circular economy
FET	Fresh water ecotoxicity
GWP	Global warming potential
LCA	Life cycle assessment
MFR	Mineral, fossils and renewable
PEF	Product Environmental Footprint
RC	Recycled content
RCA	Recycled coarse aggregate
RER	Europe

1. Introduction

Circular economy (CE) is regarded as a solution to the two sided problem we are facing today: on the one hand resources are rapidly depleted, while on the other hand waste is piling up (MacArthur, 2013). However, CE is increasingly viewed as a goal on its own. When closing material loops becomes the priority, the inherent goals of circularity can be overlooked.

Most current research on circular economy takes its scale as a given or the starting point. This research often start from the concept of circularity and explores the feasibility of system change, (potential) impact of circular measures and policies or how to measure circularity (Deutz et al., 2017; Kalmykova, Sadagopan & Rosado, 2018; Kohler et al., 2019; Paiho et al., 2020). In other words, the implications of a CE and the transition towards it are widely researched. This gives a broad understanding of the concept, but different assumptions of relevant scales are made throughout different studies.

For example, different scales are demarcated as material-, building- and city level by Pomponi and Moncaster (2017), which focusses on the scale of the object that is becoming more circular. Other research, for example Kalmykova et al. (2016), Reike et al. (2018) and Bauwens et al. (2020), uses local/regional, national and global as different scales, referring to different levels within a circular economy. Other studies assume a local scale is the most ideal for CE.

Currently, there is an ongoing discussion on the optimal geographical scale for sustainable production: making the loop as small as possible and decentralize production processes on the one hand, or create fewer, more efficient production locations based on the principle of economies of scale on the other. This optimal scale can vary significantly for different products and materials. For example, when applied to the recycling of materials, concrete cannot be transported over great distances due to the nature of the material, whereas other materials, such as steel or copper, can be transported indefinitely without decreasing in quality (Van den Berghe & Verhagen, 2021). Currently, the geographical scale of resupply and recycling chains is mostly influenced by context dependent processes of structure and agency (Elder-Vass, 2010), such as cost and convenience. The scale of the material loops may therefore change the feasibility and impact of CE considerably, due to transport cost and related emissions.

Research by Van den Berghe and Verhagen (2021) looks into the relevant scale of concrete recycling for The Hague. However, they do so to determine the spatial need for the recycling process and not to determine the optimal geographical scale of circularity for such a material. Other research by Tapia et al. (2021) that looks into spatial aspects of CE, assesses the effects of territorial factors on CE. One of their conclusions is that territorial factors such as accessibility and technology enable CE in practice. However, other than a study based on embodied energy in material loops in the Australian metal industry (Greadel et al., 2019), little research has been done on the optimal geographical scale for resupply chains.

To match the circular approach to urban metabolism a specific scale has to be defined, in order to create well defined goals and effective policies for the transition towards circular cities. Scale refers to the distance a material travels to close the loop. In other words, when can a material loop be considered closed? When the materials are recycled on site, in the region, on the continent or globally?

This research aims to explore the subject of a relevant geographical scale for the resupply of recycled materials. In addition, it introduces a framework to determine a scale that is both economically feasible and diminishes environmental impact for different materials, specifically for concrete and copper for the municipality of Leiden. On the one hand, to add to the scientific knowledge on what relevant scales are for the recycling and resupply of materials, and to create a framework that can be applied to materials that have not been assessed in this research. On the other hand, to aid the municipality of Leiden in creating effective policies to transition to a CE.

1.1 Research introduction

In the following sections the research problem, the knowledge gap, the scope and research question are described.

1.1.1 Research problem

A lot of the current research on CE starts from the concept of circularity and explores the feasibility of system change, (potential) impact of circular measures and policies or how to measure circularity (Deutz et al., 2017; Kalmykova, Sadagopan & Rosado, 2018; Kohler et al., 2019; Paiho et al., 2020). As stated before, in most of the literature a geographic scale of CE is assumed. Consequently, different assumptions of relevant scales are made throughout the literature. Furthermore, there is ongoing discussion on the optimal scale for minimising impact on the environment: making the loop as small as possible and decentralize remanufacturing and recycling processes or create fewer, more efficient locations based on the principle of economy of scale. This discussion is most prevalent in literature about food production, but has its roots in a bigger overarching discussion about the geographical scale of sustainable practices. This discussion is not only relevant for food production but also for other fields, such as CE and materials.

The lack of research in the optimal geographical scale of resupply chains poses a problem for cities aiming to become circular. Especially, since the geographical scale is a relevant factor for policies focussed on the mitigation of emissions and spatial planning.

1.1.2 Knowledge gap

From the preliminary literature review it becomes apparent that

- No framework to determine the optimal geographical scale for CE has been developed
- No research has been done on relevant geographical scales for resupply chains of materials

Thus, this research aims to present a framework that identifies relevant scales for the resupply materials. This framework will be tested against a case study of recycled concrete and copper for the municipality of Leiden. These materials are chosen because they are important within current construction practices. Moreover, copper is a highly valued, conductive material that plays an important role in electrical systems.

The objectives of this research are twofold:

- On the one hand, to add to the scientific knowledge on what relevant scales are for the recycling and resupply of materials and to create a framework that can be applied to materials that have not been assessed in this research.
- On the other hand, to aid the municipality of Leiden in creating meaningful policies to transition to CE.

1.1.3 Scope of the research

Since this research is limited in terms of time and resources, its scope has been narrowed to befit a master thesis. The research has an exploratory nature and revolves around a case study on two materials from the construction and demolition sector. The material that is most prevalent in construction and demolition waste, based on mass, is concrete. This material makes up approximately 62% of the total material outflow of buildings. In addition, the highest environmental savings can be achieved for electronic and electrical equipment of which copper is a major component (Sauer, 2020). Therefore, the two materials that are included in the case study are concrete and copper from construction and demolition waste. The focus is on the recycling of those materials, as opposed to direct reuse or other circular options. The data used will be based on the current practices and plans of the municipality of Leiden.

It is assumed the municipality of Leiden wants to adopt a CE to increase resilience and minimise environmental impact related to material use. In addition, it is assumed that economic viability plays an important role in decision making. Therefore, this research focusses on the economic and environmental factors of CE, in line with Jenssen et al. (2011).

Furthermore, it is assumed that CE is indeed the right means for the municipality to reach its goals and that a CE is feasible in the municipality of Leiden.

1.4.4 Research questions

This research aims to answer the following question:

What is the maximum geographical scale to close material recycling loops in a circular economy, based on a case study of concrete and copper for construction and demolition sector of the municipality of Leiden? To answer this question a framework is introduced that is based on two main factors: environmental and economic.

The sub questions that will help answer this research question are grouped in three categories.

1. Current situation
    a. What are the current resupply practices of the municipality of Leiden?
    b. What existing infrastructure and equipment is in place?
2. Determining the maximum distance for recycling of concrete and copper for Leiden
    a. What is the maximum geographical scale based on economic factors?
    b. What is the maximum geographical scale based on related CO_2 footprint?
    c. What infrastructure is needed for this maximum?
3. Comparing the current situation to the maximum scenario
    a. What are the similarities and differences between the current practices and the maximum scenario?
        i. How can they be overcome?
    b. Is the required infrastructure in place?

1.2 Theoretical background

This section provides theoretical background on circular economy in general and circularity in policy and cities. Circular economy is one of the main principles behind new waste management policies and is closely related to current recycling practices. Furthermore, some background is provided on discussions about geographical scale in relation to the impact of products, which is closely related to the main research question.

1.2.1 Definitions and approach of a circular economy

There is ample research to be found on CE, which in itself is a broad overarching concept. The European Commission defines CE as “an economy where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste minimized” (Eurostat, 2019). However, multiple other definitions are proposed. Kirchherr, Reike and Hekkert (2017) defined CE as “[…] an economic system that replaces the ‘end-of-life’ concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations.” From these definitions follows that CE is mostly a normative concept, that aims to replace linear flows, by circular flows, independent of the type or location of the flow.

In addition, there are multiple approaches towards a circular economy (Kalmykova, Sadagopan, & Rosado, 2018). On a theoretical level these can be depicted by the butterfly diagram of the Ellen MacArthur Foundation (MacArthur, 2013) and the 9R framework (Van Buren et al., 2016; Potting et al., 2017). Those are depicted in Figure 1 and 2 respectively. Ultimately all the different approaches and depictions boil down to the same concept: eliminating waste and reducing input of virgin materials. This is achieved by closing material loops. In other words, materials that are now discarded as waste should be resupplied as input for the production of new materials and/or products. However, just like the definitions, the different approaches don’t demarcate a geographical boundary for CE.

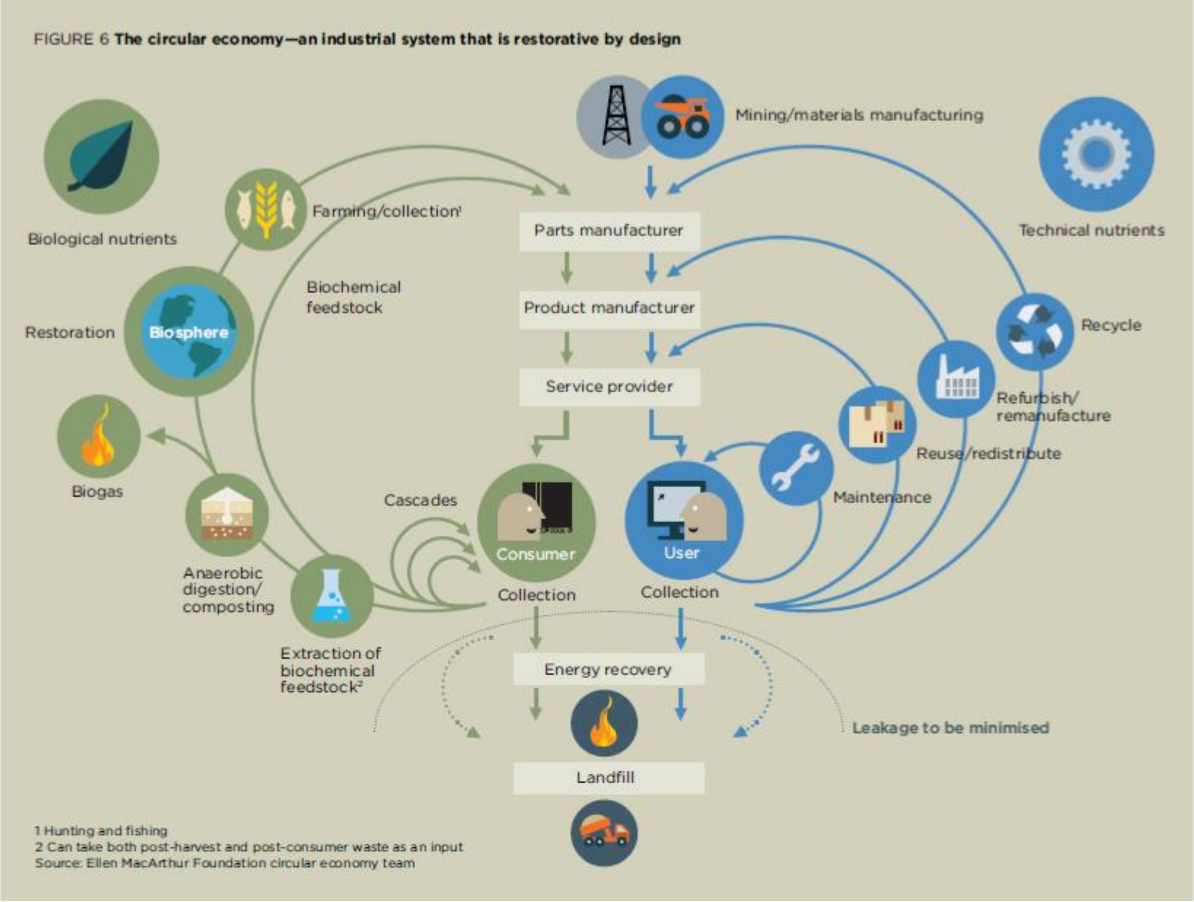
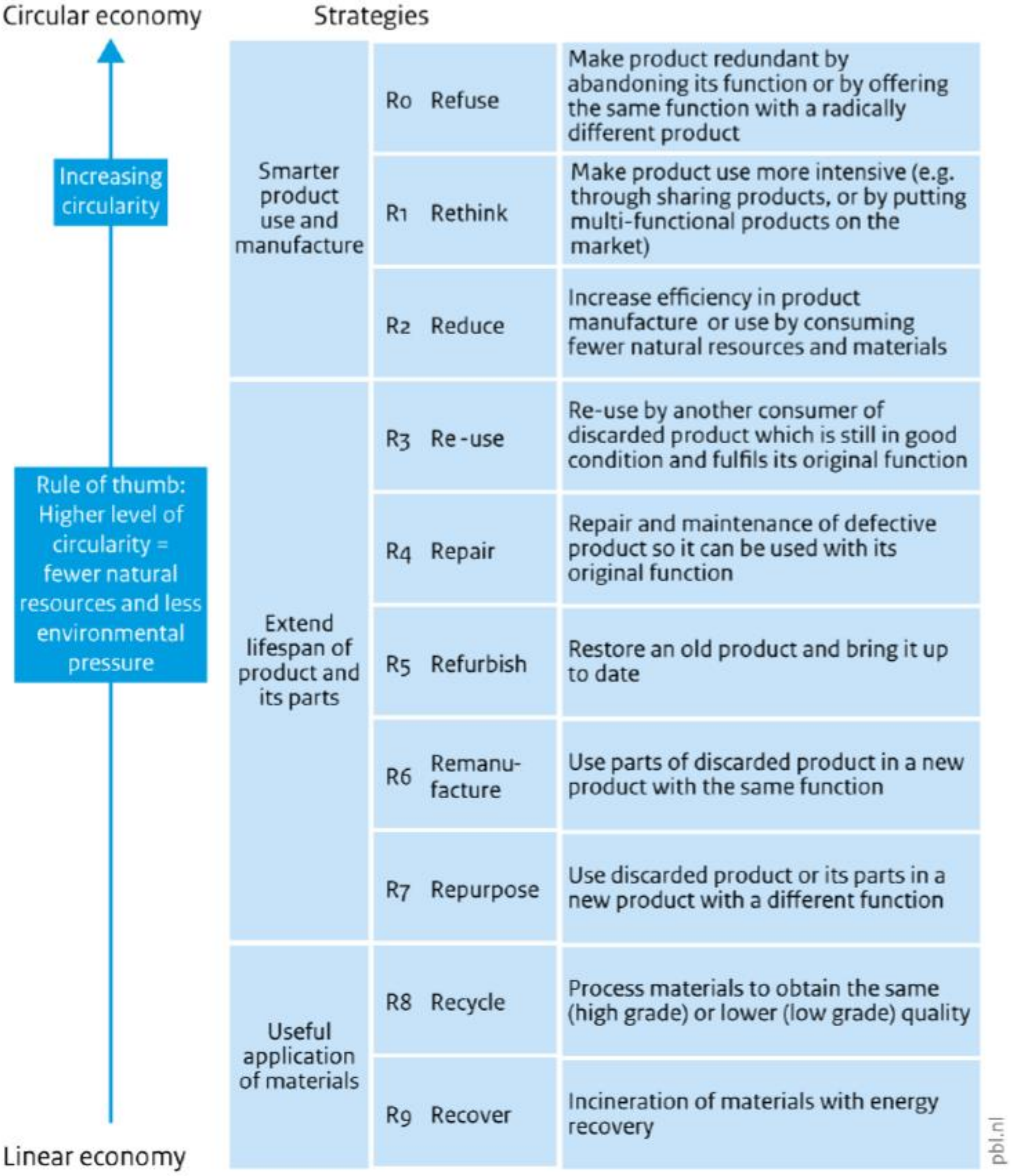


Figure 1. Butterfly diagram as depicted by MacArthur (2013).



Strategies		
Smarter product use and manufacture	R0 Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
	R1 Rethink	Make product use more intensive (e.g. through sharing products, or by putting multi-functional products on the market)
	R2 Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials
Extend lifespan of product and its parts	R3 Re-use	Re-use by another consumer of discarded product which is still in good condition and fulfils its original function
	R4 Repair	Repair and maintenance of defective product so it can be used with its original function
	R5 Refurbish	Restore an old product and bring it up to date
	R6 Remanufacture	Use parts of discarded product in a new product with the same function
	R7 Repurpose	Use discarded product or its parts in a new product with a different function
Useful application of materials	R8 Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
	R9 Recover	Incineration of materials with energy recovery

Figure 2. 9R framework as depicted by Potting et al. (2017).

1.2.2 Circular Economy in policy

Worldwide, more and more governments and cities have established ambitions to become circular, such as Paris, London and Amsterdam (Williams, 2021). The ambitions are all based on the core concept of CE: To diminish waste and virgin material use. The European Union has also formulated extensive goals on circularity, touching upon topics ranging from design, production and waste policies for different sectors. The overarching reason to become more circular is formulated as follows: “Scaling up the circular economy from front-runners to the mainstream economic players will make a decisive contribution to achieving climate neutrality by 2050 and decoupling economic growth from resource use, while ensuring the long-term competitiveness of the EU and leaving no one behind.”(EU Commission, 2020).

In line with the European goals, the Netherlands aims to become ‘a circular economy’ by 2050 and reduce the use of virgin materials by 50% in 2030 (Rijksoverheid, n.d.). Currently, the measure contributing the most to circularity within the Netherlands is recycling. In 2017 93% of the waste generated in the Netherlands was effectively reused. Of the total volume of waste 79% was recycled. Unfortunately, the recycled materials were mostly of a lesser quality than the original material, thus the consumption of virgin materials remains high (Potting et al., 2017).

Several Dutch cities, such as Den Haag, Amsterdam, Rotterdam, Utrecht and Leiden, have their own circular ambitions. However, in order to create impactful policies that help reach these ambitions it is important to know how and where to close material loops. In other words, it is important to know how to match the in- and out-flow of materials in the city to each other. In addition, according to Van den Berghe and Verhagen (2021) it is important to review the often overlooked resupply process to become a circular city. Therefore, to minimise environmental impacts, it is also important to know what a relevant scale for resupply is.

1.2.3 Circular cities

Like the definition for CE, there is no unified definition for circular cities yet. Hence, a simple roadmap for a city to become circular doesn’t exist. Prendeville et al. (2018) define circular cities as “cities that practice circular economy principles to close resource loops, in partnership with the city’s stakeholders, to realize its vision of a future-proof city.” Proposals on the transition towards circular cities are mainly focused on the national level (Schulze 2016; Lantto, Järnefelt, & Tähtinen, 2019; Sitra, 2016). The Ellen MacArthur foundations envisions circular cities to “embed the principles of a circular economy across all its functions […]” (EMF, 2017). These principles being: to design out waste and pollution; keep products, components, and materials at their highest value and in use, and regenerate the natural system.

In this process the CE concept, which is not coupled to clear geographical components or boundaries has to be aligned with the material flows coming in and out of the city. All in- and outgoing flows of a city can be described as its urban metabolism (Newell & Cousins, 2015). Within cities the construction sector contributes largely to the waste and virgin material flows of cities (UN, 2019). To match the circular approach to urban metabolism a certain scale has to be defined to be able to create well defined goals and effective policies for the transition towards circular cities. In other words, when can a material loop be considered closed? When the materials are recycled on site, in the region, on the continent or globally?

1.2.4 Local vs global production

An ongoing debate that revolves around geographical scale and sustainability focusses on the question: is a local scale or a global scale more sustainable? This also raises the question on how to define “local”? In the current debate there often are no clear definitions of local and global (Pearson et al., 2011). Instead it is often regarded as a continuous scale (Brunori et al., 2016, Smith Taillie and Jaacks, 2015).

Most research that compares local to global sourcing of products is related to the food industry. For example, Schmit et al. (2017) ranked 14 food products based on sustainability indicators. The rankings showed that global products consistently come last in terms of sustainability, even when the preference functions and weighting of the indicators were varied. The first positions of the rankings were taken either by the most local or an intermediary product. However, this was based on the weighed and combined indicators. Based only on the indicators climate change mitigation and affordability to consumers, global products had an advantage. They concluded that distance is thus not the most important factor in improving sustainability of food products, and that other criteria such as identity, governance or size play a bigger role.

This is in line with findings of Kreidenweis, Lautenbach and Koellner (2016), who minimised the greenhouse gas emissions for five food commodities. They found that despite additional greenhouse gas emissions due to transport needs for import, a large share of food production was allocated to locations abroad. When they only optimised for distance, thus ensuring local production, the total emission of greenhouse gasses was higher. Furthermore, they conclude that specialisation of certain locations in the production of certain crops can be used as a strategy to lower overall climate impact.

Nonetheless, such outcomes also depend on what factors are taken into account. When just assessing greenhouse gas emissions, certain global products may outperform local products. However, these results can change when factors such as socio-economic impacts are taken into account (Fontes, 2016). Factors that have been assessed by Schmitt et al. (2017) are environmental, economic, social, health and ethical indicators as part of an overarching sustainability indicator.

It is unclear whether the conclusions from studies of food products are generalisable to other fields, due to the differences food production and the production, or in the case of this study recycling, of other products and materials. Therefore, this research may add to the debate and shift its focus from food to other fields.

1.3 Case study: Municipality of Leiden

This section introduces the municipality that serves as a case study: the municipality of Leiden. The municipality of Leiden is very focussed on sustainability and circularity. Projects such as ‘de Duurzaamste kilometer’ and local policies aim to transform Leiden to a sustainable, future proof city. The municipality wants to adhere to the national goals and in addition focus on circular construction, valuation of material flows and social responsible purchasing (Municipality of Leiden, n.d.).

As part of their circular construction goals, the municipality of Leiden is the first city to implement a circular demolition policy within the Netherlands (Team Stadszaken.nl, 2021). This policy states that projects initiated by the municipality (mainly utility and infrastructure projects) have to adhere to new guidelines that promote circularity within demolition practices. Those practices can be categorised by the R-strategies 3 to 8 in Figure 2. This includes promoting high-quality recycling of retrieved materials, as opposed to downcycling. Off all materials in a demolition project, at least 80% have to be demolished in a circular fashion. By doing so, the municipality aims to reduce CO_2 emissions from demolition by 615kg per square meter gross floor area and reduce the amount of waste created by the construction and demolition sector (Municipality of Leiden, 2021).

By 2023 the municipality of Leiden wants to instigate a circular construction policy. This policy will affect construction projects initiated by the municipality. A project will be deemed circular when two out of eight circular principles are used. These principles are depicted in Figure 3. The circular demolition policy is part of these principles and falls in the category of value retention.

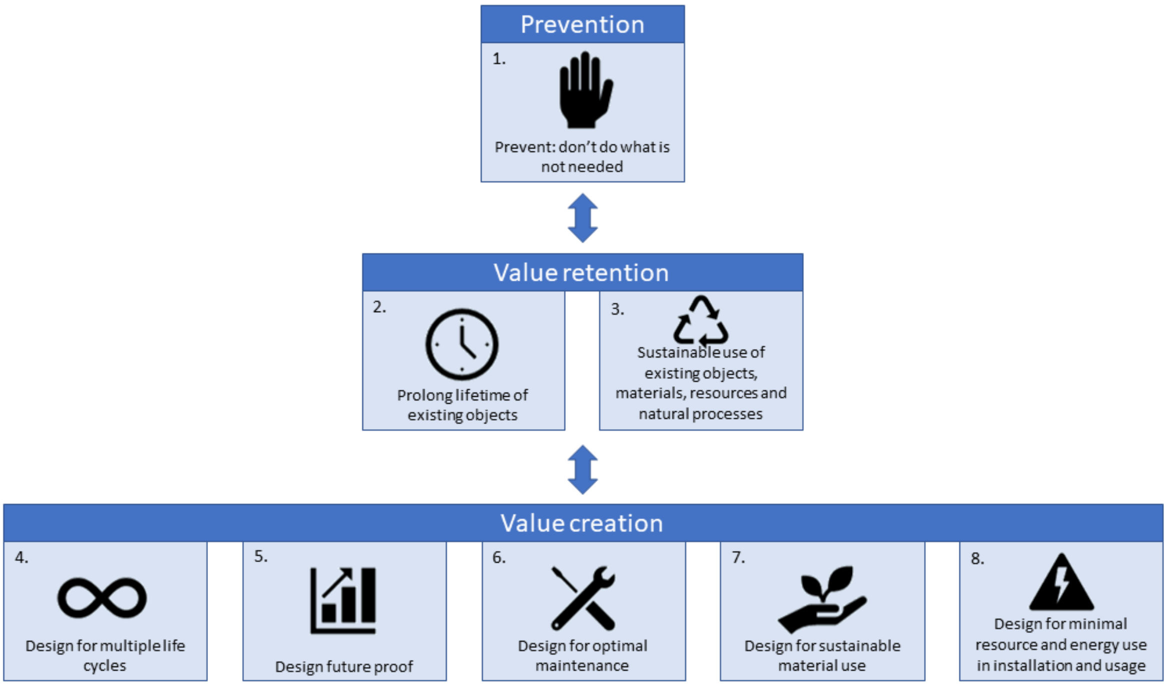


Figure 3. Circular building principles of the municipality of Leiden. Adapted from (Municipality of Leiden, 2021).

Based on the construction and demolition agendas of the municipality, the potential of material stocks can be determined for the municipality of Leiden. Research by Sauer (2020) matches the outflow of materials due to planned demolition projects to the inflow of materials needed for new construction, as seen in Figure 4. This match decreases the need for primary materials within construction projects. Mainly due to this decrease, Sauers research shows a potential CO_2 reduction of 49.8% when circular demolition is applied instead of conventional demolition. Research by Besse (2021) shows the potential ratio of re-use and recycling of materials from planned demolition projects, as shown in Figure 5. These results show the remaining importance of recycling in the construction and demolition sector to achieve circular goals.

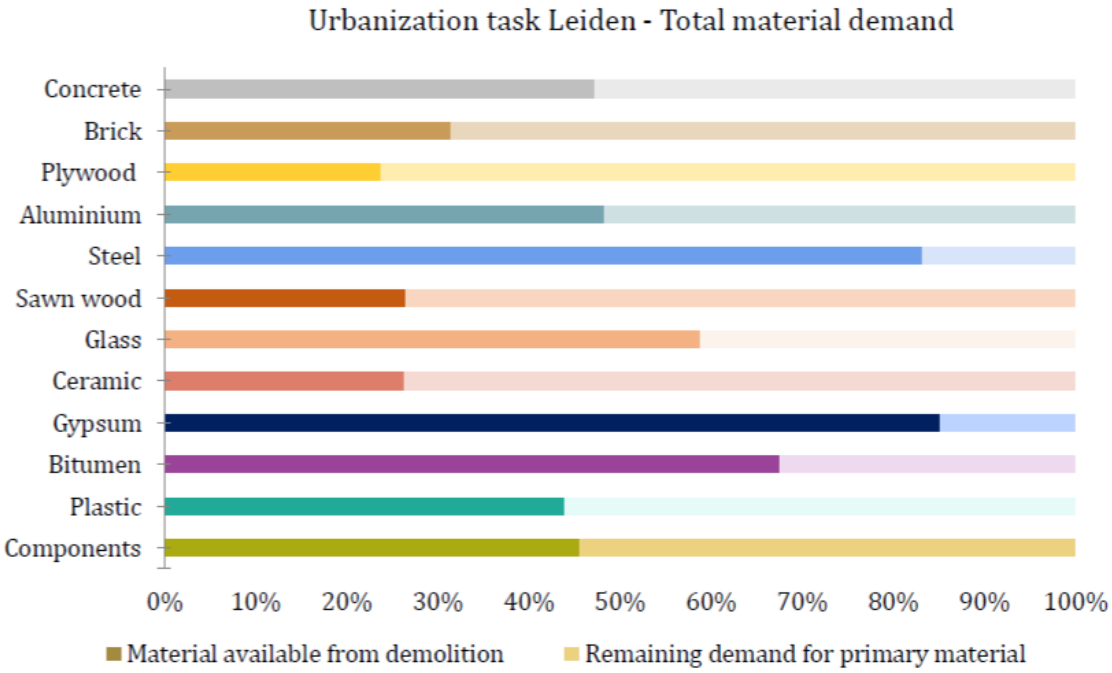


Figure 4. Percentages of material outflows from demolition for the municipality of Leiden, based on demolition projects from 2019-2030. (Sauer, 2020).

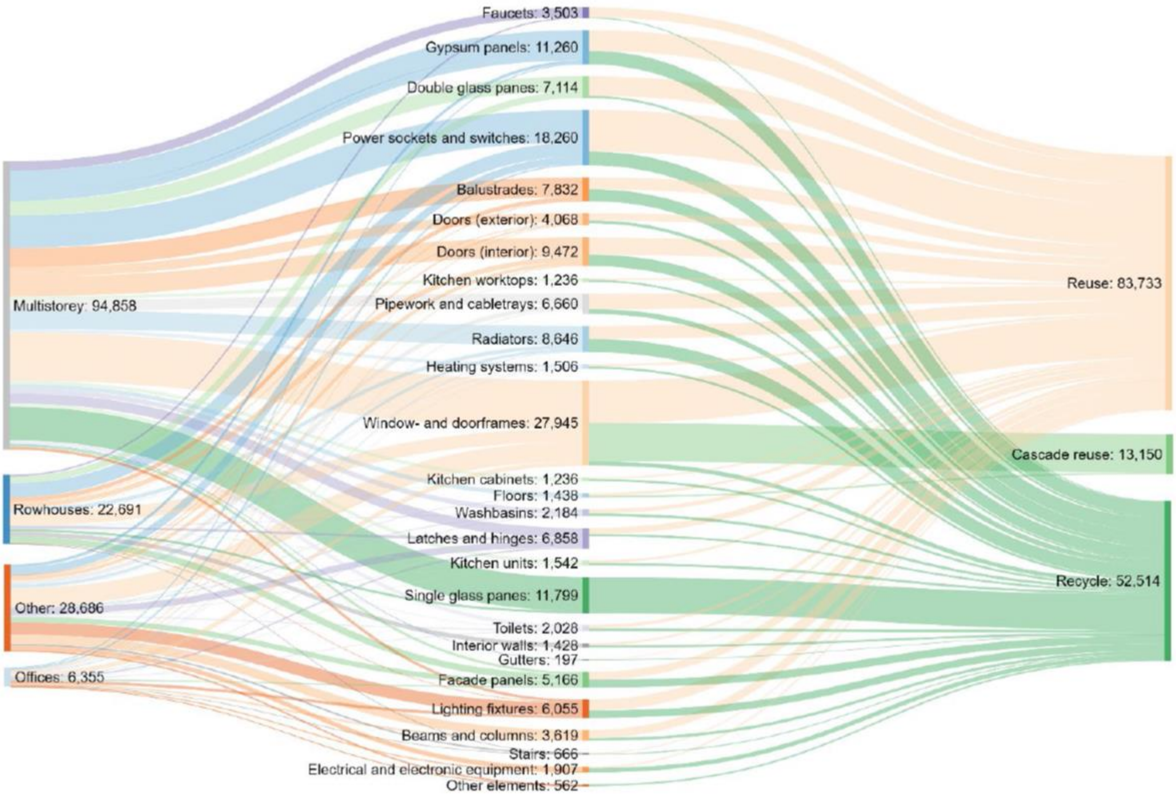


Figure 5. The number of components in the buildings that will be demolished in the municipality of Leiden and their potential end-of-life scenario. (Besse, 2021)

2. Methods

This chapter introduces the framework and the methods through which the included factors will be assessed.

2.1 Framework for geographical scale

The proposed framework will provide an optimised geographical scale for the recycling of materials based on the chosen factors. Within this research the focus is on two factors: economic and environmental. The analyses will be focussing on the maximum geographical scale for transport of waste materials to the recycling facility. The framework thus focusses on the first part of the resupply chain, as highlighted in Figure 6. It does not assess the impact of transport of a recycled material to the location where it will be used, since it is assumed that this is similar for recycled and primary produced materials. However, the use of the framework is not limited to these phases in the resupply chain, and could in principle be applied more broadly as well.

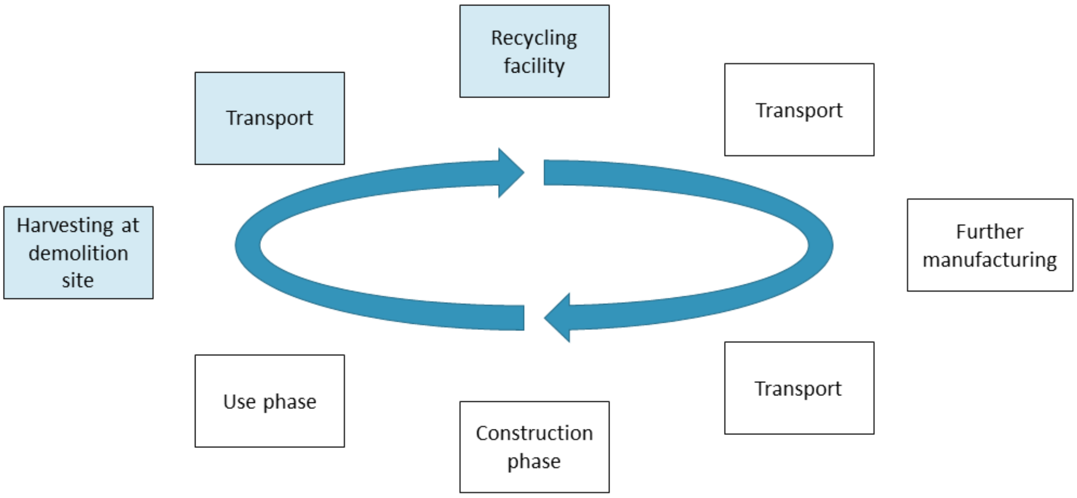


Figure 6. A simplified visualisation of a general resupply chain. In light blue the steps on which this research focusses within the resupply chain are demarcated.

Within the current use of the framework the geographical scale is determined based on the additional kilometres a waste material can be transported. To do so, for each assessed factor the maximum distance is calculated. The region in which these distances overlap gives the maximum geographical scale for the resupply chain of that material.

In this research the economic factor is based on a crude cost benefit analysis. This analysis takes basic metrics into account such as production and transport cost, and proceedings from the produced material. The environmental factor is based on CO_2 equivalent. The CO_2 equivalent will be determined through a life cycle assessment.

From both factors a maximum transport distance will be calculated, as described in sections 2.2 and 2.3. Combined these distances will indicate a maximum geographical scale for the recycling process.

2.2 Information on status quo

The current situation is assessed based on academic literature, statistics and reports from Dutch government agencies in general and the Municipality of Leiden in specific and semi structured interviews with people from the industry.

First of all the municipality of Leiden provided several municipal reports and previous research on their behalf. Second, specific data for the industry were searched for in government databases and in academic literature. Third, several companies were approached to talk about current practices and the status quo of the industry. The approached companies are a random sample, based on a google search of concrete and copper recycling companies within the Netherlands and were approached via email.

The interviews are semi structured and conducted through Microsoft teams. Lastly, the Apify web scraper tool is used to scrape addresses of companies relevant to the current practices from Google maps. For this research only the companies within South-Holland were retrieved based on several search criteria. These criteria and the complete results can be found in Appendix I-A for concrete and Appendix I-B for copper. Irrelevant inputs were manually removed, such as hardware stores.

2.3 Economic analysis

To determine the maximum geographical scale based on economic factors a crude cost benefit analysis is carried out. In this analysis only production cost, transport cost and proceeds from the sales of the recycled material are taken into account. Furthermore, a profit margin of 20% is assumed. Based on these metrics the additional budget that could be available for transport is calculated. This is also represented in Equation 1.

Eq. 1 $$(\delta P - pm) - xc > 0$$

$$\begin{aligned} \delta \mathrm{P} &= \text{proceeds} - \text{production cost};\\ \mathrm{pm} &= \text{profit margin};\\ \mathrm{c} &= \text{cost per km transport};\\ \mathrm{x} &= \text{number of possible additional km} \end{aligned}$$

The maximum geographical scale will follow from ‘x’. When the equation holds, there won’t be extra costs compared to the current situation.

The following costs are included: operational costs of the plant, including labour, energy and depreciation of equipment, transportation costs of harvested materials and demolition cost or the cost to buy harvested materials. Since energy costs are included in the production costs, energy and fuel prices will influence the distance from an economic perspective. The benefits included are solely the proceeds of the recycled materials.

Data collection

For concrete, cost indications are obtained from previous research by Zhang et al. (2019). Proceeds are based on current prices for concrete found through desk research. Some prices, such as fuel and electricity prices, highly fluctuate over time. In the research of Zhang (2019), they attempted to be as accurate as possible by using historically observed data from multiple sources and in addition having the data confirmed by relevant actors. However, in light of the current hike in energy prices, their indications are probably off. Therefore, the distances are calculated for the transport costs provided by Zhang et al. (2019) and for transport costs that are three times higher.

For copper the same transportation cost is assumed. Data on the production cost of recycled copper is based on the assumption that recycling copper is more economic than producing primary copper (Roane Metals Group LLC, 2020). In the absence of cost data for recycled copper, the cost is based on cost indications of primary copper production by Schlesinger et al. (2022). Proceeds are based on the current sales prices of copper as found on the London Metal Exchange.

2.4 Environmental analysis – Life cycle assessment

To assess the environmental impact of both concrete and copper recycling a life cycle assessment (LCA) is conducted. The goal of this LCA is to assess and compare the environmental impact of primary sourced concrete and copper and recycled concrete and copper. Furthermore, the LCA provides the impact of transport of the concrete and copper waste to the recycling plant. Based on these results a geographical scale of the transport of waste for recycling will be determined. From these LCA results the geographical scale will be calculated using Equation 2.

Eq. 2
$$\delta I - xt > 0$$

$$\begin{aligned} \delta\mathrm{I} &= \text{impact primary material} - \text{impact recycled material;} \\ \mathrm{t} &= \text{impact per km transport;} \\ \mathrm{x} &= \text{number of possible additional km} \end{aligned}$$

If this equation holds, there is still environmental gain from using the material with recycled content. When Equation 2 does not hold, the primary sourced material has less environmental impact for that impact category. The geographical scale can be calculated from x and is thus also dependent on the impact based on transport. In this research two modes of transport will be assessed: transport by road and transport by barge over inland waterways.

In this study the LCA will be used to depict stages A1 to A3, based on the ISO standard 14014.44. This describes the cradle to gate stages of the material production. It is assumed that the other stages within the life cycle are similar for the primary sourced materials and the recycled materials. Since both for concrete and copper there are legion end products with different uses, this research assesses the materials before they are processed into specific end products.

The focus of the research is on the category of climate change, measured in CO_2 equivalent. However, other categories will also be depicted in the results. The characterisation family used to calculate the indicators is Product Environmental Footprint (PEF), based on ILCD 2011 V1.0.10. The PEF family is developed by the Institute for Environment and Sustainability for European Commission (Manfredi et al., 2010). Table 1 shows the mid- and endpoint indicators assessed using the PEF family. The geographical scope of the LCA is the Netherlands, most of the data for concrete is based on this country. For copper the data is from Europe. The temporal scope is recent, 2015 to present, and the technologies assessed are the current practices.

Table 1. Mid- and endpoint indicators of Product Environmental Footprint family.

Endpoint indicator	**Midpoint indicator**	**Abbreviation**
Climate Change	Global warming potential	GWP
Ecosystem Quality	Freshwater and terrestrial acidification	FTA
	Freshwater ecotoxicity	FET
	Freshwater eutrophication	FE
	Ionising radiation	IR
	Marine eutrophication	ME
	Terrestrial eutrophication	TE
Human Health	Carcinogenic effects	CE
	Non-carcinogenic effects	NCE
	Ozone layer depletion	OLD
	Photochemical ozone creation	POC
	Respiratory effects, inorganics	REI
Resources	Land use	LU
	Mineral, fossils and renewables	MFR

Data collection

The data for both LCA's are based on a mix of desk research, scientific literature, interviews and EcoInvent version 3.4. For some processes proxies are used. The data sources for each process can be found in Appendix II-A. For each process the data is based on the Netherlands, if available. Otherwise proxies of comparable countries are used. For example, the RER and CH are assumed similar to the Netherlands and are used as proxy. All unit processes are listed in Appendix II-B.

Sensitivity analysis

To evaluate whether the results of the LCA's change significantly when parameters are slightly changed, two sensitivity analyses will be caried out for concrete and copper. The first analysis will be based on the impact of transport: instead of a truck with the EURO5 emission standard, a lower standard of EURO4 will be used. The second analysis is based on the percentage of recycled content used in the production of the material. For example, currently recycled concrete has a recycled content of 30-50%. The LCA in this research takes the upper limit of 50% recycled content. In the sensitivity analysis this will be lowered to 30%.

3. Results

This chapter presents the results of the research, starting with the overall results of the framework. Subsequently the results of the economic analysis and life cycle assessment are presented in detail.

3.1 Status quo of concrete and copper recycling in the Netherlands

In this section the results of the first sub questions are presented. These sub questions relate to the current practices around concrete and copper recycling in the Netherlands. The results provide an understanding of the current situation for both materials. First, the degree of circularity of waste handling in the construction and demolition sector is discussed in general. Next, concrete and copper will be discussed using the following structure: first, the degree of circularity for each material is discussed, including current regulations and policies. This is followed by a description of the current resupply chain of the material. Finally, for each material an overview will be given of the infrastructure that is in place.

3.1.1 Circularity of the Dutch construction and demolition sector

More than 40% of waste generated by the Netherlands is construction and demolition waste. Over 97% of waste from the construction and demolition sector has a ‘useful application’ after it is disposed of (CBS, PBL, RIVM & WUR, 2020). A useful application is defined as the reuse of a material in any way, including incineration with energy recovery (ILT, n.d.). It thus includes the R3 to R9 strategies as discussed in section 1.3.1. The sector currently recycles 95% of the volume of all its waste (CBS, PBL, RIVM & WUR, 2020). However, this includes downcycling of materials.

3.1.2 Status quo of the Dutch Concrete sector

Circularity of the Dutch concrete sector

Concrete makes up a large share of waste in de construction and demolition sector. Approximately 85% of construction and demolition waste consists of concrete and other stony materials (CBS, PBL, RIVM & WUR, 2020). These materials are widely reused as granulates for foundation of infrastructure and construction sites, as well as secondary material input for concrete production.

Regulations and industry standards of the Dutch concrete sector

The current practices are partially influenced by regulations on quality and recycling processes. There are several regulations for the quality of recycled concrete aggregates and mixed aggregates that are produced from concrete from demolition sites. First of all, the European Commission created several directives to ensure quality of the production and transaction of the recycled aggregates, the most important for recycled concrete aggregate being CPR 305. In this directive several civil engineering criteria for the recycled aggregates are defined, such as the distributions of granule size and strength (BRBS Recycling, 2021).

The European directives form the base for national regulations. The Dutch regulation for recycled concrete fall under NEN standards. Depending on the use of the recycled aggregates different NEN standards apply (BRBS Recycling, n.d.).

To test whether a material or product reaches these standards, materials are reviewed according to BRL 2506 (BRBS Recycling, 2021). This reviewing guideline is based on the ‘bouwproductenverordening’ issued by the European Commission and the NEN standards. In case of a positive review, the material or product receives the CE hallmark. Without this hallmark a product or material cannot be used within the European construction sector (BRBS Recycling, n.d.).

Second, there is a legal maximum amount of recycled aggregates that can be used in recycled concrete. Currently, this is 30-50% and this is also included in the NEN standards and BRL assessment guideline. When a product satisfies this criterium, it is granted the KOMO-certification, which is required for the use of recycled concrete in the Dutch construction sector (Profi-gids, 2022). This legal maximum is in place to ensure that the quality of recycled concrete is the same as that of primary concrete. Currently, there are some companies who are developing concretes with higher recycled content of high quality. However, legislation has not yet been updated accordingly.

Furthermore, within the industry a new standard is being created through the ‘Betonakkoord’. The Betonakkoord constitutes of a series of agreements signed by several stakeholders in the concrete industry. The stakeholders are divided as follows: seven (public) commissioners consisting of national government bodies, municipalities and ProRail; twenty suppliers; and eight construction companies. The purpose of this agreement is to reduce CO_2 emissions, promote circularity, natural and social capital as a contribution to the sustainability of the Dutch society and economy (Betonakkoord, 2018).

Some of the objectives of the Betonakkoord are: 30% reduction of CO_2 emissions and 100% high value recycling of concrete by 2030. This will stimulate the growth of initiatives for high value recycling of concrete, since currently there are not a lot of players on an industrial level (Betonakkoord, 2018).

Current practices of high value concrete recycling

Currently, there are several different practices in use for high value concrete recycling and several more are being developed. The most commonly used methods are ‘Wet processing’ and ‘Advanced dry recovery (ADR)’ (Zhang et al., 2010). Therefore these are the processes that are reviewed in this research. Furthermore, several organisations are developing new ways to recycle concrete. One of these organisations is the Rutte Groep. They developed a method that enables them to recycle all components of waste concrete. To this end they use the so called ‘smart liberator’ (Rutte Groep, n.d.).

Wet Processing makes use of pre-crushed concrete rubble. This is transported to a treatment plant where it is broken down to 22mm. It is then sieved into recycled coarse aggregate, 4-22mm, and sieve sand, <4mm. After sieving the recycled coarse aggregates are washed in a long water bed. Finally, the recycled coarse aggregate is used for the production of concrete, instead of primary sourced natural coarse aggregates. The residues of the washing process are sedimented and the generated sludge is disposed through landfilling. The sieve sand consists of dirt, sand and hydrated cement and is therefore hard to recycle in a high value application. Consequently, sieve sand is treated as a waste or low value material, which can be used as land levelling and road foundation (Zhang et al., 2019).

The advanced dry recycling method starts with the crushing of larger 0.5m chunks, of concrete rubble to granules of 22mm. It is then sieved to 12-22mm and <12mm. The 12-22mm granules make up about 20% of the crushed concrete. This recycled aggregate is then used in the production of recycled concrete. The granules that are smaller than 12mm are fed into the advanced dry recycling system. This system sorts the granules into 4-12mm and <4mm. The first is used as recycled aggregate in the production of recycled concrete and the latter is sieve sand, which is treated similar as the sieve sand from wet processing (Zhang et al., 2019).

All recycling methods have similar steps: harvesting, sorting, recycling to aggregates and producing recycled concrete from a mix of recycled aggregates and primary materials. The differences are in the method used for recycling waste concrete to aggregates and the locations of the different steps. Therefore, several different resupply chains are possible. Based on interviews with BRBS Recycling and Rutte Groep, the current resupply chain for concrete in the Netherlands is as depicted in Figure 7. Sorting is mostly done at the demolition site, during harvesting. This minimizes the pollution of the harvested materials and thereby enhances the quality of the granulate. These steps are mostly done by the demolition company, which gets instructions on the sorting process from the recycler. Furthermore, recycling to aggregates and recycled concrete production are on the same site.

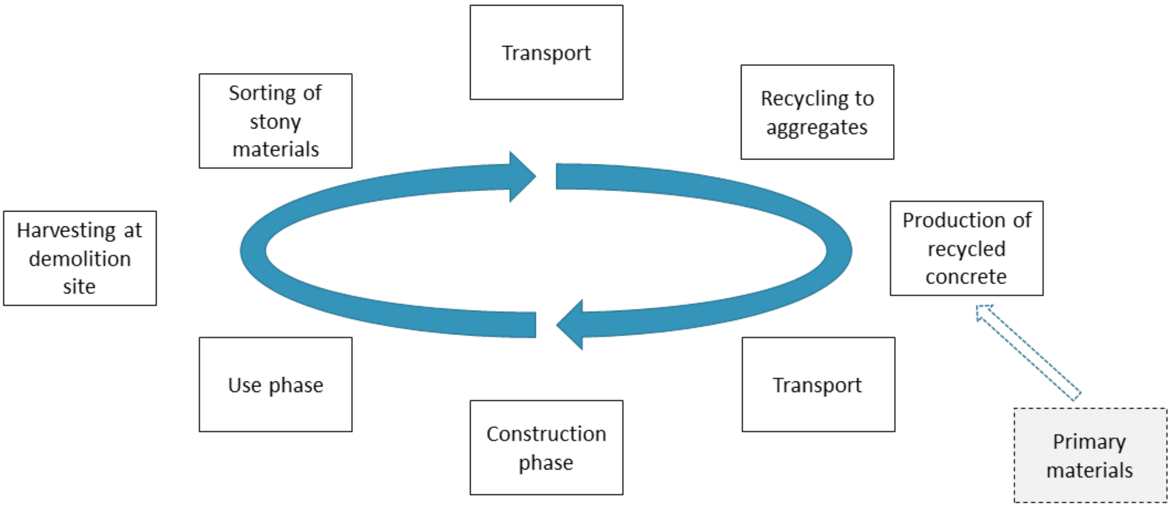


Figure 7. Most prevalent resupply chain for high value concrete recycling in the Netherlands.

Usually concrete and stony materials are not transported more than 30-40 kilometres to the recycling facility. At the moment this distance is said to be mostly dictated by transport cost. Thus, fluctuations in fuel cost also influence this distance. However, the Rutte Groep works with an average of 50 kilometres of transport, partially due to the dispersion of the facilities currently available.

Current infrastructure for concrete recycling in South-Holland

Based on the data from the address scrape tool current companies working within the concrete recycling supply chain are plotted in Figure 8. Demolition companies are the most prevalent, and widely available throughout South-Holland. There are also three recycling locations within the 50km radius. Next to the companies, a 30km and 50km radius are plotted. These radii depict the current distance over which concrete rubble is normally transported. However, the area within this radius is not entirely the same as the area covered by the same distance over road. Moreover, the starting/endpoint of transport will rarely exactly be the centre of Leiden. Therefore, the depicted area can deviate from actual places concrete rubble is transported to and from.

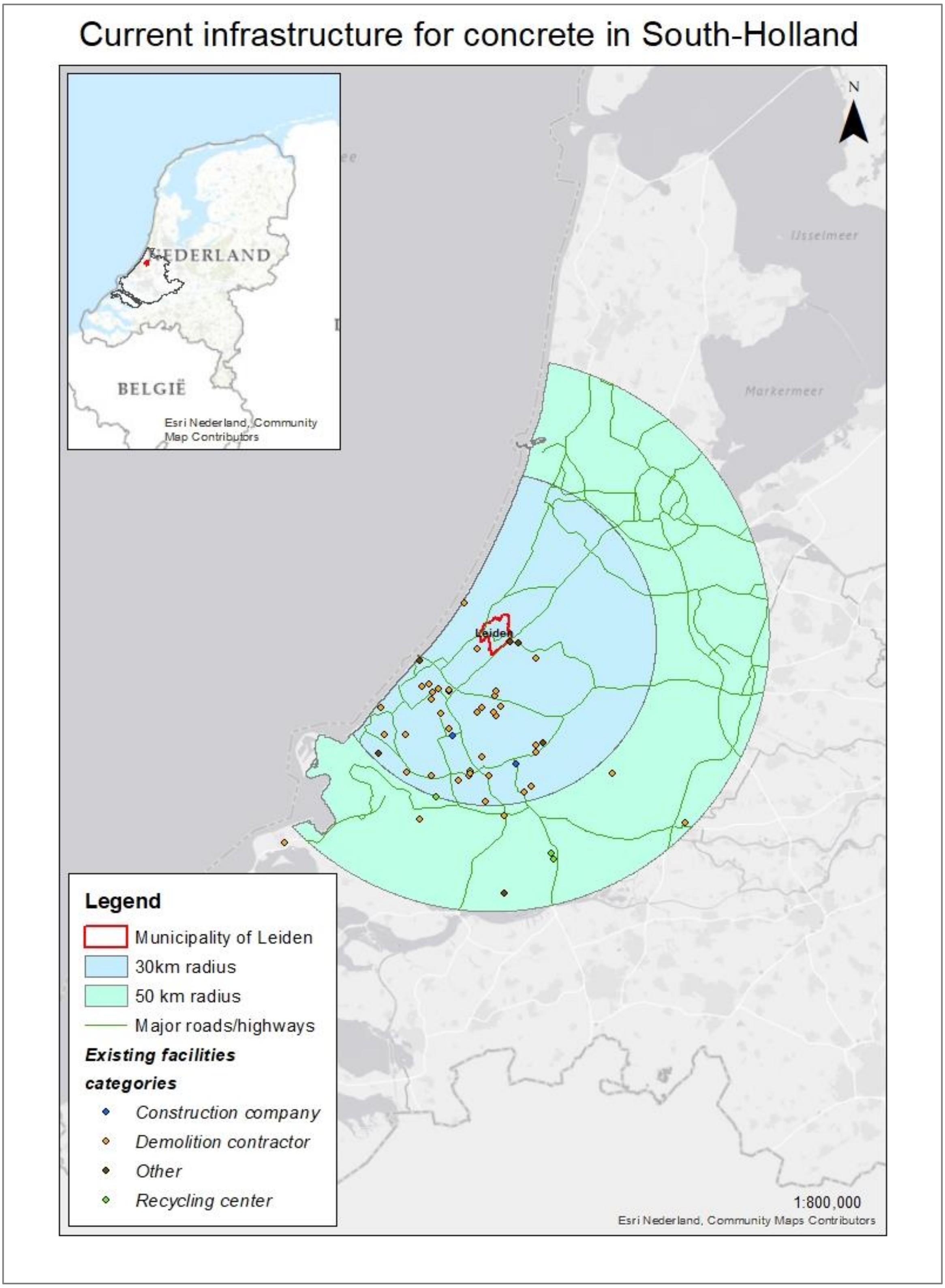


Figure 8. Current facilities and infrastructure for concrete recycling in South-Holland.

3.1.3 Status quo of the Dutch Copper sector

Circularity of the Dutch copper sector

Globally, one third of the consumed copper comes from secondary sources. This means it has either been retrieved from a discarded product or as waste from manufacturing (Gloser et al., 2013). The ratio of primary and secondary sourced copper has been constant over the last 40 years, though the absolute quantities have increased (ICSG, 2013).

Within the EU, 73% of all copper waste is recycled (Bertram, Graedel, Rechberger and Spatari, 2002). This includes copper from municipal solid waste, construction and demolition waste, waste from electronics, end-of-life vehicles and imported copper waste. Although there is no specific data for copper recycling in the Netherlands, it is assumed that the European data apply to the Netherlands as well. For metal waste in general 98% is recycled (Statline, 2021). Furthermore, the Dutch metal recycling industry prevents the emission of 14400 kilotons of CO_2. However, Dutch recyclers can only process one third of Dutch scrap metal, thus a considerable amount of scrap metal is exported to be recycled (Recycling Nederland, n.d.). It is mostly exported within the EU and bound for recycling (Bertram, Graedel, Rechberger and Spatari, 2002).

Regulations and industry standards of the Dutch copper sector

For the recycling of copper there are several regulations set by the European Commission. These regulations focus on two aspects: export and trade, and quality control. However, the emphasis lies on export regulations. Since copper is a component in many different products, including electronics, the trade of discarded products is limited by the Basel Convention (Basel Convention, 2019). On top of that, the Weight Shipment Regulations regulate trade and export of metal scrap (Argus, 2022).

The European Commission also issued a regulation for the quality of recycled copper. This is regulation 705/2013 and it describes how scrap copper needs to be processed to be regarded as a material again, instead of a waste (European Commission, 2013).

The quality control is partially market based, since high quality copper is needed for multiple applications, such as wiring. In addition, the Dutch Metal Recycling Federation supports and enforces European regulation to prevent unfair competition and ensure the recycled copper is of a high enough quality (Grondstofprijs, n.d.).

Current practices high value copper recycling

There are several types of copper recycling. One is direct remelt, in which copper scraps from industry are directly recycled into new copper. The copper scrap from industry is usually from high quality (Fu, Ueland and Olivetti, 2017). Another type of recycling is the recycling of post-consumer copper. This type of copper scrap is usually of lower quality, since it can be contaminated or corroded. The focus in this research is on copper from the construction and demolition sector and thus the encountered copper scrap consists mostly of post-consumer copper wires and pipes.

The different types of copper recycling all follow the same general steps: harvesting, sorting, cleaning, and remelting to recycled copper. The differences are mostly based on the application and quality of the recycled copper.

In this research the following method is reviewed: treatment of copper scrap through electrolysis. The copper scrap is first cleaned, both mechanically and chemically. This stage is critical, since impurities can cause heightened stresses and fractures in the recycled copper. Afterwards the copper is compacted and transported to a recycling facility. The scrap copper is then melted together with pure copper. Sand and limestone are added to this process to remove by-products. After the scrap and pure copper have melted, the molten copper is cooled in moulds. The resulting ingots or plates are electrolysed to further refine the copper, which results in 99.9% pure copper. From this copper the desired products can then be manufactured (Nonye, 2021). This process is depicted in Figure 9.

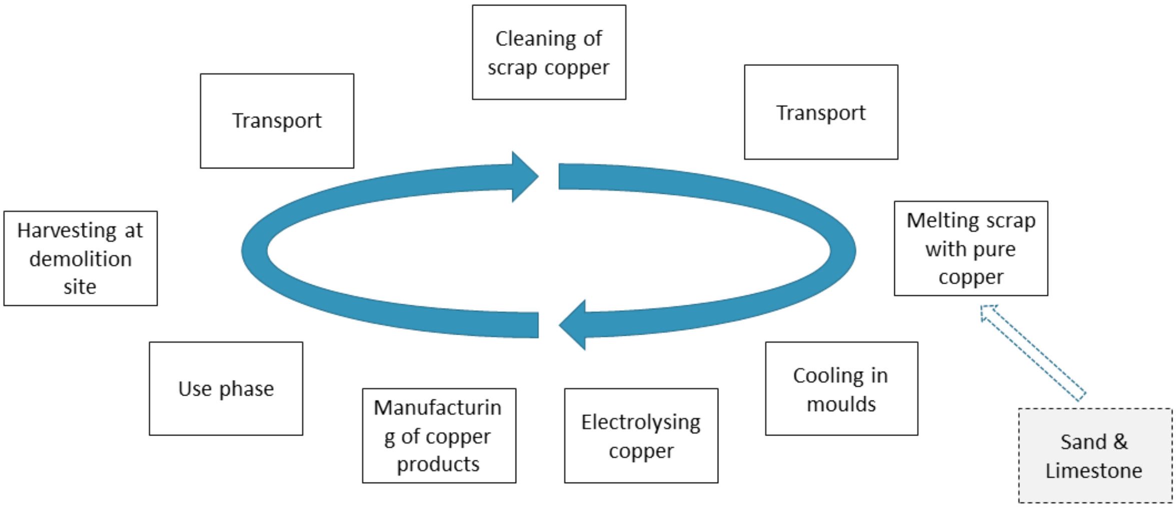


Figure 9. Resupply chain for copper recycling, as reviewed in this research.

No current distances for the transport of scrap copper could be corroborated through interviews or other sources. Nonetheless, it is assumed copper is not transported further than 250 kilometres, because of the prevalence of recycling facilities within the Netherlands. However, data from Centraal Bureau Statistiek indicates that quite some metal waste is exported (Statline, 2021). For this research, it is assumed this is exported to recycling facilities in neighbouring countries within the previously assumed radius. Most of this copper is probably exported to Germany, which is the biggest copper recycler in the EU (Bertram, Graedel, Rechberger and Spatari, 2002).

Current infrastructure for copper recycling in South-Holland

Based on the data from the address scrape tool current companies working within the copper recycling supply chain are plotted in Figure 11. Recycling facilities seem to be prevalent, however, some scrap dealers and collection points mark themselves as recycling centres. Thus, not all recycling facilities in Figure 10 do the actual remelting of copper scrap to recycled copper. Figure 10 shows the facilities as well as a radius of 250 kilometres around the centre of Leiden. This radius depicts the current distance copper scrap is transported. However, the area within this radius is not entirely the same as the area covered by the same distance over road. In addition, the starting/endpoint of transport will rarely exactly be the centre of Leiden. Therefore, the depicted area can deviate from actual places concrete rubble is transported to and from.

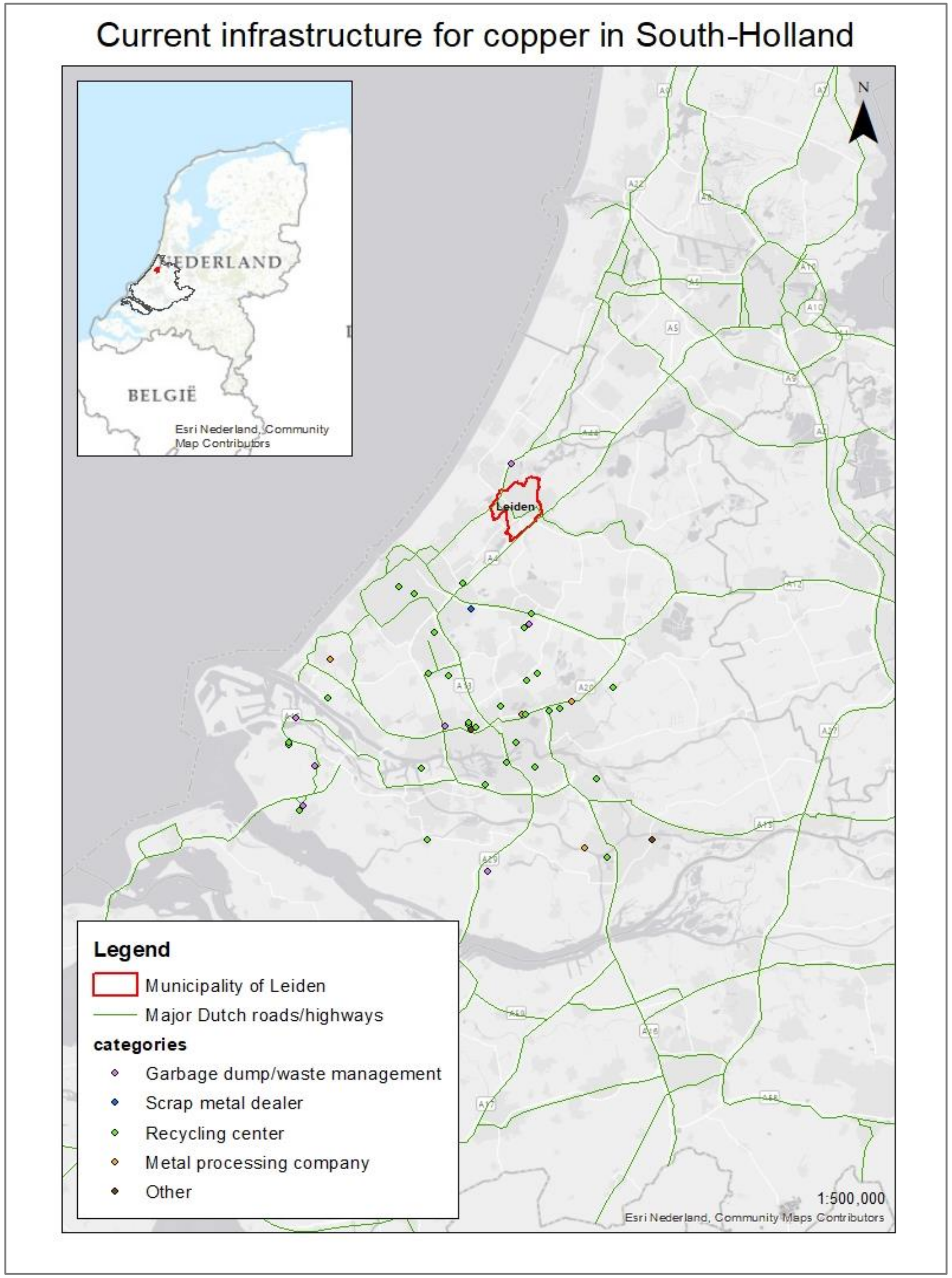


Figure 11. Current facilities and infrastructure for copper recycling in South-Holland.

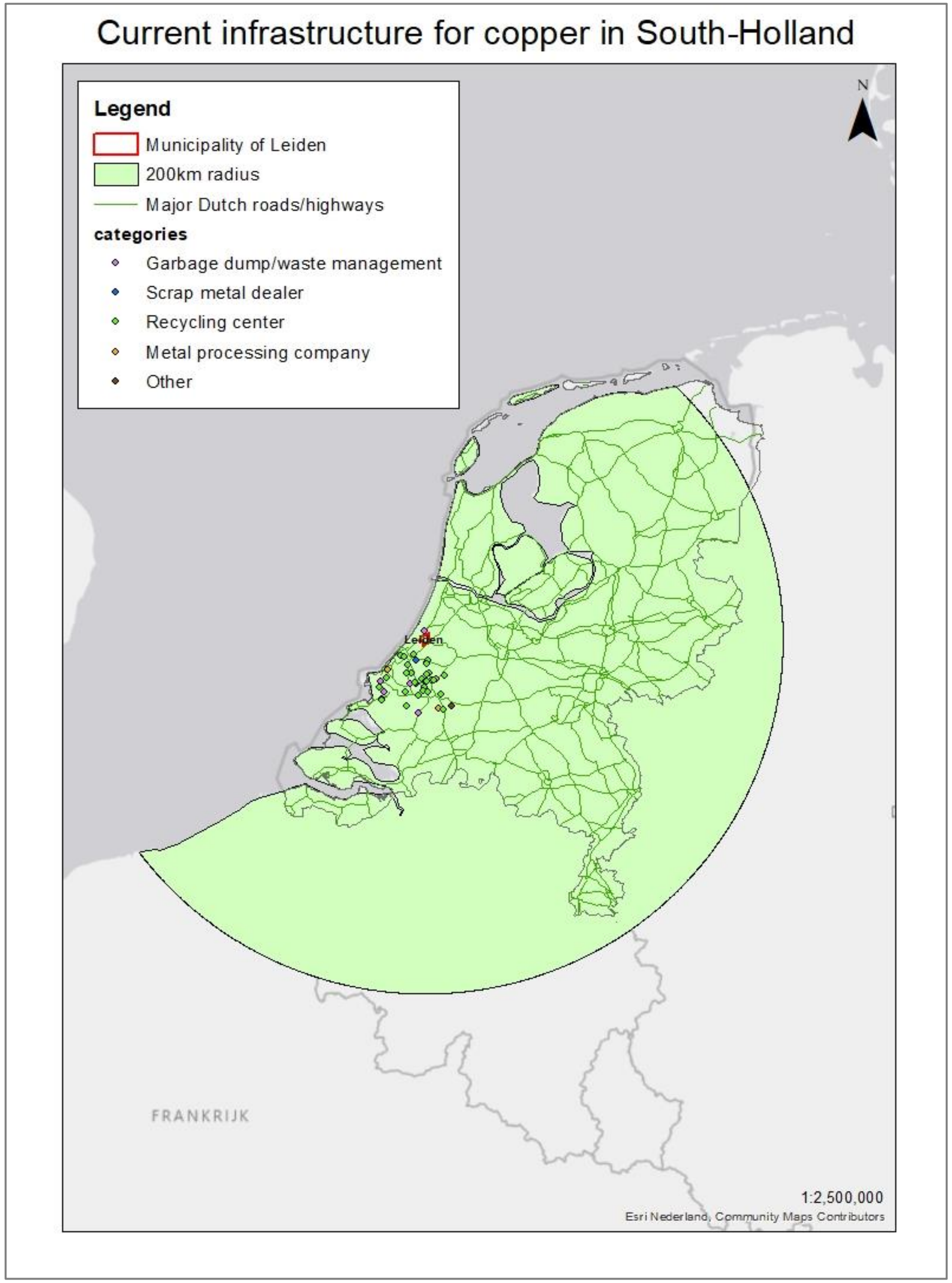


Figure 10. Current facilities and infrastructure for copper recycling in South-Holland, including a 250km radius for scrap copper transport.

3.2 Framework results

In this section the results of both the economic and the environmental part of the framework are combined in an maximum scenario for both concrete and copper recycling.

3.2.1 Scenarios for concrete recycling in South-Holland

Based on the results the framework indicates that concrete rubble can be transported from 70km up to 110km depending on the transportation mode. Currently, economic cost does not limit this. Within this distance from Leiden, a lot of transport, sorting and concrete production facilities are available. However, it is unclear to what extend these facilities are able to recycle concrete. As for the new method of high value concrete recycling, there is currently only one plant in the Netherlands. This plant is situated in Zaandam, which is approximately 50km from Leiden. This makes the plant within range for recycling concrete rubble from the municipality of Leiden. However, for concrete there is another limiting factor due to drying time on transporting new concrete. The ideal distance to transport concrete is between 20-30 km (Van den Berghe and Verhagen, 2021). This prevents closing the loop on municipal scale on the supply side of the material.

In the near future it is expected that more high value recycling will become the standard, due to the 'betonakkoord'. However, to be able to supply Leiden with circular concrete, a mixing plant within 30km of the municipality should be realised. It is also possible to separate the recycling and mixing steps. Thus, only requiring a mixing plant in a 30km radius of the municipality of Leiden and a recycling plant within 70 km. This does require additional transport of the reclaimed materials from the recycling to the mixing plant, thus an additional analysis is necessary to determine the distances these plants can be apart. Another solution of the supply side of concrete is using a mobile mixing plant. However, this also requires additional analyses in terms of additional emissions related to the mobile plant and additional cost. Also, both options would need a shift in the current mindset and practices within the industry.

Figure 12 shows the area that lies within a 70km radius for transport by truck and 110km radius for transport by barge. All current facilities within South-Holland are now easily accessible. As well as the existing high value recycling facilities in Zaandam. For concrete, more high value recycling plants need to be in place, or a way to overcome the distribution hurdle for freshly produced concrete. All other infrastructure, such as demolishers, sorting locations and transport facilities, is in place.

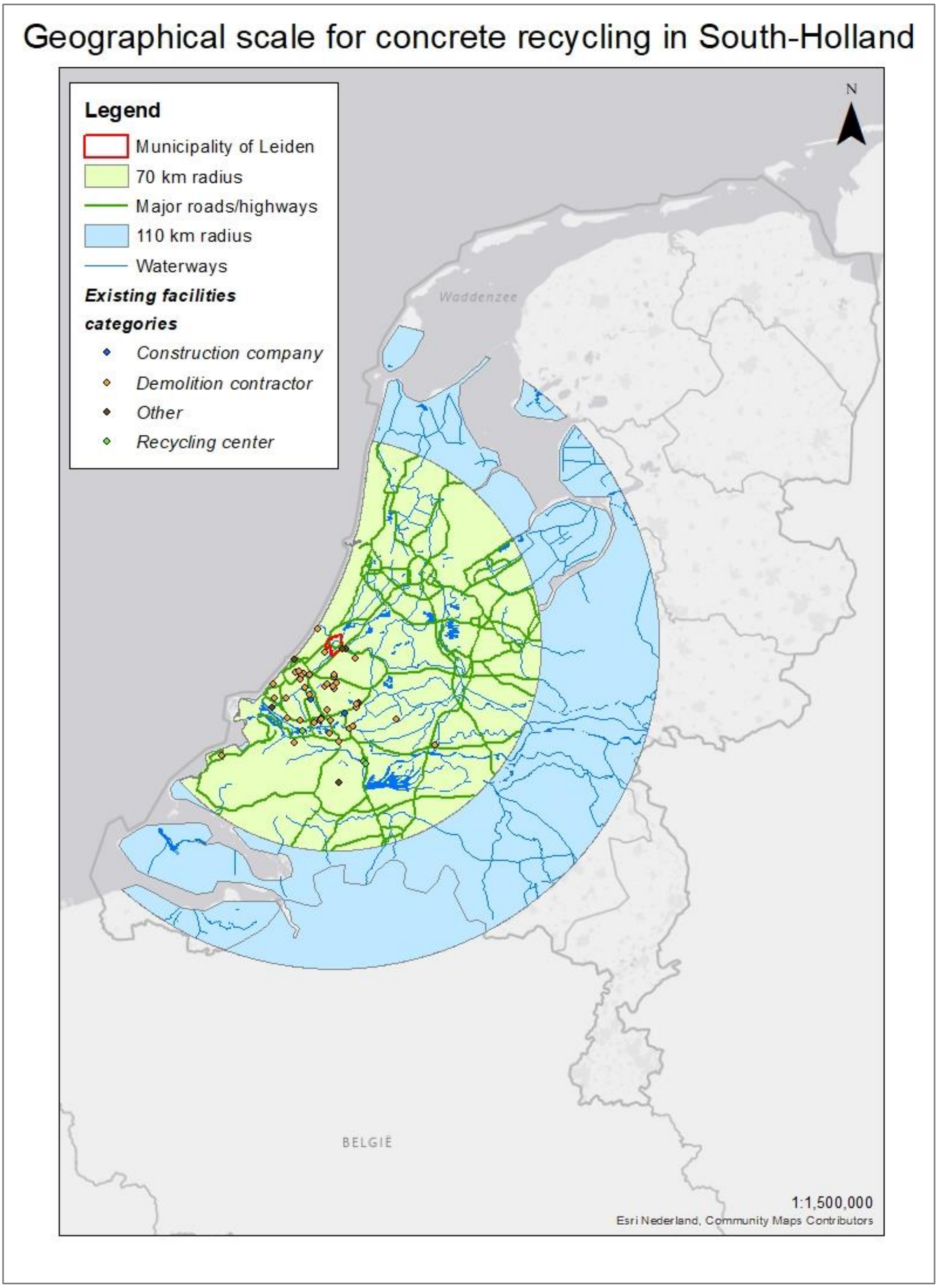


Figure 12. Resulting scenario for concrete recycling, based on the framework.

3.2.2 Scenarios for copper recycling in South-Holland

Based on the result for copper it seems that environmental impact and economic cost are not the determining factors for geographic scale. Based on environmental impact scrap copper can be transported by truck from Leiden throughout Europe, North Africa, the Balkan, parts of Russia and parts of the Middle East. Economic cost is not a limiting factor either in this case. The limits based on the environmental results are depicted in Figure 13 and Figure 14. The transport limit by road is depicted by the radius of 4330km and the transport limit by barge by the 11500km radius. There are many locations now within the radius that are not realistically reachable by road or inland waterways, due to the lack of accessible infrastructure. To add some additional insights in the radius copper can be transported by other transport modes, the distances for transport by transoceanic tanker, aircraft and train are also calculated. Appendix IV-E gives an overview of the methods and data used to calculate the results for these transport modes. Figure 15 and Figure 16 show the distances that copper can be transported by train and aircraft respectively. By train copper can be transported from 9430km up to 13000km, based on the engine/fuel type. Two types of trains are shown: diesel trains and electric trains. By aircraft copper can be transported from 327km up to 509km, depending on the EcoInvent data used. Here the results are shown for intra- and intercontinental freight transport by aircraft. The calculations for transport by transoceanic tanker resulted in a distance of 91200km, which is more than twice the circumference of the world. Note that for these transport modes only the environmental limit is calculated, but no limits based on cost. In practice probably a combination of different transport modes will be utilized to transport copper scrap from the demolition site to the recycling facility.

From the results follows that Copper could be transported further than it currently is. However, it does raise the question why the current transportation distances are so much smaller than the possibilities based on environmental and cost factors. It would thus be interesting to find out what other factors are determining a relevant geographical scale for copper recycling.

All in all the framework gives a positive outlook for both concrete and copper: both recycled materials are now outperforming their primary sourced counterpart in terms of GWP and can be transported further based on cost.

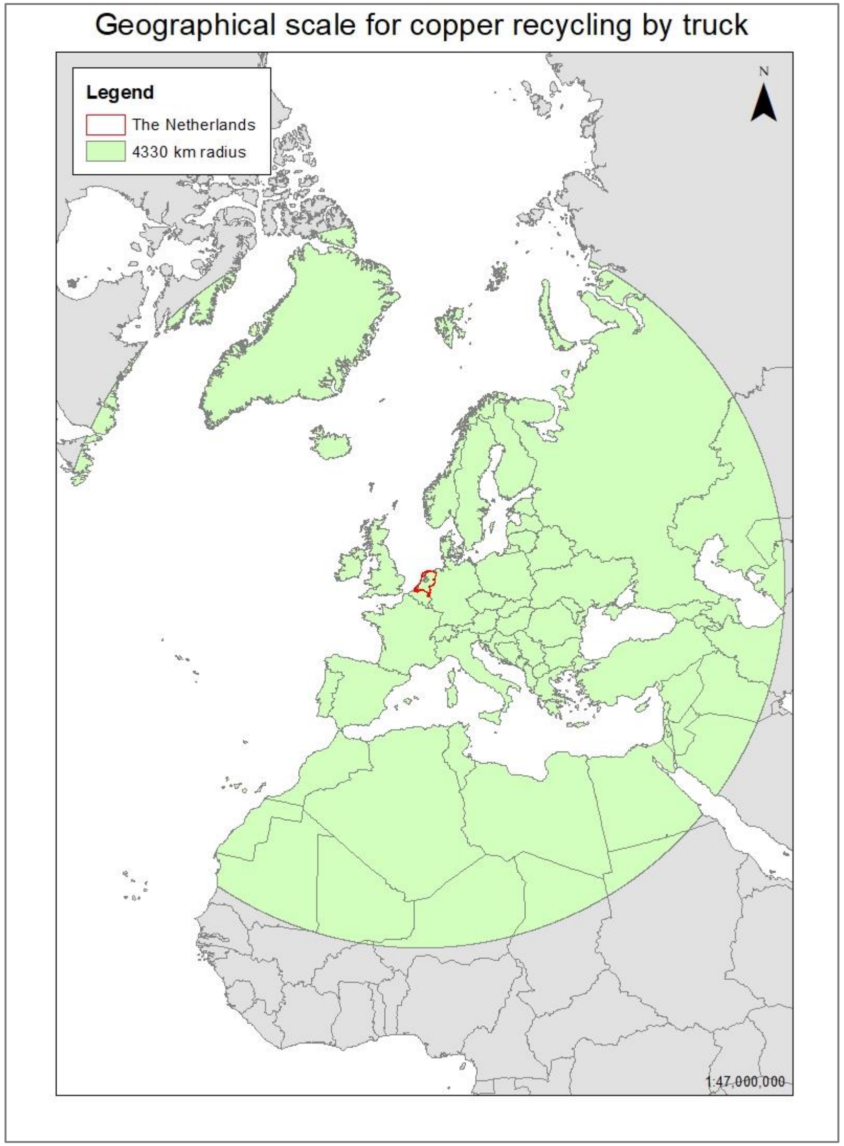


Figure 14. Resulting scenario for copper recycling by truck, based on the framework.

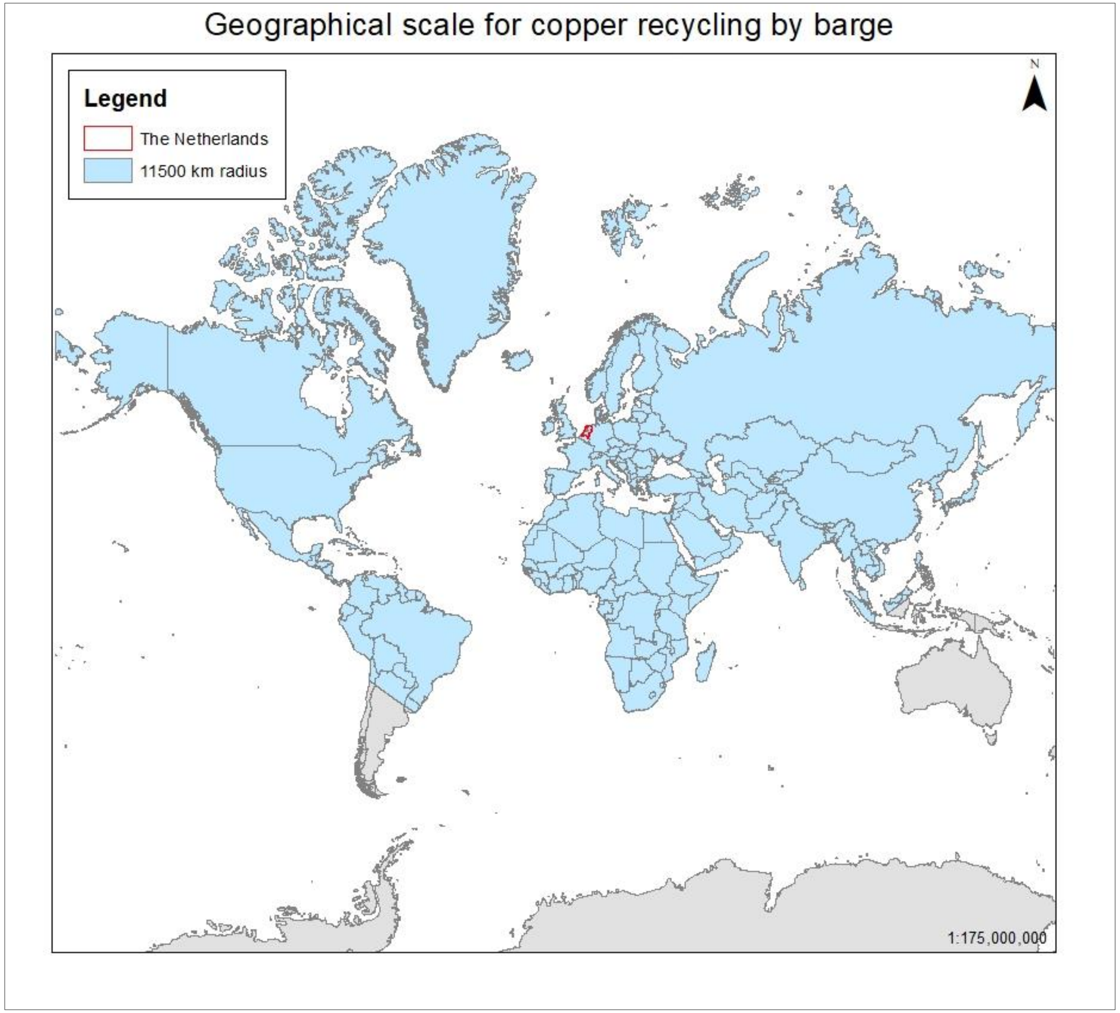


Figure 13. Resulting scenario for copper recycling by barge, based on the framework.

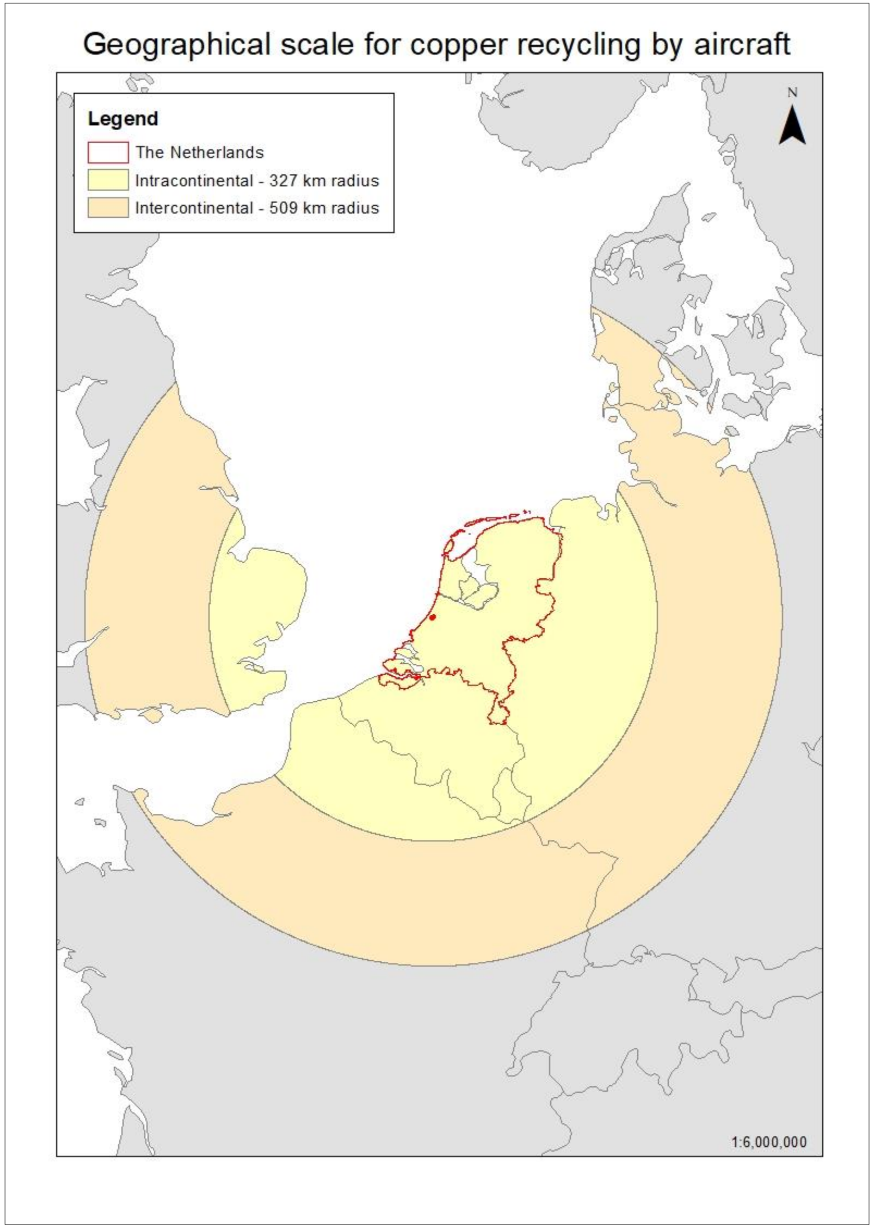


Figure 16. Resulting scenario for copper recycling by aircraft, based on the framework.

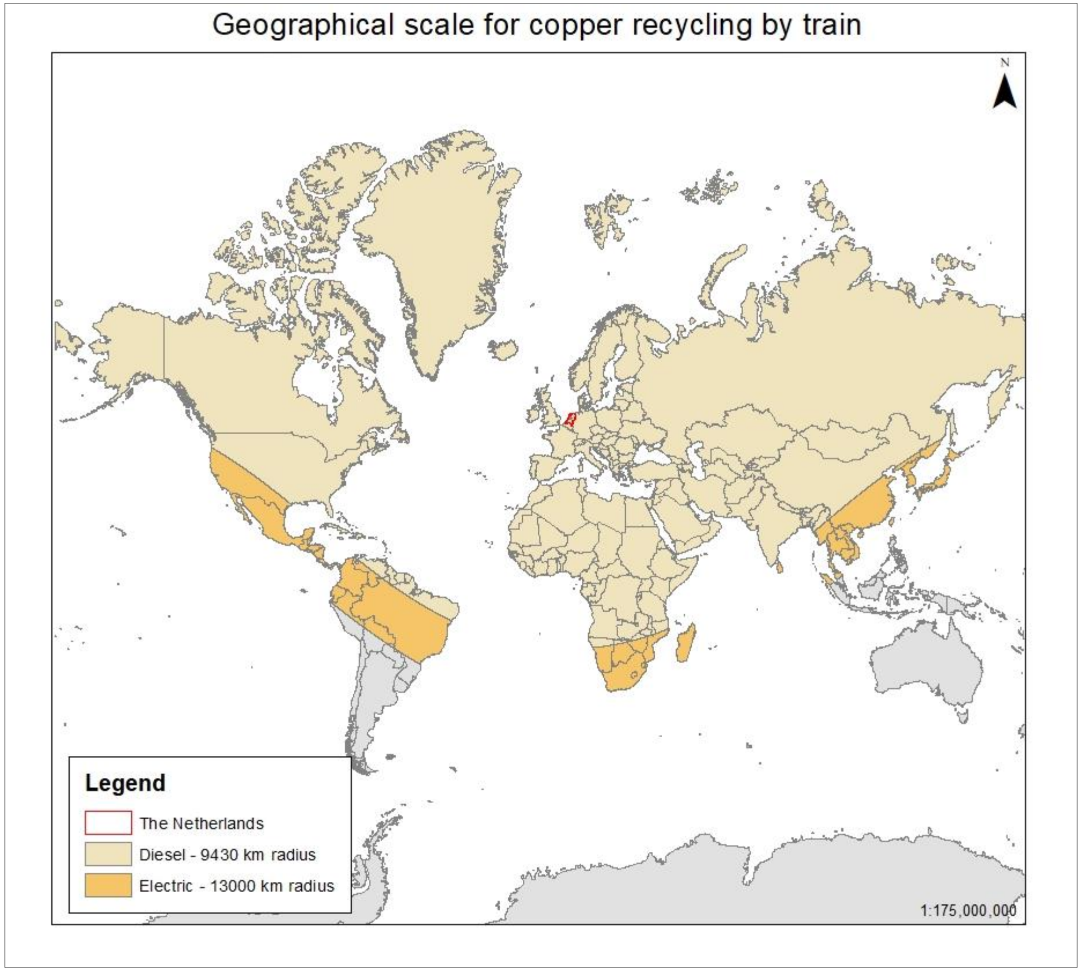


Figure 15. Resulting scenario for copper recycling by train, based on the framework.

3.3 Results of the economic analysis

This section gives a detailed overview of the results and intermediate results of the economic analysis of concrete and copper. From this analysis a maximum distance is calculated based on cost. As described in section 2.2.

3.3.1 Economic results for concrete

The calculated cost are all based on the report of Zhang et al. (2019). The numbers used in the calculations for cost are approximated from the graph in Figure 17. Zhang et al. assume an initial transport of 70km from demolition site to recycling plant. Transport cost are €0.1/tkm (Zhang et al., 2019). The proceeds are based on the average, €145.94/m^3, of several sources stating the market price for concrete (Betonmortel.net, n.d.; Concrete Network, 2021; Mollie Beton, n.d.). Both the cost and proceeds are calculated for 100 tonnes of concrete.

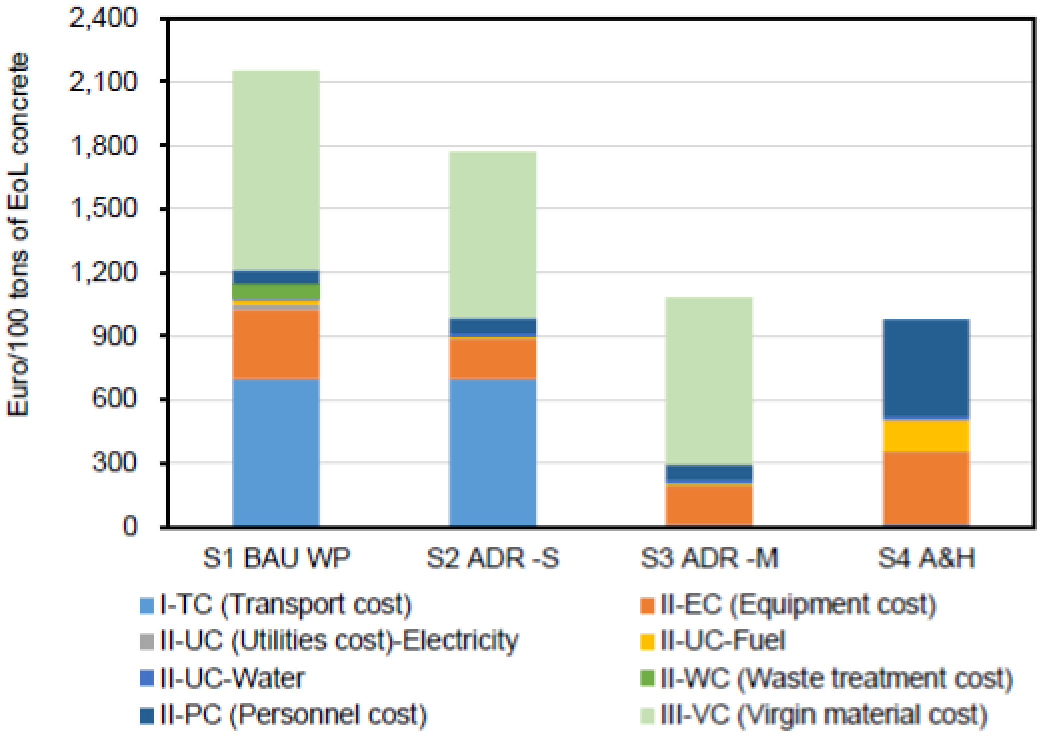


Figure 17. Cost of concrete recycling as calculated and depicted by Zhang et al. (2019). S1 BAU WP, shows the cost for wet processing, S2 ADR-S shows the cost for advanced dry recycling. S3 and S4 are two types of concrete recycling that are not included in this research.

The calculations based on equation 1 are presented in Table 2. The calculations result in possible additional transport between 390km and 430km, depending on the recycling method used. However, these calculations don't take a profit margin into account. Also, this result is highly dependent on fuel prices. Zhang et al. (2019) based their price calculations on 0.73€/L Diesel. This is currently significantly higher, at 1.73€/L (Evofenedex, n.d.).

Table 2. Calculation of geographical scale for concrete recycling based on cost. Based on data of Zhang et al. (2019). All prices are in euros for a 100 tonnes of concrete.

	Cost	Proceeds	Difference (δP)	Transport cost /km (c)	additional km (x)
wet processing	2150	6080.833	3930.833	10	393.0833
Advanced dry recycling	1750	6080.833	4330.833	10	433.0833

Therefore, the calculations are also carried out with transport cost of €0.3/tkm and a profit margin of 20% of the total proceeds. The results of these calculations are presented in Table 3. These results are considerably lower than the results in Table 2, ranging from 90km to a little over 100km. Combined with the assumed initial transport of 70km from demolition site to recycling plant, this gives a total distance of 160-170km.

Table 3. Calculation of geographical scale for concrete recycling based on cost, including 20% profit margin and higher transport prices. All prices are in euros for a 100 tonnes of concrete.

	Cost	**Profit margin (pm)**	**Proceeds**	**Difference (δP)**	**Transport cost /km (c)**	**additional km (x)**
wet processing	2150	1216.167	6080.833	2714.667	30	90.48889
Advanced dry recycling	1750	1216.167	6080.833	3114.667	30	103.8222

3.3.2 Economic results for copper

For copper the same transport cost per tkm are assumed as for concrete. Due to lack of data on the cost of recycling copper, cost for primary copper are used. It is assumed that this will be an overestimation of the actual recycling cost and thus result in an underestimation of potential additional kilometres. The production cost are based on data from (Schlesinger et al., 2022) and the proceeds are based on prices from the London Metal Exchange (LME, n.d.). Table 4 shows the results for copper without a profit margin and transport cost of €0.1/tkm. Based on these data, the distance copper scrap can be transported is almost 56000 km.

Table 4.Calculation of geographical scale for copper recycling based on cost. All prices are in euros for a 100 tonnes of copper.

Production	**Proceeds**	**Difference (δP)**	**Transport cost/km (c)**	**Additional km (x)**
383545.9	941000	557454.1	10	55745.41

As for concrete, the transport distance for copper is recalculated including a 20% profit margin and transport cost of €0.3/tkm. The results are shown in Table 5. Although, these calculations allow for a significant lower distance, copper scrap can still be transported approximately 12300 km. For reference, this is more than the beeline distance between the municipality of Leiden and Bali, Indonesia.

Table 5. Calculation of geographical scale for copper recycling based on cost, including 20% profit margin and higher transport prices. All prices are in euros for a 100 tonnes of copper.

Production	**Profit margin (pm)**	**Proceeds**	**Difference (δP)**	**Transport cost/km (c)**	**Additional km (x)**
383545.9	188200	941000	369254.1	30	12308.47

3.4 Results of the environmental analysis – Life cycle analysis

This section presents a detailed overview of the results of the life cycle assessment for both concrete and copper, as well as the results of the sensitivity analyses conducted. Based on these results a maximum distance is calculated, as described in section 2.3.

To calculate these distances, the impact caused by the transport of the waste materials is needed. The impact of transport for both materials is calculated using data from EcoInvent 3.4. The land based transport is modelled as a truck of undefined size that adheres to the EURO5 standard for trucks. This is the second highest environmental standard for trucks in the EU. Transport over inland waterways is based on the use of a barge. Details for both transportation modes can be found in Appendix II-B in the list of unit processes.

To increase the ease of comparing emissions from transport and production of concrete and copper, the unit of the reference flow is made compatible with the reference flow of both transport modes. Note that the reference flow for transport is for 1 km. This is shown in Table 6.

Table 6. Reference flows of transport for concrete and copper alternatives.

Unit of reference flow	**Reference flow of transport**	**Comment**
1 m^3 concrete	2.4 t*km	Density of concrete is 2400 kg/m^3
1 kg copper	0.001 t*km	# t*km for 1 kg

3.4.1 LCA results for concrete

The functional unit for concrete is the production of one cubic meter of concrete for building construction. The assessed alternatives are: primary concrete, recycled concrete through wet processing and recycled concrete through advanced dry recycling (ADR). The reference flows for each alternative are listed in Table 7.

Table 7. Reference flows of LCA for concrete production.

Product	**Reference flow**
Primary concrete	Production of 1 m^3 of primary concrete for building construction
Recycled concrete – wet processing	Production of 1 m^3 of recycled concrete for building construction, using wet processing
Recycled concrete – advanced dry recycling	Production of 1 m^3 of recycled concrete for building construction, using advanced dry recycling

The flow diagrams of the primary, wet processed recycled, and advanced dry recycled concrete are shown in Figure 18, Figure 19 and Figure 20 respectively. The LCA's are conducted using the CMLCA software.

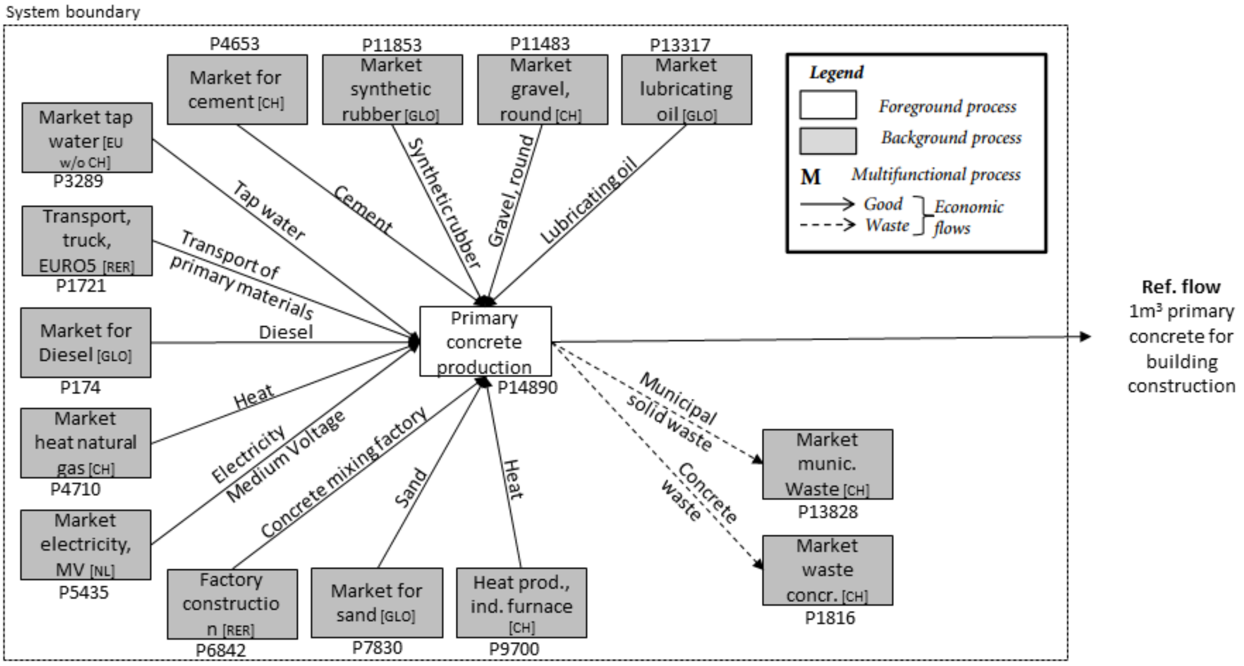


Figure 18. Flow diagram of primary produced concrete, based on the EcoInvent 3.4 process for the production of primary concrete for construction in the RER.

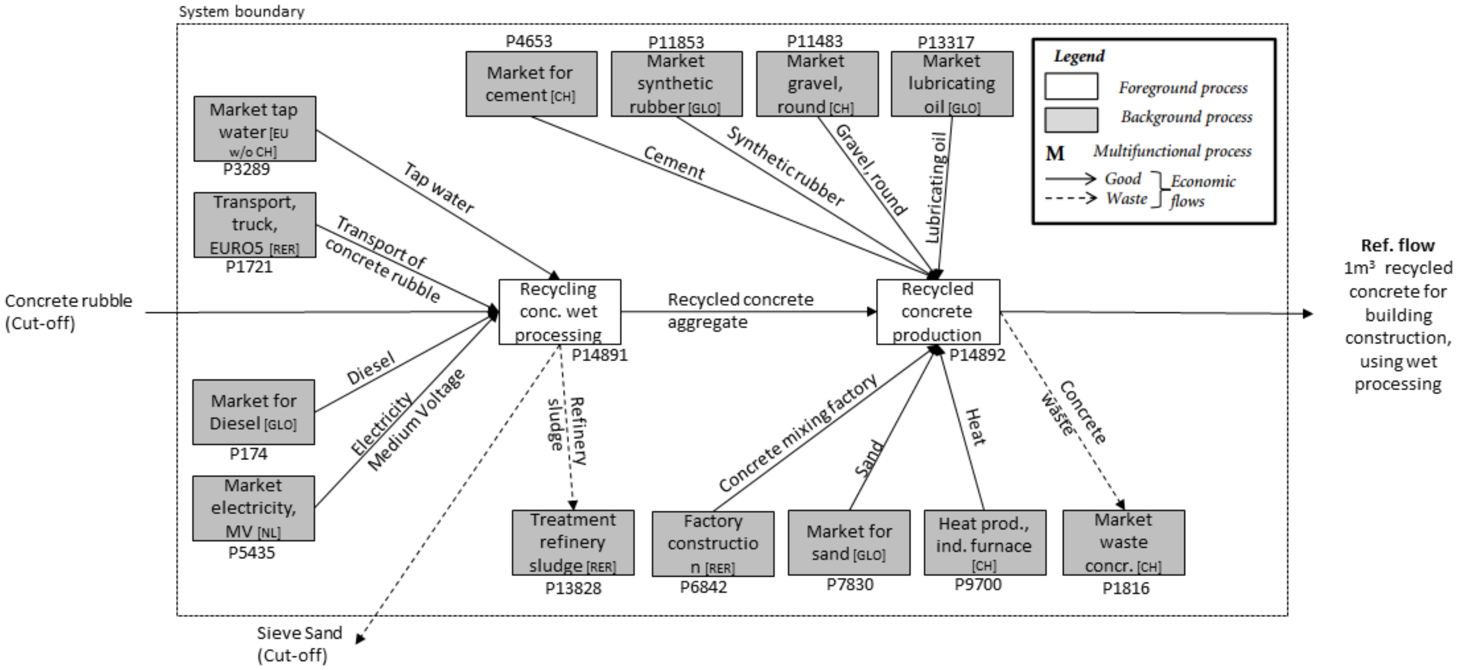


Figure 19. Flow diagram of recycled concrete using wet processing, based on the process as described by Zhang et al. (2019).

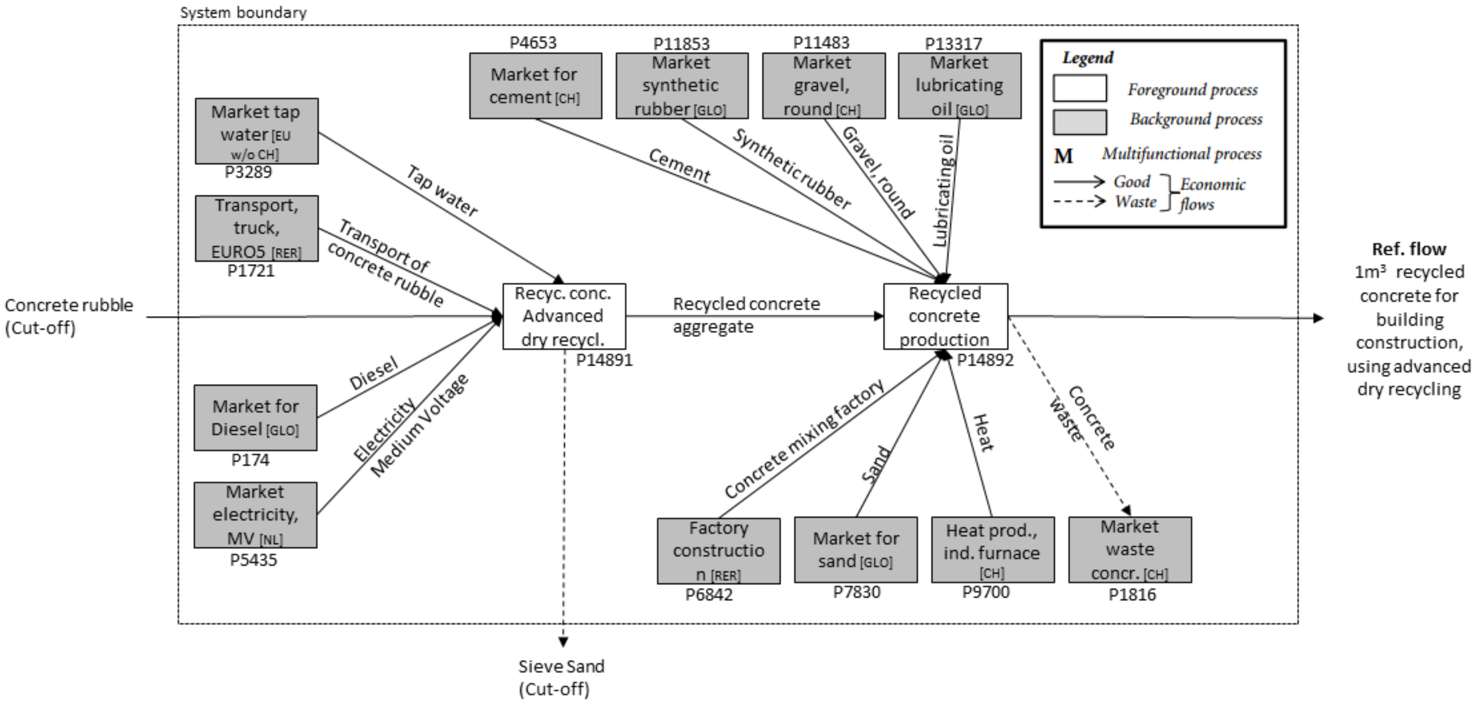


Figure 20. Flow diagram of recycled concrete using advanced dry recycling, based on the process as described by Zhang et al. (2019).

The production of recycled concrete is modelled based on processes as described by Zhang et al. (2019). Furthermore, it is assumed that 50% of the aggregates used to produce recycled concrete are recycled aggregates, in line with the maximum allowed recycled content for the KOMO certification (Profi-gids, 2022). Also, it is assumed that tap water and a medium voltage electricity mix are used for all processes. Lastly, it is assumed that after the harvested concrete is processed into recycled aggregates, the mixing procedure for recycled concrete is the same as for primary concrete. As in the research of Zhang et al (2019) sieve sand is cut-off, because its application is uncertain. Also demolition is cut-off, since this happens either way, whether the concrete is recycled or not and should be included in the last stages of the life cycle assessment. However, in this research only the stages A1 to A3 are considered.

The transport distances of primary materials to the production plant are based on average distance to the municipality of Leiden of gravel, sand and cement production plants within the Netherlands (Dekker Groep, n.d.; Europages, n.d.; Global Cement, 2012; Kramer, 2020). Cement is partially imported from Belgian and German producers (Global Cement, 2012; Kramer, 2020). For all transport a EURO5 class truck is assumed as mode of transport.

LCA results for concrete

Table 8 shows the results per impact category, based on the Product Environmental Footprint characterisation family. Recycled concrete, using wet processing has the lowest impact on all but two categories. These categories are ‘fresh water ecotoxicity’ and ‘non-carcinogenic effects’. In these two categories recycled concrete using advanced dry recycling has less impact. When focussing on global warming potential (kg CO_2-eq) wet processing performs best and interestingly primary concrete outperforms recycled concrete from advanced dry recycling.

Table 8. LCA results for concrete production for 14 indicators, based on Product Environmental Footprint family developed by the Institute for Environment and Sustainability for European Commission.

Indicator	**Primary concrete**	**Recycled concrete, wet processing**	**Recycled concrete, advanced dry recycling**	**Unit**
GWP	244	237	255	kg CO2-Eq
FTA	0.67	0.556	0.979	mol H+-Eq
FET	686	1.76E+03	546	CTUh.m3.yr
FE	0.0292	0.0279	0.0282	kg P-Eq
IR	6.52E-05	5.08E-05	6.75E-05	mol N-Eq
ME	0.182	0.174	0.336	kg N-Eq
TE	2.17E+00	1.81E+00	3.85E+00	mol N-Eq
CE	5.16E-06	4.41E-06	5.19E-06	CTUh
NCE	2.84E-05	5.75E-05	2.28E-05	CTUh
OLD	1.18E-05	6.61E-06	1.36E-05	kg CFC-11-Eq
POC	0.534	0.429	0.979	kg ethylene-Eq
REI	0.0498	0.0354	0.0883	kg PM2.5-Eq
LU	1.12E+03	756	831	kg Soil Organic Carbon
MFR	0.00588	0.00325	0.00329	kg Sb-Eq

In Figure 21, Figure 22 and Figure 23, three impact categories are depicted for primary and recycled concrete. These categories are 'Global warming potential' (GWP), since this is the focus of the research, and 'Fresh water ecotoxicity' (FET) and 'Mineral, fossils and renewables' (MFR), since these are the categories with the highest normalised impact for concrete production and the transportation of 1 cubic meter of concrete per tkm. In other words, transport will have the most effect on those last two categories. A table with the results and normalised results for all indicators for concrete production can be found in Appendix III-A. Figure 21 shows the results for GWP. From these results it appears that recycled concrete, using wet processing, has the lowest impact in the category 'global warming potential'.

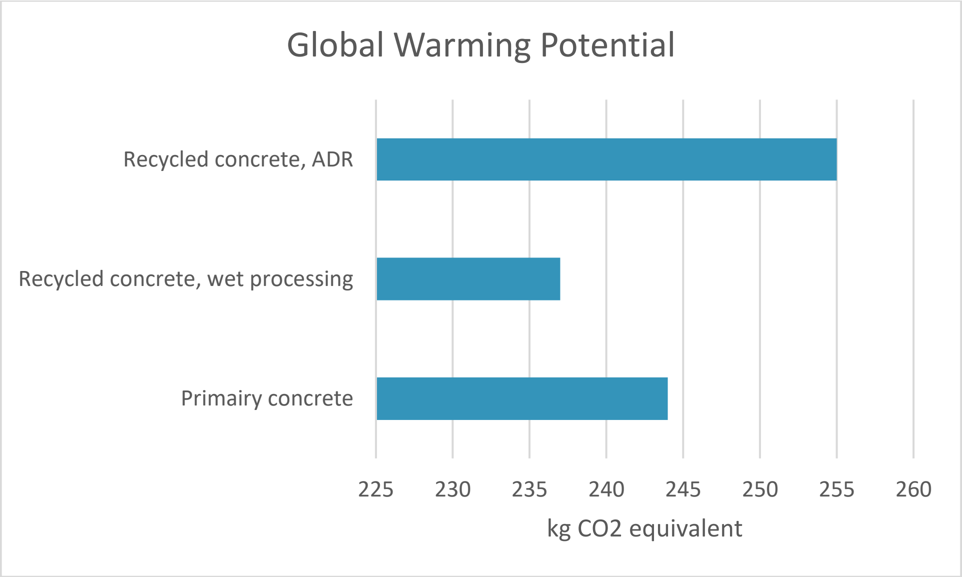


Figure 21. LCA results for the production of 1m^3 primary and recycled concrete for impact category 'Global warming potential'. Global warming potential is expressed in kg CO$_2$ equivalent, in line with the units dictated by the Product

Environmental Footprint characterisation family, developed by the Institute for Environment and Sustainability for European Commission.

In Figure 22 the results for FET are depicted. It stands out that recycling concrete through wet processing has a considerably larger impact on this category.

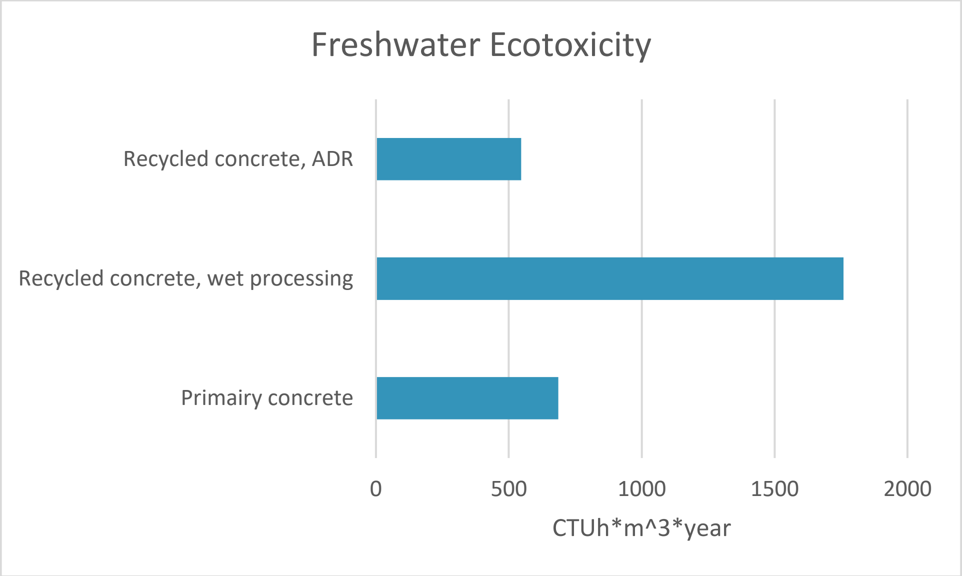


*Figure 22. LCA results for the production of 1m^3 primary and recycled concrete for impact category 'Fresh water ecotoxicity'. Fresh water ecotoxicity is expressed in Comparative Toxicity Unit for humans for the equivalent of polluted water in m^3*year, in line with the units dictated by the Product Environmental Footprint characterisation family, developed by the Institute for Environment and Sustainability for European Commission.*

Figure 23 depicts the results for MFR. It shows that both recycling methods perform similar in this category. However, primary concrete has nearly double the impact of recycled concrete.

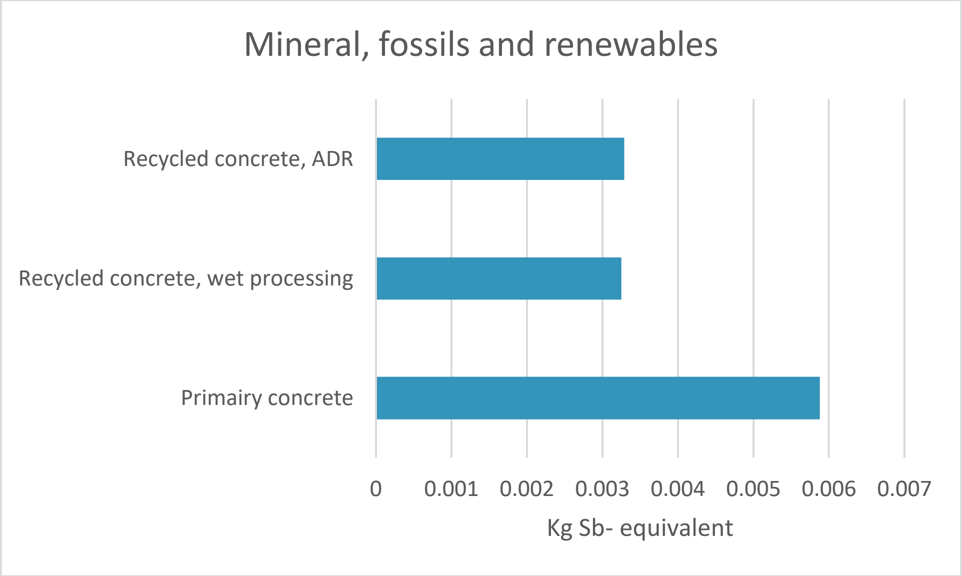


Figure 23. LCA results for the production of 1m^3 primary and recycled concrete for impact category 'Mineral, fossils and renewables'. Mineral, fossils and renewables is expressed in kg antimony(Sb) equivalent, in line with the units dictated by the Product Environmental Footprint characterisation family, developed by the Institute for Environment and Sustainability for European Commission.

In the results of Table 8 the concrete rubble for recycling is transported over a distance of 50 km. Any possible deviation of this distance based on environmental impact is calculated using Equation 2. The results of this calculation are depicted in Appendix III-B. The results show that there is a great difference based on the indicator one considers. For example, looking at wet processed recycled concrete, the results range from a reduction of distance of approximately 600km to an addition of approximately 225km compared to the status quo. On average the transport by barge for wet processed recycled concrete and by truck for advanced dry recycled concrete have to be reduced significantly. However, when transporting wet processed recycled concrete by truck the distance can be increased by an average of approximately 4.69km, or 36.1km if 'non-carcinogenic effects' are disregarded. Recycled concrete from advanced dry recycling, transported by barge, can be transported an additional 147km on average.

Table 9 shows the results for GWP, FET and MFR. The results for FET wet processed recycling and for GWP advanced dry recycling have negative values for the difference and additional kilometres of transport. This corresponds with Figure 21 and Figure 22, that show that the impact for those recycling methods are bigger than the impact of primary concrete. This means that based on these categories recycled concrete should be transported less than 50km.

However, the difference in impact between primary concrete and wet processed recycled concrete based on FET cannot be negated by decreasing transport. The results show that the transported distance should be decreased by 607 km by truck, which is more than the 50km it is being transported. Thus to decrease the impact of this recycling method on FET, additional measures should be taken.

Table 9. Calculations of geographical scale based on environmental impact for recycling of concrete.

Indicator	**Difference (δI)**		**transport impact (t)**		**Unit**	**# additional km/m^3 concrete (x)**			
						truck		barge	
	wet processed	Advanced dry rec.	truck	barge		wet processed	Advanced dry rec.	wet processed	Advanced dry rec.
GWP	7.00E+00	-1.10E+01	3.06E-01	1.15E-01	kg CO2-Eq	2.29E+01	-3.59E+01	6.09E+01	-9.57E+01
FET	-1.07E+03	1.40E+02	1.77E+00	2.89E-01	CTUh.m3.yr	-6.07E+02	7.91E+01	-3.72E+03	4.84E+02
MFR	2.63E-03	2.59E-03	2.11E-05	8.71E-07	kg Sb-Eq	1.25E+02	1.23E+02	3.02E+03	2.97E+03

The indicator that will be used to develop further scenarios is 'global warming potential'. For this indicator, the results show that recycled concrete using advanced dry recycling should only be transported 14km. However, wet processed recycled concrete can be transported up to approximately 70km by truck and 110 by barge.

Sensitivity analysis

The first sensitivity analysis is based on the emission type of the truck used to transport the concrete rubble. EURO4 trucks are compared with the previously reviewed EURO5 trucks. The complete results of the sensitivity analysis based on truck type can be found in Appendix III-C. Table 10 shows the results for GWP, FET and MFR. From these results it is visible that usage of trucks with a lower environmental standard does not significantly change the outcomes. The table shows the difference between the possible additional kilometres a cubic meter of concrete can be transported based on the EURO5 and EURO4 emission standards for trucks. The results show that the difference stays well below 5% for these categories. For GWP it is only 0.65%, thus the emission standard of the trucks used are not of considerable impact on the results of this study.

Table 10. Sensitivity analysis based on EURO emission standard for trucks. Comparing the results of EURO5 trucks with EURO4 trucks for concrete.

Indicator	**transport impact (t)**		**Unit**	**# additional km/m^3 concrete (x)**				**difference EURO5 vs. EURO4 truck**	
				EURO5		EURO4			
	EURO5	EURO4		wet processed	Advanced dry rec.	wet processed	Advanced dry rec.	wet processed	Advanced dry rec.
GWP	3.06E-01	3.08E-01	kg CO2-Eq	2.29E+01	-3.59E+01	2.27E+01	-3.57E+01	0.65%	0.65%
FET	1.77E+00	1.80E+00	CTUh.m3.yr	-6.07E+02	7.91E+01	-5.97E+02	7.78E+01	1.67%	1.67%
MFR	2.11E-05	2.17E-05	kg Sb-Eq	1.25E+02	1.23E+02	1.21E+02	1.19E+02	2.76%	2.76%

The second sensitivity analysis is based on the amount of recycled content in the produced concrete. Current recycled concretes contain 30 to 50 percent recycled coarse aggregate. In this analysis the results for concrete with 30% recycled coarse aggregate are compared to the results of the previously assessed concrete with 50% recycled coarse aggregate. The results for all categories can be found in Appendix III-D. Table 11 shows the results for the difference in potential additional kilometres of transport for GWP, FET and MFR. From these results it is apparent that the analysis is highly sensitive to changes in composition. The change in the composition of the material results in a difference in possible additional kilometres of at least 85 percent. However, from 50 to 30 percent recycled content is a big jump. Therefore, an additional analysis is carried out for a 5 percent difference in composition. The last two columns in Table 11 show the results for GWP, FET and MFR for 45% recycled coarse aggregate, compared to 50% recycled coarse aggregate. This shows that even for a 5% change in composition the difference in results are considerable, especially for GWP. The full results are also shown in Appendix III-D.

Table 11. Sensitivity analysis based on composition of recycled concrete: 50% RCA vs 30% RCA and 50% RCA vs 45% RCA.

Indicator	**Difference 50% vs 30% RCA**		**Difference 50% vs 45% RCA**	
	Wet processing	Advanced dry rec.	Wet processing	Advanced dry rec.
GWP	84.58%	109.36%	42.86%	36.36%
FET	100.05%	99.06%	12.10%	4.29%
MFR	69118.00%	69540.19%	0.00%	0.39%

3.4.2 LCA results for Copper

In this section the functional unit and flow diagrams for the life cycle assessment of recycled and primary copper are presented, followed by the results of the LCA and sensitivity analyses.

The functional unit for copper is the production of one kilogram of copper. The assessed alternatives are: primary copper and recycled copper. The recycling process for copper is based on electrolytic refining of copper scrap and includes all steps from copper scrap to recycled copper. The reference flows for each alternative are listed in Table 12.

Table 12. Reference flows of LCA for copper production.

Product	**Reference flow**
Primary copper	Production of 1 kg copper from primary sourced materials
Recycled copper	Production of 1 kg copper from copper scrap

The flow diagrams of primary produced copper and recycled copper are shown in Figure 24 and Figure 25. The LCA's are conducted using the CMLCA software. The processes used to model the production of primary and recycled copper are both based on EcoInvent 3.4 processes.

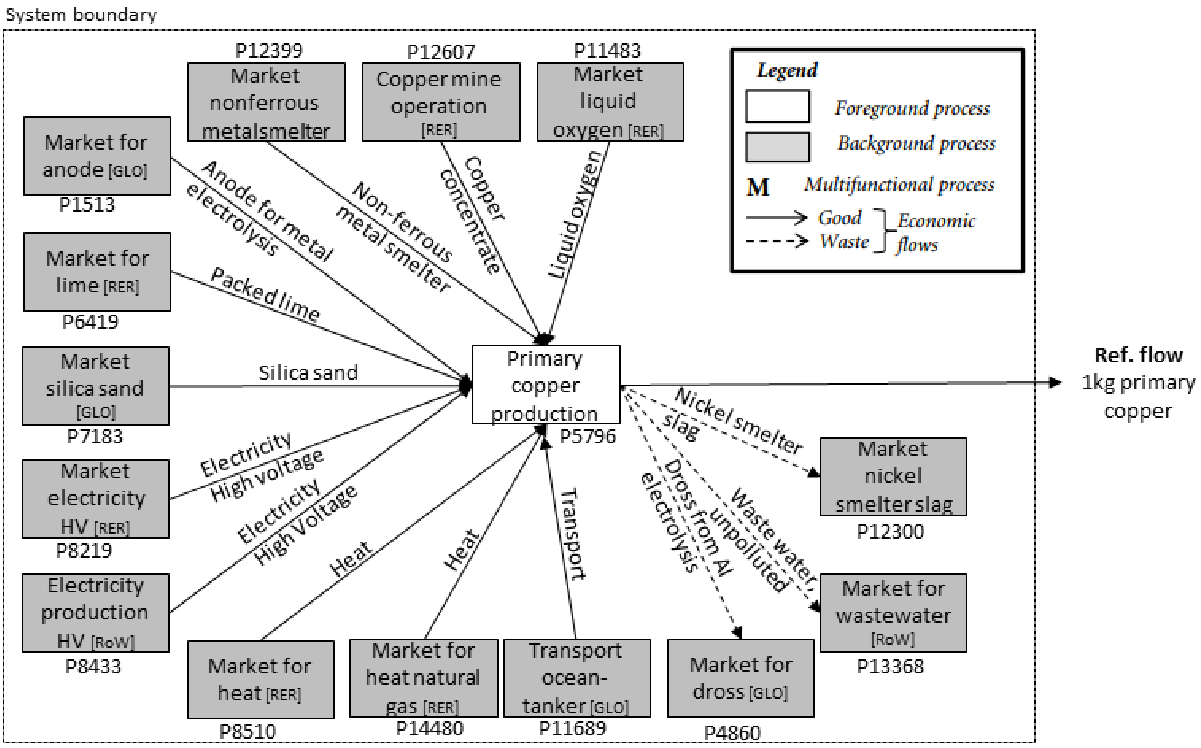


Figure 24. Flow diagram of primary copper, based on the EcoInvent 3.4 process for primary copper production in the RER .

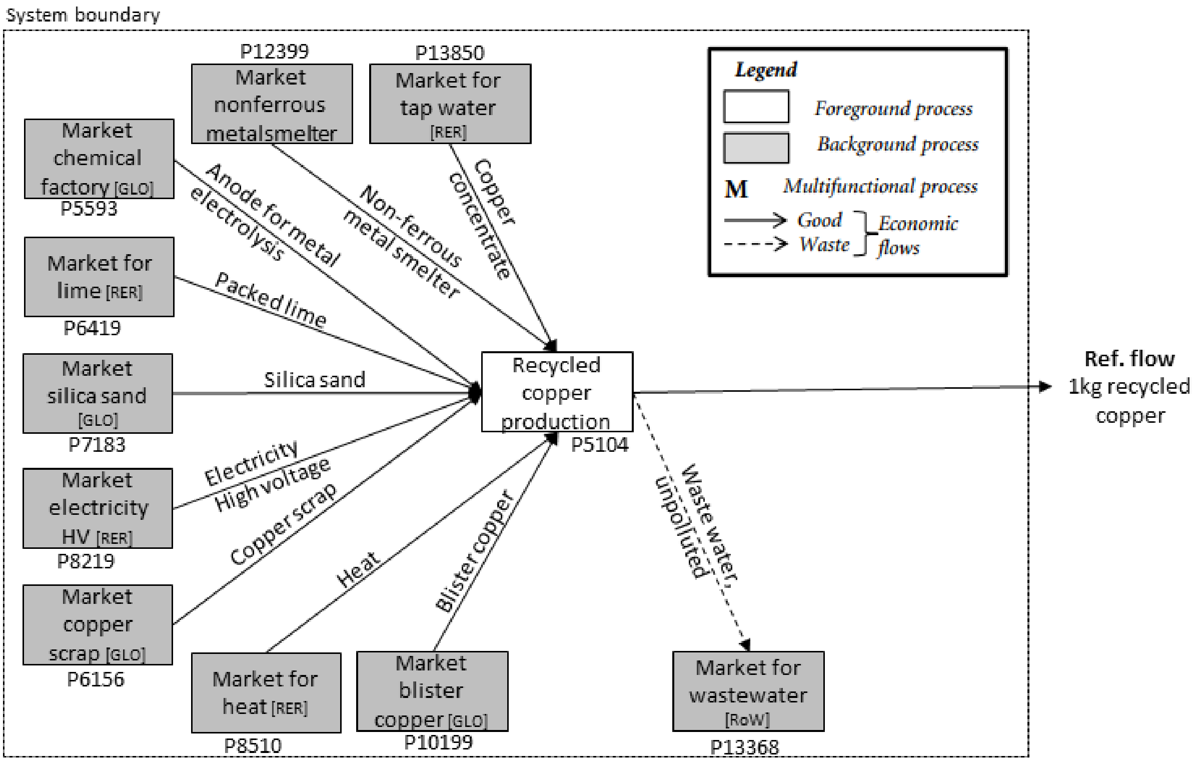


Figure 25. Flow diagram of recycled copper, based on the EcoInvent 3.4 process for copper scrap treatment using electrolysis in the RER.

LCA results for copper

The results per impact category for the production of copper are shown in Table 13. The results show that Recycled copper has less environmental impact in all categories except 'ionising radiation'. However, the difference is small in this category. Recycled copper has a significantly smaller impact on all other midpoint indicators related to ecosystem quality and most midpoint indicators related to human health. The 'global warming potential' only shows a decrease of approximately 15% compared to primary copper.

Table 13. LCA results for copper production for 14 indicators, based on Product Environmental Footprint family developed by the Institute for Environment and Sustainability for European Commission.

Indicator	**Primary copper**	**Recycled copper**	**Unit**
GWP	2.13E+00	1.58E+00	kg CO2-Eq
FTA	8.24E-02	2.53E-02	mol H+-Eq
FET	9.19E+02	5.20E+02	CTUh.m3.yr
FE	2.30E-02	1.34E-02	kg P-Eq
IR	9.66E-07	8.51E-07	mol N-Eq
ME	2.14E-01	3.82E-03	kg N-Eq
TE	1.17E-01	4.43E-02	mol N-Eq
CE	1.55E-06	8.49E-07	CTUh
NCE	4.10E-05	2.81E-05	CTUh
OLD	2.09E-07	1.11E-07	kg CFC-11-Eq
POC	2.57E-02	0.00963	kg ethylene-Eq
REI	7.53E-03	0.00266	kg PM2.5-Eq
LU	2.22E+01	7.31E+00	kg Soil Organic Carbon
MFR	4.06E-03	0.000574	kg Sb-Eq

Figure 26, Figure 27 and Figure 28 show three impact categories for primary and recycled copper. These categories are 'Global warming potential' (GWP), since it is the focus of the research, and 'Freshwater ecotoxicity' (FET) and 'Mineral, fossil and renewables' (MFR), since these are the categories with the highest normalised impact for copper production and the transportation of 1 kg of copper per tkm. In other words, transport will have the most effect on those last two categories. A table with the results and normalised results for all indicators for copper production can be found in Appendix IV-A.

Figure 26 shows a clear difference between the impact of recycled copper compared to the impact of primary sourced copper in terms of CO_2 equivalent. However, the difference is only 0.55 kg CO_2 equivalent.

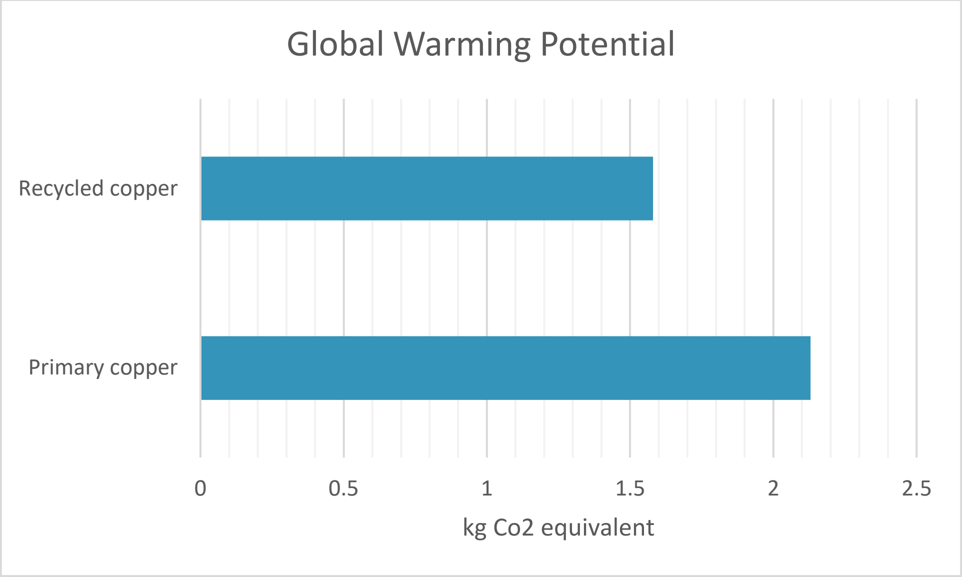


Figure 26. LCA results for the production of 1kg primary and recycled copper for impact category 'Global warming potential'. Global warming potential is expressed in kg CO_2 equivalent, in line with the units dictated by the Product Environmental Footprint characterisation family, developed by the Institute for Environment and Sustainability for European Commission.

From Figure 27 can be seen that primary copper has almost the double the impact of recycled copper on fresh water ecotoxicity.

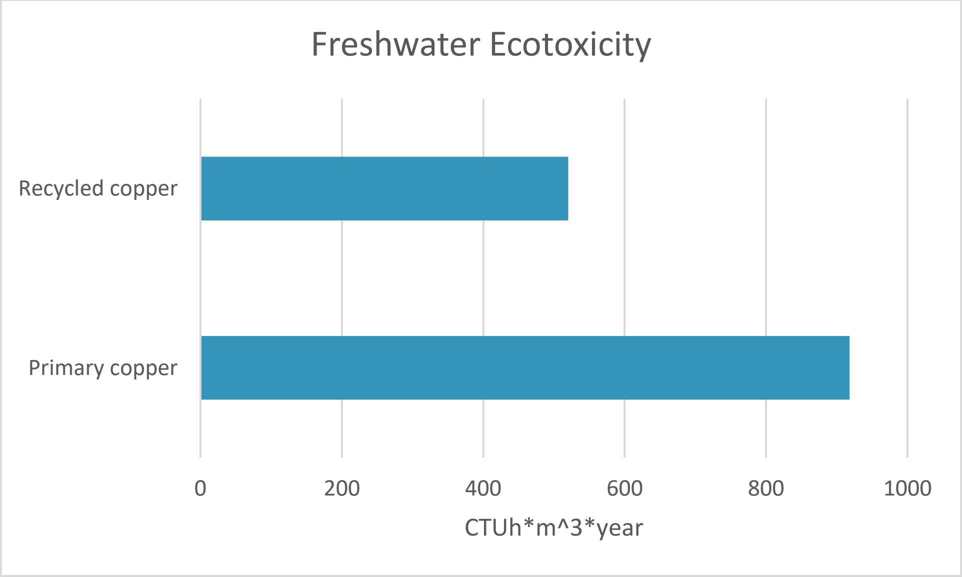


*Figure 27. LCA results for the production of 1kg primary and recycled copper for impact category 'Fresh water ecotoxicity'. Fresh water ecotoxicity is expressed in Comparative Toxicity Unit for humans for the equivalent of polluted water in m^3*year, in line with the units dictated by the Product Environmental Footprint characterisation family, developed by the Institute for Environment and Sustainability for European Commission.*

Figure 28 depicts the results for MFR. This category shows the biggest relative difference between recycled and primary copper. Primary copper has 7 times the impact of recycled copper on this category.

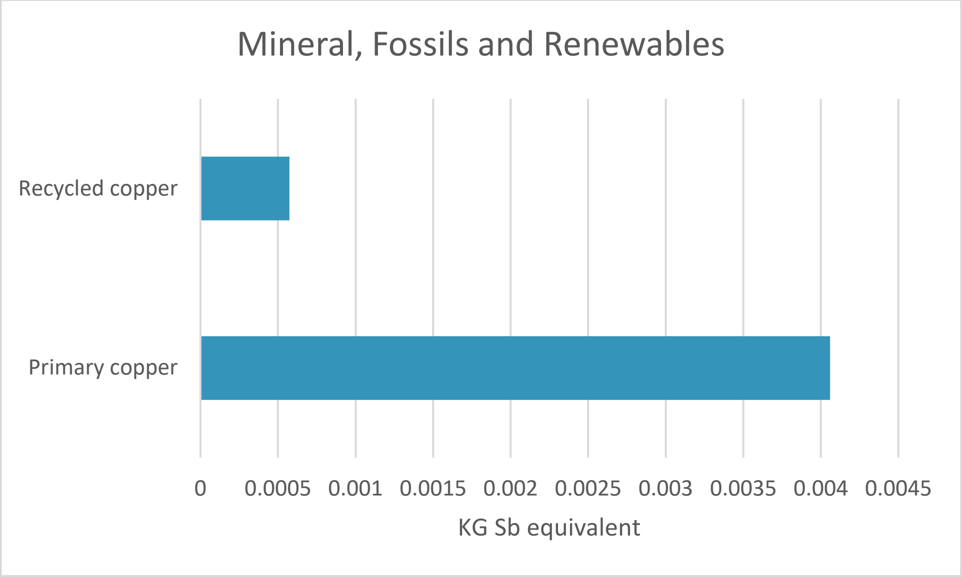


Figure 28. LCA results for the production of 1kg primary and recycled copper for impact category 'Mineral, fossils and renewables'. Mineral, fossils and renewables is expressed in kg antimony(Sb) equivalent, in line with the units dictated by the Product Environmental Footprint characterisation family, developed by the Institute for Environment and Sustainability for European Commission.

Using equation 2 the upper limit based on environmental impacts is calculated. The results are shown in Table 14 for GWP, FET and MFR, the results for other categories can be found in Appendix IV-B. Since the results of Table 13 don't include impacts caused by transport from the demolition/harvesting site to the recycling plant, the results shown in Table 14 show the total distance scrap copper can be transported for recycling.

The results show, scrap copper can be transported over great distances for all categories when compared to primary sourced copper. By truck, scrap copper can be transported from almost 2000km up to over 1.3 million km, depending on the category. For transport by barge, this ranges from approximately 5900km up to just under 9.6 million km. For reference, this upper limit is almost 240 times around the earth. On average scrap copper can be transported approximately 0.3 million km by truck and 1.4 million km by barge, before it has a higher environmental impact than primary sourced copper. Naturally, these distances are also limited by practical matters, such as available roads and waterways.

When focussing on 'global warming potential', scrap copper can be transported 4330km by truck and 11500km by barge.

Table 14. Calculations of geographical scale based on environmental impact for recycling of copper.

Indicator	**Difference (δI)**	**Transport impact (t)**		**Unit**	**# additional km/kg copper (x)**	
		truck	barge		truck	barge
GWP	5.50E-01	1.27E-04	4.80E-05	kg CO2-Eq	4.33E+03	1.15E+04
FET	3.99E+02	5.33E-07	4.79E-07	mol H+-Eq	5.41E+05	3.33E+06
MFR	3.49E-03	8.77E-09	3.63E-10	kg Sb-Eq	3.97E+05	9.60E+06

Sensitivity analysis

The first sensitivity analysis is based on the emission type of the truck used to transport the scrap copper. EURO4 trucks are compared with the previously reviewed EURO5 trucks. The complete results of the sensitivity analysis based on truck type can be found in Appendix IV-C. Table 15 shows the results for GWP, FET and MFR. The results clearly indicate that the emission standard of the used truck does not have a significant impact on the results of this study. Again, the change stays well below 5 percent and the change for GWP is only 0.78%.

Table 15. Sensitivity analysis based on EURO emission standard for trucks. Comparing the results of EURO5 trucks with EURO4 trucks for copper.

Indicator	**transport impact (t)**		**Unit**	**# additional km/kg copper (x)**		**Difference EURO5 vs EURO4**
	EURO5	EURO4		EURO5	EURO4	
GWP	1.27E-04	1.28E-04	kg CO2-Eq	4.33E+03	1.95E+03	0.78%
FET	7.38E-04	7.50E-04	CTUh.m3.yr	5.41E+05	5.31E+05	1.60%
MFR	8.77E-09	9.03E-09	kg Sb-Eq	3.97E+05	3.86E+05	2.88%

The second sensitivity analysis is based on the composition of the recycled copper. The copper recycling process that is considered in this research uses 92% recycled content. This is compared to a situation in which 87% recycled content is used. Results for all impact categories can be found in Appendix IV-D. The results highly vary between the different categories, as can be seen in Table 16. For example in MFR there is only a change of approximately 9%, whereas for GWP this is 92%. Again, composition of the recycled material has a big impact on the results of this research.

Table 16. Sensitivity analysis based on composition of recycled copper: 92% recycled content vs 87% recycled content.

Indicator	**# additional km/kg copper**		**difference 92% vs 87% recycled content**
	92%	87%	
GWP	1.97E+03	1.57E+02	92.00%
FET	5.39E+05	1.15E+05	78.64%
MFR	3.97E+05	3.61E+05	9.15%

4. Discussion & Conclusion

In the following sections several aspects of the research are discussed and the results are related to overarching themes of circular economy and local versus global production, as described in section 1.3. Subsequently, the limitations of the research, recommendations for academia and recommendations for the municipality of Leiden are discussed. Finally, the chapter concludes with the overall conclusions of the research.

4.1 Discussion of the framework

The research addresses the lack of a defined optimal geographical scale for resupply chains within a circular economy. It does so by proposing a framework that offers insights in the maximum scale for various materials. The framework consists of the analysis of two factors that influence the geographical scale of resupply chains: a crude cost benefit analysis for the economic factor and a life cycle assessment to calculate the impact on climate change (CO_2 equivalent) for the environmental factor. Based on the outcomes of these analyses maximum distances are calculated. The framework is applied to two materials from the construction and demolition sector of the municipality of Leiden as a case study: concrete and copper. For concrete this results in a maximum geographical scale of 72.9km if transported by truck and 130.9km if transported by barge, for wet processed recycled concrete. Interesting to note is that advanced dry recycled concrete can only be transported 14km and is thus in current practices outperformed by primary concrete in terms of impact on climate change. For concrete the limiting factor is the environmental impact, not the cost. Based on the cost the rubble can be transported over a distance of 160km. For copper the economic and environmental factor both do not seem to be limiting. Based on cost scrap copper can be transported up to 123000km. Based on the environmental factor, copper scrap can be transported 4330km by truck and 11500km by barge. The latter is clearly limited by the availability of inland waterways.

4.1.1 Discussion of the results

For concrete the framework results in clear boundaries that can be applied in practice. The concrete rubble can be transported slightly further than currently is the practice. Most of the infrastructure related to the maximum geographical scale is already in place. The biggest constraint in the resupply of concrete is the limited distance the recycled concrete can be transported before it sets. To overcome this hurdle a change in infrastructure is needed: either by separating the recycling process of the concrete rubble to aggregates from the mixing process, or by adapting more on site mixing methods, such as the use of mobile mixing plants. This does ask for a change in mindset of the industry. Furthermore, the results for concrete show that the recycling method has a big impact on the results. The wet processing resulted in a considerably lower impact than the advanced dry recycling. This makes the development and adoption of new and potentially even better performing methods interesting. One of the companies working on such a new method is the Rutte Groep. Based on the results of their own environmental impact assessments, concrete rubble could be transported as far as 570km. This makes their techniques very promising. In conclusion the results for concrete give a positive outlook on the current practices, since the industry operates within the geographical limits.

For copper the results are less practical. The distance of 12300km, based on the cost, is not realistic by road based or inland waterway transport. Thus, when looking into this geographical scale a different mode of transportation should be assessed. The geographical scale based on environmental impact has more practical relevance. It shows that copper can be transported throughout Europe, North Africa and even to parts of Russia and the Middle East by road transport. By inland waterways or train copper can be transported around the whole world with the exception of Oceania and parts of Southeast Asia and South America. A clear limitation is the availability, or lack thereof, of inland waterways and train tracks from the Netherlands to these parts of the world. It also raises the question whether barge is a fitting transportation mode for copper, since it is usually for the transport of bulk materials. By transoceanic tanker it can be transported twice around the world. Only for transport by aircraft the distance is relatively small: 327-509km. Within this radius the Netherlands, Belgium, Luxembourg and parts of France and Germany are accessible. This makes it an inconvenient way for transporting copper scrap. A general limitation for the transport of copper scrap over large distances is formed by European regulations on the export of waste and scrap metal, as described in section 1.5.3. For copper the framework also has a positive outlook, since the general practices operate well within the proposed maximum limits. In addition, all the infrastructure is in place to fully operate within these geographical limits. It would be interesting to find out what currently is the determining factor for the geographical scale of the copper resupply chain. This could be done by assessing additional factors, such as supply chain security and value retention.

In general, the results showcase the potential of the framework. It offers a clear maximum geographical boundary, for the recycling of materials. With that it provides substantiated argumentation for a certain geographical scale for recycling. This can be used by decisionmakers in planning and regulations and by academia as a base for future research in the field of circularity. Furthermore, it indicates some interesting aspects of the different types of materials. For example, environmental and economic aspects don't seem to be limiting factors for copper, whereas the environmental aspect really limits the geographical scale for concrete. It also shows that, to be more practically applicable for a material such as copper, more factors can be included in the framework.

4.1.2 Applicability of the framework

The application of the framework in this research results in a clear indication of the maximum distance that waste materials can be transported to be recycled, based on global warming potential and cost. Even though the framework is not very sensitive to small changes in emissions from transport (by using trucks with lower emission standards), it is sensitive to small changes in composition of the recycled material. Therefore, the results are not easily generalisable to all types of recycled concrete or copper and various analyses need to be done for various material compositions. This also implies that the results for concrete are not generalisable for other stony materials and for copper not generalisable for other non-ferrous metals. The results of the framework could be used by government agencies to aid in decision making around new policies or spatial planning. For example, policies around sourcing of materials and the promotion of circular practices. However, this also implicates that higher tiers of government agencies, such as nationals and European agencies could do more with the results. Companies could use the framework as a tool to determine where to source their recycled materials from and recyclers could use the framework to determine where to locate new facilities.

Users of the results need to be advised on its limitations and the current lack of generalisability to other materials. Lastly, they should be aware that the framework focusses on the distance that waste materials can be transported over before recycling, but does not indicate the distance over which the recycled material can be resupplied or transported for further manufacturing into consumer products.

Furthermore, the used methods within the framework provide the upper limit of transport of waste materials to a recycling facility. When this limit is exceeded, the recycled material has a higher global warming potential than the primary sourced alternative. Caution is warranted when using the framework, because the upper limit is optimising for global warming potential related to sourcing of primary materials. Therefore, if this maximum would always be utilised, overall impact will not decrease, but remain the same.

4.2 Framework in relation to circularity

The results of the research show that waste materials can be transported over bigger distances than currently happens. This implies that material loops can be bigger. However, it is dependent on material properties whether the resupply distance of the recycled material to the location of use can also be increased. For example, the supply distance of concrete is limited by the drying time of the concrete to approximately 30km (Van den Berghe and Verhage, 2021). This raises the question how to approach circularity. A closed material loop implies that a material has to be transported the same distance both ways, to be used at approximately the same location. However, if a less strict view of circularity is taken in to account, this opens up the possibility to reuse a material in a different location and on a different distance from the harvesting/demolition site. This could translate into separate recycling and mixing facilities or mobile concrete mixing facilities. However, this asks for additional analysis of the environmental impact of these production processes and possible additional cost.

When the definition of a circular economy as stated by the European Commission is regarded, there is room for less literal views on circularity. As stated in section 1.3.1, the European Commission defines a circular economy as “an economy where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste minimized” (Eurostat, 2019). This thus leaves room for the resupply to different locations than the harvesting location. The framework fits well with this definition of circularity.

In addition, circularity is currently restricted for some materials by regulations and safety standards. For example, KOMO regulations limit the maximum recycled content in concrete. This calls for an active approach in reviewing and updating such standards, so circularity gets increasingly encouraged. The ‘betonakkoord’, described in section 1.5.2, will likely accelerate this, together with front runner companies that are already experimenting with recycled concretes with a higher recycled content.

4.3 Framework as addition to local vs global production debate

In terms of the debate around the sustainability of local production versus global production, the framework can add substantiated arguments for certain scales. The results of the framework also show that this scale is highly material dependent. The two materials that are considered here are a good example: copper can be transported 30-50 times further than concrete based on environmental impact and over 160 times further based on the cost calculations.

Furthermore, the framework and this research can serve as a starting point for the debate to broaden from food production to material production and recycling more generally. Previous research by Schmitt et al. (2017) and Kreidenweis, Lautenbach and Koellner (2016) indicates that for food production often global production is better in terms of CO_2 footprint and cost. The results of this research indicate that this is not the case for the recycling of materials. At least for the recycling of concrete and copper there is a clear upper limit for the geographical scale. For concrete the scale is not global. The maximum scale for concrete recycling would be local. However, for copper the scale is regional by aircraft and truck and global for transport by barge, train and transoceanic tanker. Previous research also indicates that the results change based on the indicators used (Schmitt et al., 2017). This has yet to be verified for the recycling of materials.

Finally, the framework in its current form only indicates an upper limit for the geographical scale. The results thus provide reasons why certain material loops should not be closed on a global scale, but it does not provide reasoning on how local the loops should be closed. To add more substantiated arguments for how small a material loop can be, a lower limit should be added to the framework.

4.4 Limitations of the research

There are some additional limitations of the research to consider. These are described below.

Within the current research, the framework is based on two factors. These factors were chosen based on assumptions about the municipality of Leiden. Choosing or adding different factors could alter the outcomes or add a deeper understanding of what relevant geographical scales are for closing material loops. On top of that the environmental factor is now only based on the global warming potential, but this indicator is just one of myriad indicators that measure the impact of products and processes on our environment and the results show that other indicators give vastly different results. Singling out another indicator will give different end results, as can be seen in the comparison with the results for ‘Fresh water ecotoxicity’ and ‘Mineral, fossil and renewables’. The results of this research are thus not an absolute representation of the environmental impact of the assessed materials. Therefore, more indicators should be assessed or a different one could be chosen.

This also translates to more detailed level: the framework in its current form does not take recycling efficiency into account. For example, the recycling of concrete using wet processing has a lower global warming potential and is thus favoured by the framework. Whereas the recycling of concrete using advanced dry recycling has a higher recycling efficiency. In addition, the framework does not review the quality of a recycling process. Some materials, such as plastics, can only be recycled for a certain amount of times, due to the loss of quality. These are aspects that are relevant for a circular economy in which the goal is to minimise waste and environmental impact, but that are not incorporated in the framework.

Most information about the recycling processes of concrete were only corroborated by one company. Furthermore, the data used in the LCA and cost analysis for concrete are mostly based on one source. This may have created a slight bias towards the practices of this company or based on the data from the used research. The data used for copper couldn't be corroborated by companies, since none of the approached companies replied. Also, the data used for the calculation of geographical scale based on cost are based on a lot of assumptions, due to a lack of available data. For future research it is recommended to verify and improve upon the data used in this research. Furthermore, current cost analyses are very crude. To give a better, more refined result a proper cost-benefit analysis should be carried out. However, the used data do give a good indication of the functionality of the framework.

In the current form of the framework, a negative difference in environmental impact is compensated for by decreasing transport. In other words, if the recycled material has a higher impact than primary sourced materials, the difference is minimised by decreasing the distance over which a waste material is transported. However, there are clear limitations to how much the transport can be decreased, based on the initial distance the waste is transported, 50km for concrete in this research, for example. Other ways of decreasing the impact of a recycled material should thus also be considered when trying to decrease its impact, but that is beyond the scope of this thesis.

The depictions of the area that can be reached are now based on a starting point in the city centre of Leiden and a certain radius from there. This does not correspond with the actual area that can be reached by travelling said distance over road or waterways. Therefore, the depicted areas can deviate from the actual area. Especially the waterway network imposes limitations on the areas that can be reached, since it is not as vast and widely available as the road network. Furthermore, changing the starting point will obviously change the relevant area. However, the figures serve illustrative purposes and give an indication of the outcomes of the framework.

4.5 Recommendations

The recommendations are split into two sections: first the recommendations for future research and second the recommendations for the municipality of Leiden on how to use the results of this research.

4.5.1 Recommendations for academia

There are myriad options and recommendations for future research and improvements on the current framework. However, I would suggest starting with the following:

First of all, corroborate the current framework and look deeper into additional relevant factors, such as socio economic and social aspects, and supply chain security. For new factors, meaningful methods need to be determined to translate the factor into a distance. Second, apply the framework to more materials and material classes to create a database and to determine whether there are some generalisable results based on certain material properties. This research has focussed on the construction and demolition sector, but the applicability of the framework should be tested for materials from other sectors as well. Finally, to truly define an optimal geographical scale, a lower geographical limit should also be determined. In other words, when is a resupply chain too small? This requires additional research and would be very valuable to add to the framework. Future research could look into finding a lower limit based on environmental impacts, effects of economy of scale and the volume of supply and demand of materials.

One way to incorporate a minimum distance is to reason from the perspective of a recycling facility: First determine how much material in and output a recycling facility needs to be economically feasible and to produce a consistent and reliable output. Then, the available waste streams have to be analysed: how much waste is produced in the nearby region. How big is the region that is needed to provide the recycling facility with enough input for a stable operation? This will lead to a minimal feasible geographical scale for the recycling of materials based on monetary factors and supply and demand. Environmental factors related to economies of scale could also be assessed. Additional factors that can influence the minimum scale are the demands for the output of a recycling facility and political and social/community support. For example if a town or neighbourhood opposes a recycling facility in their midst due to noise or smell disturbances, this can limit the possibilities to build such facilities on very local scales.

4.5.2 Recommendations for municipality of Leiden

For the municipality of Leiden, I would recommend to use the framework and its results for two purposes: enhancing and creating regulations and initiatives such as ‘circulair sloopbeleid’ (circular demolition policy) and to use the results for decision making in spatial planning. The framework currently consists of two factors that influence the geographical scale of material resupply chains. By calculating the maximum distance based on those factors, a maximum geographical scale for a material can be determined.

For example, the circular demolition policy could be complemented with indications of the maximum distances that waste materials can be transported over to the recycling plant. In other words, it could state that to satisfy the circular demands, concrete rubble cannot be transported further than 70km from the demolition site. This process should then be repeated for more materials. This helps to keep emissions from recycling low and adds to the sustainability goals of the municipality.

The framework can help in decisions around spatial planning by giving insight in what acceptable distances are for recycling facilities to be located from the city. Based on these distances and the existing infrastructure, the framework will give insights in whether or not more recycling facilities need to be realised. When more facilities need to be realised, the municipality can plan accordingly and reserve or assign areas for this purpose. When deciding whether there are enough facilities within the geographical scale, also the capacity of the evaluated facilities need to be taken into account.

Depending on what factors are taken into account within the framework, it could also be used in combination with certain specific goals. For example, if the municipality has specific goals for the permissible CO_2 emissions or impact on freshwater ecotoxicity, the framework could be used to determine relevant geographical scales that comply with these goals. This could also be done for factors that are currently not included, such as socio-economic factors.

Furthermore, the municipality can use the results of the framework to encourage more collaboration within and with relevant regions in the Netherlands. Also, the framework could prove useful for other government agencies that work on regulations and spatial planning related to recycling and circularity, especially since most data used is for the Netherlands and not specific to the municipality of Leiden.

4.6 Conclusion

In conclusion, the framework presented in this research has proven to be successful in determining the maximum geographical scale a waste material can be transported for recycling, based on environmental and economic factors.

The analysis of the environmental factor is based on an LCA. The results of the LCA show that both concrete and copper in this case study can be transported further then they currently are. However, the analysis is sensitive to changes in the percentage of recycled content in the produced material. Also, for concrete the results really depend on the recycling process that is used. Thus, the results are not generalisable. The analysis of the economic factor is based on cost and proceeds. It indicates for both materials that this is currently not the limiting factor for geographical scale, with a maximum transport distance of 170km for concrete and 12300km for copper. However, this factor can strongly fluctuate due to hikes in energy and transport prices.

The framework resulted in an upper limit of 72.9km for the transport of concrete rubble to the recycling plant and 110.9km by barge. This is only for wet processed recycled concrete. The results for advanced dry recycling indicate that for this method concrete rubble can only be transported 14km. Note that concrete is limited by the distance freshly mixed concrete can be transported before it cures. This showcases that determining a relevant geographical scale for recycling also needs to review the distribution side of the recycled material or ways to overcome material specific hurdles. For copper scrap the upper limit of transport to the recycling facility is 4330km by road transport and 11500km by barge.

From the framework it can thus be concluded that the current general practices are well within the upper limits calculated. In general, the framework has the potential to help decision making for specific materials on the geographical scale of the recycling process.

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Appendix I – Results address scraper

A. Results for concrete

title	categories	address	location/lat	location/lng	scrapedAt	searchString
Gamma	Hardware store	Driemanssteeweg 120, 3084 CB Rotterdam, Netherlands	51.8649078	4.4598417	2022-06-28T10:49:20.092Z	concrete recycling Zuid Holland
HORNBACH Bouwmarkt Den Haag	Home improvement store	Singel 115, 2497 GS Den Haag, Netherlands	52.0289138	4.3595069	2022-06-28T10:49:29.947Z	concrete recycling Zuid Holland
HORNBACH Bouwmarkt Wateringen	Home improvement store	's-Gravenzandseweg 71-72, 2291 PE Wateringen, Netherlands	52.0170837	4.2759025	2022-06-28T10:49:37.212Z	concrete recycling Zuid Holland
Praxis Bouwmarkt	Building materials store	Laan van 's-Gravenmade 81, 2495 BD Den Haag, Netherlands	52.0498683	4.3562667	2022-06-28T10:49:44.106Z	concrete recycling Zuid Holland
Praxis Bouwmarkt Delft	Building materials store	Rijnweg 1, 2627 BR Delft, Netherlands	51.9959747	4.3660179	2022-06-28T10:49:52.310Z	concrete recycling Zuid Holland
KARWEI construction Hillegom	Home improvement store	Satellietbaan 14, 2181 MH Hillegom, Netherlands	52.3010104	4.5882994	2022-06-28T10:50:01.502Z	concrete recycling Zuid Holland
KARWEI	Home improvement store	Walserij 101, 2211 SL Noordwijkerhout, Netherlands	52.247774	4.492873	2022-06-28T10:50:08.571Z	concrete recycling Zuid Holland
KARWEI	Home improvement store	Uitenhagestraat 87, 2571 PV Den Haag, Netherlands	52.0694685	4.2938672	2022-06-28T10:50:18.028Z	concrete recycling Zuid Holland
Intratuin Rhoon	Garden center	Stationsstraat 5, 3161 GH Rhoon, Netherlands	51.86411	4.4291894	2022-06-28T10:50:26.315Z	concrete recycling Zuid Holland
Karwei bouwmarkt Katwijk aan Zee	Home improvement store	Ambachtsweg 19, 2222 AH Katwijk aan Zee, Netherlands	52.199572	4.433115	2022-06-28T10:50:33.961Z	concrete recycling Zuid Holland
KARWEI	Home improvement store	Van Foreestlaan 2, 2404 HC Alphen aan den Rijn, Netherlands	52.1365228	4.6487389	2022-06-28T10:50:40.662Z	concrete recycling Zuid Holland
KARWEI	Home improvement store	Burgemeester Keijzerweg 24, 3352 AR Papendrecht, Netherlands	51.8447302	4.6824456	2022-06-28T10:50:48.074Z	concrete recycling Zuid Holland
Praxis Bouwmarkt Spijkenisse	Building materials store	Morseweg 2, 3208 KX Spijkenisse, Netherlands	51.8506605	4.3047108	2022-06-28T10:50:54.773Z	concrete recycling Zuid Holland
KARWEI	Home improvement store	Noordeinde 200, 3341 LW Hendrik-Ido-Ambacht, Netherlands	51.8461328	4.6566003	2022-06-28T10:51:01.989Z	concrete recycling Zuid Holland
Hoveniersbedrijf J. van Stijn Tuinverzorging	Landscaper	Burgemeester Hendrixstraat 37, 2651 JS Berkel en Rodenrijs, Netherlands	52.0004663	4.4852301	2022-06-28T10:51:09.749Z	concrete recycling Zuid Holland
KARWEI	Home improvement store	IJsseldijk 361, 2922 BK Krimpen aan den IJssel, Netherlands	51.9203129	4.5856829	2022-06-28T10:51:16.726Z	concrete recycling Zuid Holland
Praxis Bouwmarkt Rotterdam Feijenoord	Building materials store	Stadionweg 31F, 3077 AP Rotterdam, Netherlands	51.8963783	4.5343276	2022-06-28T10:51:25.699Z	concrete recycling Zuid Holland
KARWEI	Building materials store	Hoofdweg 11, 2908 LB Capelle aan den IJssel, Netherlands	51.9547513	4.5706185	2022-06-28T10:51:33.586Z	concrete recycling Zuid Holland
KARWEI	Home improvement store	Marconistraat 121, 2809 PG Gouda, Netherlands	52.0047379	4.6868463	2022-06-28T10:51:40.584Z	concrete recycling Zuid Holland

KARWEI	Home improvement store	De Lasso-Zuid 21, 2371 EV Roelofarendsveen, Netherlands	52.2024574	4.6209974	2022-06-28T10:51:47.943Z	concrete recycling Zuid Holland
Bouwhof - Make your home.	Home goods store	Edisonstraat 115, 2723 RT Zoetermeer, Netherlands	52.0575485	4.5181765	2022-06-28T10:51:55.169Z	concrete recycling Zuid Holland
KARWEI	Home improvement store	Lorentzweg 4, 2991 XM Barendrecht, Netherlands	51.8679772	4.5457164	2022-06-28T10:52:02.667Z	concrete recycling Zuid Holland
Hubo bouwmarkt Delfgauw	Hardware store	Delftsestraatweg 131, 2645 AB Delfgauw, Netherlands	52.0097118	4.3957471	2022-06-28T10:52:10.203Z	concrete recycling Zuid Holland
KARWEI	Home improvement store	Vlasbaan 17, 2352 AH Leiderdorp, Netherlands	52.1636027	4.5169661	2022-06-28T10:52:18.410Z	concrete recycling Zuid Holland
KARWEI	Home improvement store	Rostock 3, 2993 LH Barendrecht, Netherlands	51.8488235	4.5097894	2022-06-28T10:52:27.480Z	concrete recycling Zuid Holland
Karwei bouwmarkt Rotterdam	Building materials store	Maashaven Zuidzijde 100, 3081 AE Rotterdam, Netherlands	51.8964976	4.4894371	2022-06-28T10:52:34.942Z	concrete recycling Zuid Holland
Gamma	Building materials store	Noorderhelling 60, 3078 HH Rotterdam, Netherlands	51.8949427	4.5333316	2022-06-28T10:52:42.987Z	concrete recycling Zuid Holland
KARWEI	Hardware store	Nieuwe Langeweg 30, 3194 DB Hoogvliet Rotterdam, Netherlands	51.8695503	4.3724278	2022-06-28T10:52:50.815Z	concrete recycling Zuid Holland
Karwei bouwmarkt Numansdorp	Home improvement store	Voltastraat 1, 3281 NG Numansdorp, Netherlands	51.7481569	4.4517312	2022-06-28T10:52:58.702Z	concrete recycling Zuid Holland
Kalkman Projecten B.V.	Machining manufacturer	Parallelweg 12, 2921 LE Krimpen aan den IJssel, Netherlands	51.9127035	4.5808582	2022-06-28T10:53:06.861Z	concrete recycling Zuid Holland
KARWEI construction Westland De Lier	Home improvement store	Leehove 7, 2678 MA De Lier, Netherlands	51.9711074	4.2255964	2022-06-28T10:53:15.683Z	concrete recycling Zuid Holland
KUIPERS Infra	Contractor	Oude Klemsedijk 1c, 3291 LL Strijen, Netherlands	51.734852	4.5122158	2022-06-28T10:53:22.996Z	concrete recycling Zuid Holland
KARWEI	Home improvement store	Importweg 2, 2645 EC Delfgauw, Netherlands	51.9970762	4.3957694	2022-06-28T10:53:32.000Z	concrete recycling Zuid Holland
Hubo	Building materials store	Woutersweg 2b, 2691 PR 's-Gravenzande, Netherlands	51.9911111	4.1680556	2022-06-28T10:53:39.178Z	concrete recycling Zuid Holland
KARWEI Building Maassluis	Home improvement store	Elektraweg 9, 3144 CB Maassluis, Netherlands	51.926016	4.2461062	2022-06-28T10:53:45.878Z	concrete recycling Zuid Holland
KARWEI	Building materials store	Berkelse Poort 1, 2651 JX Berkel en Rodenrijs, Netherlands	51.9900498	4.4746872	2022-06-28T10:53:53.264Z	concrete recycling Zuid Holland
Karwei bouwmarkt Boskoop	Building materials store	Westpark 1, 2771 RV Boskoop, Netherlands	52.0758697	4.6322144	2022-06-28T10:54:02.365Z	concrete recycling Zuid Holland
Karwei bouwmarkt Bodegraven	Home improvement store	Lemsteraak 2, 2411 NC Bodegraven, Netherlands	52.085941	4.7382531	2022-06-28T10:54:09.181Z	concrete recycling Zuid Holland
Kruiswijk Groep B.V.	Demolition contractor	Handelsweg 5, 2861 GN Bergambacht, Netherlands	51.9297752	4.793852	2022-06-28T10:54:15.762Z	concrete recycling Zuid Holland
Cementbouw Betonmortel BV - Zoeterwoude	Concrete contractor	Hoge Rijndijk 267, 2382 AN Zoeterwoude, Netherlands	52.1402579	4.5425877	2022-06-28T10:54:22.505Z	concrete recycling Zuid Holland
Demtech B.V.	Construction equipment supplier	Handelsweg 4, 2382 NG Zoeterwoude, Netherlands	52.141101	4.5219746	2022-06-28T10:54:29.857Z	concrete recycling Zuid Holland

YKMA design	Industrial design company	Bagijnhof 137, 2611 AN Delft, Netherlands	52.0136078	4.3538472	2022-06-28T10:54:37.186Z	concrete recycling Zuid Holland
Smyth Antislip	Building materials store	Edisonstraat 9c, 2723 RS Zoetermeer, Netherlands	52.0635023	4.5235324	2022-06-28T10:54:44.419Z	concrete recycling Zuid Holland
Mustang Demolition	Demolition contractor	Noordeindseweg 346a, 2651 LM Berkel en Rodenrijs, Netherlands	52.0205026	4.4851751	2022-06-28T10:54:51.601Z	concrete recycling Zuid Holland
Krommenhoek Metals b.v.	Recycling center	Keenstraat 28, 3044 CD Rotterdam, Netherlands	51.9310092	4.4206045	2022-06-28T10:54:58.180Z	concrete recycling Zuid Holland
J.K. van den Dool BV - Recycling	Garden center	Oostdorperweg 206c, 2241 BG Wassenaar, Netherlands	52.1563404	4.4058345	2022-06-28T10:55:04.666Z	concrete recycling Zuid Holland
Jansen Recycling Group BV	Recycling center	Van Leeuwenhoekweg 21, 3316 AV Dordrecht, Netherlands	51.7998483	4.636088	2022-06-28T10:55:11.767Z	concrete recycling Zuid Holland
Regionaal Sorteercentrum West B.V.	Recycling center	Waterpas 100, 2495 AT Den Haag, Netherlands	52.0607125	4.363365	2022-06-28T10:55:18.707Z	concrete recycling Zuid Holland
BERG — Ruimte Scheppen | Vestiging De Lier	Recycling center	Noord-Lierweg 42A, 2678 LV De Lier, Netherlands	51.988068	4.2499599	2022-06-28T10:55:27.759Z	concrete recycling Zuid Holland
Recycling Combination REKO B.V.	Recycling center	Vondelingenplaat 17, 3196 KL Vondelingenplaat, Netherlands	51.888702	4.332855	2022-06-28T10:55:35.964Z	concrete recycling Zuid Holland
A. Pektas	Demolition contractor		51.9227391	4.3206051	2022-06-28T10:56:42.651Z	demolition Zuid Holland
Van Gent Vloeren en Projecten	Demolition contractor		51.9274825	4.2537247	2022-06-28T10:56:48.734Z	demolition Zuid Holland
Rodibo BV Betonboringen	Demolition contractor	Bovendijk 212, 3045 PD Rotterdam, Netherlands	51.9554083	4.4511346	2022-06-28T10:56:57.619Z	demolition Zuid Holland
Krasimir Loonbedrijf	Demolition contractor		52.06713	4.2912658	2022-06-28T10:57:04.180Z	demolition Zuid Holland
Sloopbedrijf Kaya	Demolition contractor		52.0716542	4.3098684	2022-06-28T10:57:10.447Z	demolition Zuid Holland
Baran Support B.V.	Demolition contractor	Huijsmansstraat 89a, 3117 KL Schiedam, Netherlands	51.9150628	4.3893767	2022-06-28T10:57:17.181Z	demolition Zuid Holland
V.O.F. Wubben-Vollebregt, Grond- en Sloopwerken	Demolition contractor		52.0327085	4.1845998	2022-06-28T10:57:24.278Z	demolition Zuid Holland
Aktas Betonvlechter	Demolition contractor		52.0641317	4.3341068	2022-06-28T10:57:30.519Z	demolition Zuid Holland
Korfra	Demolition contractor	Hoofdweg Zuid 42, 3a, 2912 EE Nieuwerkerk aan den IJssel, Netherlands	51.9631652	4.5930714	2022-06-28T10:57:37.577Z	demolition Zuid Holland
Vladimiros Sonidis Diensten	Demolition contractor		52.0580619	4.3198154	2022-06-28T10:57:43.881Z	demolition Zuid Holland
Firma Stok - Onderhoud & klusbedrijf	Construction company	Dynamoweg 17, 2627 CG Delft, Netherlands	51.9878647	4.3727471	2022-06-28T10:57:50.389Z	demolition Zuid Holland
Tanis Goeree	Demolition contractor	Hofdijksweg 20, 3253 KB Ouddorp, Netherlands	51.8108841	3.9367612	2022-06-28T10:57:57.328Z	demolition Zuid Holland
CL Sloopwerken	Demolition contractor		52.0716542	4.3098684	2022-06-28T10:58:03.445Z	demolition Zuid Holland

Lukasz Koziol Bouw	Demolition contractor		52.0716542	4.3098684	2022-06-28T10:58:09.490Z	demolition Zuid Holland
Vv Demolition Bv		Hoogeveenenweg 34, 2913 Nieuwerkerk aan den IJssel, Netherlands	51.9794387	4.6090911	2022-06-28T10:58:16.884Z	demolition Zuid Holland
Sandom Bouwservice	Demolition contractor		52.0716542	4.3098684	2022-06-28T10:58:24.182Z	demolition Zuid Holland
Moes Flex	Demolition contractor		52.0716542	4.3098684	2022-06-28T10:58:30.572Z	demolition Zuid Holland
Holland Milieutechniek B.V.	Demolition contractor	Arnhemseweg 5b, 2994 LA Barendrecht, Netherlands	51.8596439	4.5126298	2022-06-28T10:58:37.371Z	demolition Zuid Holland
Rijnmond Afbouw	Construction company	Van der Helmstraat 249, 3067 HE Rotterdam, Netherlands	51.9440473	4.5412915	2022-06-28T10:58:45.059Z	demolition Zuid Holland
Onderhouds- en Sloopbedrijf West	Demolition contractor	Ambachtsheerstraat 42, 3077 GJ Rotterdam, Netherlands	51.899202	4.562843	2022-06-28T10:58:52.389Z	demolition Zuid Holland
Mustang Demolition		Nieuw Oranjekanaal 75, 3151 XL Hoek van Holland, Netherlands	51.9583809	4.1791961	2022-06-28T10:58:59.870Z	demolition Zuid Holland
F.A. Adviezen	Demolition contractor		51.9995349	4.3636978	2022-06-28T10:59:06.186Z	demolition Zuid Holland
Sevink Sloopwerken	Demolition contractor	Wit-geellaan, 2718 AB Zoetermeer, Netherlands	52.0373374	4.4976189	2022-06-28T10:59:13.088Z	demolition Zuid Holland
Georgios Sloopwerken	Demolition contractor		52.0716542	4.3098684	2022-06-28T10:59:19.968Z	demolition Zuid Holland
Van Zundert Sloopwerken	Demolition contractor	Van Vredenburchweg 132, 2283 TG Rijswijk, Netherlands	52.046963	4.316813	2022-06-28T10:59:26.704Z	demolition Zuid Holland
J.J. van der Hoeven en Zn. B.V.	Demolition contractor	Schietlood 15-17, 2495 AP Den Haag, Netherlands	52.0622539	4.3628104	2022-06-28T10:59:34.844Z	demolition Zuid Holland
Karabag Dienstverlening	Demolition contractor		52.0716542	4.3098684	2022-06-28T10:59:40.889Z	demolition Zuid Holland
MB DEMOLITION	Demolition contractor	Industrieweg 2, 2254 AE Voorschoten, Netherlands	52.1302949	4.4347266	2022-06-28T10:59:47.561Z	demolition Zuid Holland
Dylan Support	Demolition contractor	Noordeindseweg 416, 2651 LP Berkel en Rodenrijs, Netherlands	52.0271105	4.4815157	2022-06-28T10:59:54.849Z	demolition Zuid Holland
Sloopwerken Rotterdam	Demolition contractor	Stationsplein 2, 3013 AJ Rotterdam, Netherlands	51.923972	4.469572	2022-06-28T11:00:01.455Z	demolition Zuid Holland
JS sloop & bouw	Demolition contractor		52.0716542	4.3098684	2022-06-28T11:00:08.193Z	demolition Zuid Holland
Dietz Allround	Demolition contractor		51.9995349	4.3636978	2022-06-28T11:00:14.917Z	demolition Zuid Holland
A.D.W. Sloop B.V.	Demolition contractor		52.0716542	4.3098684	2022-06-28T11:00:21.930Z	demolition Zuid Holland
D B Dragon Klussen & Sloopbedrijf	Demolition contractor	Dunantstraat 1487, 2713 TV Zoetermeer, Netherlands	52.0541028	4.4819557	2022-06-28T11:00:29.977Z	demolition Zuid Holland
JaapHoek Sloopwerken	Demolition contractor	Zuidstraat 109, 2225 GV Katwijk aan Zee, Netherlands	52.2024721	4.3997134	2022-06-28T11:00:37.656Z	demolition Zuid Holland

Vermeulen Contractors B.V.	Demolition contractor	Boezemweg 17, 2641 KG Pijnacker, Netherlands	52.025957	4.4371496	2022-06-28T11:00:45.581Z	demolition Zuid Holland
Andre Van Kuijk Sloopbedrijf	Demolition contractor	Godschalkstraat 3, 3084 RA Rotterdam, Netherlands	51.882351	4.462871	2022-06-28T11:00:52.995Z	demolition Zuid Holland
Dante Sloopwerken	Demolition contractor		52.0621658	4.4866142	2022-06-28T11:00:59.214Z	demolition Zuid Holland
Sloopkenners.nl	Demolition contractor	Thurledeweg 125, 3044 ER Rotterdam, Netherlands	51.9236155	4.4162024	2022-06-28T11:01:06.617Z	demolition Zuid Holland
Vermeulen sloop- en milieutechnieken	Demolition contractor	Boezemweg 17, 2641 KG Pijnacker, Netherlands	52.025957	4.4371496	2022-06-28T11:01:13.858Z	demolition Zuid Holland
BERG — Ruimte Scheppen | Vestiging Naaldwijk | Kassensloop, Teeltwisseling en Afval	Demolition contractor	Hoge Noordweg 30, 2671 DZ Naaldwijk, Netherlands	51.9886978	4.2486383	2022-06-28T11:01:23.208Z	demolition Zuid Holland
Van Huizen Aanneming & Verhuur B.V.	Demolition contractor		52.0231424	4.3429324	2022-06-28T11:01:31.578Z	demolition Zuid Holland
Van Vliet Sloopwerken B.V.	Demolition contractor	Boezem 17, 4206 CA Gorinchem, Netherlands	51.8508088	4.9837625	2022-06-28T11:01:39.063Z	demolition Zuid Holland
Demolition Contractors & Consultancy Bv	Demolition contractor	Lorentzweg 33F, 3208 LJ Spijkenisse, Netherlands	51.8530265	4.2897966	2022-06-28T11:01:46.773Z	demolition Zuid Holland
Mshw Support BV	Demolition contractor	Breevaartstraat 67, 3044 AG Rotterdam, Netherlands	51.9268042	4.4208113	2022-06-28T11:01:53.885Z	demolition Zuid Holland
Van der Jagt Groep	Demolition contractor	Van der Giessenweg 11, 2921 LP Krimpen aan den IJssel, Netherlands	51.907263	4.5818465	2022-06-28T11:02:01.187Z	demolition Zuid Holland
Force Group B.V.	Demolition contractor	Galgeweg 3, 2671 MR Naaldwijk, Netherlands	51.989163	4.193066	2022-06-28T11:02:07.778Z	demolition Zuid Holland
Gebr. De Hollander B.V.	Demolition contractor	Galgweg 3, 2391 MV Hazerswoude-Dorp, Netherlands	52.114532	4.588918	2022-06-28T11:02:15.653Z	demolition Zuid Holland
G. Hol Sloopwerken B.V.	Demolition contractor	Bostelweg 21, 3059 LB Rotterdam, Netherlands	51.974924	4.593033	2022-06-28T11:02:23.967Z	demolition Zuid Holland
Kaslee Projecten B.V.	Demolition contractor	Katwijkerlaan 33, 2641 PC Pijnacker, Netherlands	52.0348377	4.4494659	2022-06-28T11:02:31.070Z	demolition Zuid Holland
Delft University of Technology (TU Delft)	Technical university	Mekelweg 5, 2628 CD Delft, Netherlands	52.0021919	4.3735766	2022-06-28T11:03:41.174Z	Concrete rubble Zuid Holland
Zuid-Holland Dak	Roofing contractor	Messstraat, 2586 XX Den Haag, Netherlands	52.1082447	4.2853023	2022-06-28T11:03:48.178Z	Concrete rubble Zuid Holland
Julianahaven Recycling	Recycling center	Kilkade 12, 3316 BC Dordrecht, Netherlands	51.791178	4.6423494	2022-06-28T11:03:55.507Z	Concrete rubble Zuid Holland

B. Results for copper

title	categories	address	location/lat	location/lng	scrapedAt	searchString
Forest Metal Group BV	Wholesaler	Boezembocht 35, 3034 KA Rotterdam, Netherlands	51.9431871	4.4985281	2022-06-28T11:16:02.143Z	copper recycling Zuid Holland
Sea2Cradle B.V.	Recycling center	Scheepmakershaven 59, 3011 VD Rotterdam, Netherlands	51.9157058	4.4868085	2022-06-28T11:16:11.171Z	copper recycling Zuid Holland
Van Helvert Metalen	Recycling center	Overschieseweg 86, 3044 EH Rotterdam, Netherlands	51.9331702	4.4092614	2022-06-28T11:16:19.178Z	copper recycling Zuid Holland
Van Leeuwen Metaal Recycling	Recycling center	Doklaan 22, 3081 AD Rotterdam, Netherlands	51.8948965	4.4709447	2022-06-28T11:16:28.698Z	copper recycling Zuid Holland
Krommenhoek Metals b.v.	Recycling center	Keenstraat 28, 3044 CD Rotterdam, Netherlands	51.9310092	4.4206045	2022-06-28T11:16:36.291Z	copper recycling Zuid Holland
Geelhoed Metaalhandel BV	Scrap metal dealer	Ambachtshof 2, 2632 BB Nootdorp, Netherlands	52.0506558	4.4103812	2022-06-28T11:16:44.182Z	copper recycling Zuid Holland
Metaalrecycling C. Kooijman	Recycling center	Breeweg 31, 3075 LJ Rotterdam, Netherlands	51.890934	4.51757	2022-06-28T11:16:51.883Z	copper recycling Zuid Holland
KARWEI	Home improvement store	De Lasso-Zuid 21, 2371 EV Roelofarendsveen, Netherlands	52.2024574	4.6209974	2022-06-28T11:17:38.922Z	copper recycling Zuid Holland
Karwei bouwmarkt Boskoop	Building materials store	Westpark 1, 2771 RV Boskoop, Netherlands	52.0758697	4.6322144	2022-06-28T11:17:40.551Z	copper recycling Zuid Holland
Karwei bouwmarkt Bodegraven	Home improvement store	Lemsteraak 2, 2411 NC Bodegraven, Netherlands	52.085941	4.7382531	2022-06-28T11:17:47.283Z	copper recycling Zuid Holland
Van Pelt Recycling	Recycling center	Klompenmakerstraat 10, 2984 BB Ridderkerk, Netherlands	51.8791559	4.6166167	2022-06-28T11:17:54.513Z	copper recycling Zuid Holland
Milieustraat Hellevoetsluis	Garbage dump	Rijksstraatweg 252A, 3223 KE Hellevoetsluis, Netherlands	51.8479385	4.1414065	2022-06-28T11:19:32.988Z	metal recycling Zuid Holland
Gemeentewerf Oegstgeest	Garbage collection service	Haarlemmerstraatweg 30, 2343 LB Oegstgeest, Netherlands	52.1981685	4.4736194	2022-06-28T11:19:40.868Z	metal recycling Zuid Holland
Veerhaeve Trade		Hoge Filterweg 580, 3063 KL Rotterdam, Netherlands	51.9070934	4.5250128	2022-06-28T11:19:49.176Z	metal recycling Zuid Holland
Stadswerf Brielle	Garbage dump service	Het Woud 53, 3232 LN Brielle, Netherlands	51.8886083	4.1605374	2022-06-28T11:19:56.889Z	metal recycling Zuid Holland
Metaalhandel G. van Bladel		1e Stoofweg 4, 3247 LR Dirksland, Netherlands	51.7118097	4.0914507	2022-06-28T11:20:03.986Z	metal recycling Zuid Holland
BioBasura B.V.	Waste management service	Jozef Oreliosingel 235, 3122 CS Schiedam, Netherlands	51.9315288	4.3703116	2022-06-28T11:20:12.479Z	metal recycling Zuid Holland
Van Gils Automotive	Auto parts store	Spiegelstraat 6, 2631 RS Nootdorp, Netherlands	52.0504341	4.4166612	2022-06-28T11:20:20.384Z	metal recycling Zuid Holland
Milieustraat Westmaas	Waste management service	Smidsweg 20-a, 3273 LK Westmaas, Netherlands	51.7841695	4.443463	2022-06-28T11:20:28.073Z	metal recycling Zuid Holland
Afvalbrengstation	Recycling center	Uitenhagestraat 4, 2571 VV Den Haag, Netherlands	52.0716067	4.2911091	2022-06-28T11:20:36.669Z	metal recycling Zuid Holland

D. Metselaar & Zn. V.o.f.	Iron ware dealer	Onderweg 35-37, 2742 LA Waddinxveen, Netherlands	52.0455555	4.6382146	2022-06-28T11:20:44.344Z	metal recycling Zuid Holland
R. C.H. Vreeswijk		Pater Jornaweg 13bij, 2742 KM Waddinxveen, Netherlands	52.0368647	4.6461884	2022-06-28T11:20:51.868Z	metal recycling Zuid Holland
Reedijk Used Tyres B.V.	Wholesaler	Pieter Zeemanweg 200, 3316 GZ Dordrecht, Netherlands	51.7737855	4.6329097	2022-06-28T11:21:00.778Z	metal recycling Zuid Holland
Milieupark Hillegersberg-Schiebroek	Recycling center	Melanchtonweg 139, 3045 PN Rotterdam, Netherlands	51.9521503	4.4611983	2022-06-28T11:21:09.411Z	metal recycling Zuid Holland
Zelfbrengdepot Zoetermeer	Garbage dump	Argonstraat 25, 2718 SM Zoetermeer, Netherlands	52.0355835	4.50446	2022-06-28T11:21:17.302Z	metal recycling Zuid Holland
Afvalbrengpunt Lansingerland (Renewi)	Recycling center	Bosland 51, 2661 DV Bergschenhoek, Netherlands	51.986516	4.5195444	2022-06-28T11:21:24.284Z	metal recycling Zuid Holland
Milieupark Prins Alexander	Recycling center	Nikkelstraat 131, 3067 GD Rotterdam, Netherlands	51.9481415	4.5386775	2022-06-28T11:21:32.398Z	metal recycling Zuid Holland
D.M.S. Dutch Metal Service B.V.	Contractor	Willem Dreeslaan 192, 2729 NJ Zoetermeer, Netherlands	52.0635213	4.5329039	2022-06-28T11:21:40.590Z	metal recycling Zuid Holland
Bob Metals Bv		Ajaxstraat 7, 3054 SC Rotterdam, Netherlands	51.9620948	4.4899697	2022-06-28T11:21:47.473Z	metal recycling Zuid Holland
J.I. van Gelderen B.V.	Metal construction company	Strickledeweg 40, 3044 EK Rotterdam, Netherlands	51.9277536	4.4124714	2022-06-28T11:21:56.069Z	metal recycling Zuid Holland
Textiel Bank Nederland	Recycling center	Van Veenendaalweg 18, 3088 HG Rotterdam, Netherlands	51.8725973	4.4368166	2022-06-28T11:22:03.079Z	metal recycling Zuid Holland
Firma F., N. & K. van der Meer	Metal processing company	Eglantierbaan 6, 2908 LV Capelle aan den IJssel, Netherlands	51.9575378	4.5755326	2022-06-28T11:22:10.579Z	metal recycling Zuid Holland
Nedvang	Recycling center	Overgoo 13, 2266 JZ Leidschendam, Netherlands	52.0764948	4.3951968	2022-06-28T11:22:18.679Z	metal recycling Zuid Holland
Blue Phoenix Group	Recycling center	Watermanweg 106a, 3067 GG Rotterdam, Netherlands	51.9502003	4.5571806	2022-06-28T11:22:25.173Z	metal recycling Zuid Holland
W. van den Berg Metaalrecycling	Metal processing company	Veilingweg 52, 3034 KB Rotterdam, Netherlands	51.9436278	4.4954699	2022-06-28T11:22:33.681Z	metal recycling Zuid Holland
Metaalhandel & Recycling Hulters	Metal processing company	Zoutverkopersstraat 4-B, 3334 KJ Zwijndrecht, Netherlands	51.8095536	4.5992176	2022-06-28T11:22:42.171Z	metal recycling Zuid Holland
De IJzervreter	Recycling center		51.84333	4.1357787	2022-06-28T11:22:48.676Z	metal recycling Zuid Holland
A & M Recycling Bv	Waste management service	Dintelweg 71, 3198 LB Europoort Rotterdam, Netherlands	51.937833	4.127897	2022-06-28T11:22:55.971Z	metal recycling Zuid Holland
JOBO OLD IRON & METAL COLLECTION	Metal construction company	Westvlietweg 71Q, 2495 AA Den Haag, Netherlands	52.063235	4.3643213	2022-06-28T11:23:04.267Z	metal recycling Zuid Holland
Milieustraat Oostvoorne	Recycling center	Langeweg 26, 3233 LM Oostvoorne, Netherlands	51.9102664	4.1168704	2022-06-28T11:23:12.558Z	metal recycling Zuid Holland
Recycling Combination REKO B.V.	Recycling center	Vondelingenplaat 17, 3196 KL Vondelingenplaat, Netherlands	51.888702	4.332855	2022-06-28T11:23:20.464Z	metal recycling Zuid Holland
Firma Gebroeders Koot	Recycling center	Industrieweg 5B, 2712 LA Zoetermeer, Netherlands	52.0471561	4.5082638	2022-06-28T11:23:28.327Z	metal recycling Zuid Holland

Avalex	Recycling center	Voltaweg 11, 2627 BD Delft, Netherlands	51.9827832	4.375061	2022-06-28T11:23:36.476Z	metal recycling Zuid Holland
Metalimex Metaalhandel	Recycling center	Overschieseweg 68, 3044 EG Rotterdam, Netherlands	51.9351647	4.4093356	2022-06-28T11:23:43.165Z	metal recycling Zuid Holland
A. Aantjes Recycling	Recycling center	Handelstraat 9-11, 3264 XZ Nieuw-Beijerland, Netherlands	51.81546	4.343817	2022-06-28T11:23:49.886Z	metal recycling Zuid Holland
Bas van den Ende	Recycling center	Nieuw Oranjekanaal 75, 3151 XL Hoek van Holland, Netherlands	51.9585573	4.1788451	2022-06-28T11:23:57.390Z	metal recycling Zuid Holland
Ben Jansen Metaalrecycling	Recycling center	Lagosweg 7, 2622 CZ Delft, Netherlands	51.9846963	4.3429127	2022-06-28T11:24:04.402Z	metal recycling Zuid Holland
van Puffelen Metaalrecycling	Recycling center	Broekmolenweg 25, 2289 BE Rijswijk, Netherlands	52.0261826	4.3504005	2022-06-28T11:24:10.771Z	metal recycling Zuid Holland
EMR - European Metal Recycling B.V.	Metal construction company	Quebecstraat 3, Havennummer 4522, 3197 KL Botlek Rotterdam, Netherlands	51.8923506	4.2774032	2022-06-28T11:24:17.392Z	metal recycling Zuid Holland
DPE Metaalrecycling West-Voorne B.V.	Recycling center	Dalweg 10, 3233 KK Oostvoorne, Netherlands	51.9116238	4.116786	2022-06-28T11:24:24.769Z	metal recycling Zuid Holland
Goedegebuure Metaal Recycling	Recycling center	Kryptonstraat 200, 2718 TD Zoetermeer, Netherlands	52.0324989	4.4979242	2022-06-28T11:24:31.123Z	metal recycling Zuid Holland
Remet Recycling B.V.	Metal processing company	Braillestraat 1, 2691 HX 's-Gravenzande, Netherlands	51.9970423	4.1812504	2022-06-28T11:24:37.796Z	metal recycling Zuid Holland
Bal Oud Papier & Metalen	Recycling center	Van der Kunstraat 24, 2521 BC Den Haag, Netherlands	52.0650776	4.3179861	2022-06-28T11:24:44.960Z	metal recycling Zuid Holland
Jansen Recycling Group BV	Recycling center	Van Leeuwenhoekweg 21, 3316 AV Dordrecht, Netherlands	51.7998483	4.636088	2022-06-28T11:24:53.390Z	metal recycling Zuid Holland
Gerlag metals Metaalhandel	Metal construction company	Barmweg 28, 2651 NV Berkel en Rodenrijs, Netherlands	52.0201607	4.4730911	2022-06-28T11:25:00.322Z	metal recycling Zuid Holland
International Metal Trading BV	Recycling center	Kortenoord 57, 2911 BD Nieuwerkerk aan den IJssel, Netherlands	51.9730738	4.6438568	2022-06-28T11:25:06.776Z	metal recycling Zuid Holland
Stolk Recycling B.V.	Metal construction company	De Geer, Fruiteniersstraat 25, 3334 KA Zwijndrecht, Netherlands	51.8122547	4.596416	2022-06-28T11:25:13.287Z	metal recycling Zuid Holland
Stal Metals Recycling Drechtsteden	Junk dealer	Kerkeplaat 2, e123, 3313 LC Dordrecht, Netherlands	51.818521	4.7095318	2022-06-28T11:25:20.372Z	metal recycling Zuid Holland
Hoefnagel Metals Recycling B.V.	Wholesaler	Marconistraat 3, 3133 KL Vlaardingen, Netherlands	51.903702	4.310096	2022-06-28T11:25:27.872Z	metal recycling Zuid Holland
Do- Metals | Oud IJzer Accu's en Metalen	Recycling center	Weg en Land 38, 2661 KR Bergschenhoek, Netherlands	51.979078	4.5028883	2022-06-28T11:25:34.396Z	metal recycling Zuid Holland
Lion Metals	Recycling center	Boezembocht 31, 3034 KA Rotterdam, Netherlands	51.9437127	4.5005196	2022-06-28T11:25:42.881Z	metal recycling Zuid Holland

Appendix II – LCA

A. Sources of the unit processes

	Process	**Source**	**Comment**
Concrete	Primary concrete production	EcoInvent 3.4	Primary concrete production, for building construction, with cement CEM II/A
	Wet processing	Zhang et al. (2019)	
	Advanced dry recycling	Zhang et al. (2019)	
	Recycled concrete production	EcoInvent 3.4	copy of EcoInvent process for primary concrete, with adjusted inputs for recycled content
Copper	Primary copper production	EcoInvent 3.4	copper production, primary [RER]
	Recycled copper production	EcoInvent 3.4	treatment of copper scrap by electrolytic refining [RER]
Transport	Transport by truck (EURO5)	EcoInvent 3.4	transport, freight, lorry, all sizes, EURO5 to generic market for transport, freight, lorry, unspecified [RER]
	Transport by truck (EURO4)	EcoInvent 3.4	transport, freight, lorry, all sizes, EURO4 to generic market for transport, freight, lorry, unspecified [RER]
	Transport by barge	EcoInvent 3.4	transport, freight, inland waterways, barge [RER]

B. List of unit processes

Concrete	**Primary concrete production, for building construction, with cement CEM II/A[CH]**				
	Economic inflows				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	[G174]	diesel, burned in building machine_market for diesel, burned in building machine[GLO]	0.4	megajoule	EcoInvent 3.4
	[G1721]	transport, freight, lorry, unspecified_transport, freight, lorry, all sizes, EURO5 to generic market for transport, freight, lorry, unspecified[RER]	266	ton kilometer	EcoInvent 3.4
	[G3289]	tap water_market for tap water[Europe without Switzerland]	175	kilogram	EcoInvent 3.4
	[G4653]	cement, alternative constituents 6-20%_market for cement, alternative constituents 6-20%[CH]	290	kilogram	EcoInvent 3.4
	[G4710]	heat, district or industrial, natural gas_market for heat, district or industrial, natural gas[CH]	5.7	megajoule	EcoInvent 3.4
	[G5435]	electricity, medium voltage_market for electricity, medium voltage[NL]	4.3	kilowatt hour	EcoInvent 3.4
	[G6842]	concrete mixing factory_concrete mixing factory construction[CH]	4.17E-07	unit	EcoInvent 3.4
	[G7830]	sand_market for sand[GLO]	705	kilogram	EcoInvent 3.4
	[G9700]	heat, district or industrial, other than natural gas_heat production, light fuel oil, at industrial furnace 1MW[CH]	8.2	megajoule	EcoInvent 3.4
	[G11483]	gravel, round_market for gravel, round[CH]	1.25E+03	kilogram	EcoInvent 3.4
	[G11853]	synthetic rubber_market for synthetic rubber[GLO]	0.12	kilogram	EcoInvent 3.4
	[G13317]	lubricating oil_market for lubricating oil[GLO]	0.02	kilogram	EcoInvent 3.4
	Economic outflows				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	[W1816]	waste concrete_market for waste concrete[CH]	5.38	kilogram	EcoInvent 3.4
	[W13828]	municipal solid waste_market for municipal solid waste[CH]	0.05	kilogram	EcoInvent 3.4
	[G14890]	Primary concrete, high exacting requirements_concrete production, for building construction, with cement CEM II/A[CH]	1	cubic meter	EcoInvent 3.4
	Environmental resources				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	Environmental emissions				

	Label	*Name*	*Value*	*Unit*	*Data Source*
	Recycling concrete rubble, wet processing				
	Economic inflows				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	[G174]	diesel, burned in building machine_market for diesel, burned in building machine[GLO]	1.05E+03	megajoule	
	[G1721]	transport, freight, lorry, unspecified_transport, freight, lorry, all sizes, EURO5 to generic market for transport, freight, lorry, unspecified[RER]	5.05E+03	ton kilometer	
	[G3289]	tap water_market for tap water[Europe without Switzerland]	670	kilogram	
	[G5435]	electricity, medium voltage_market for electricity, medium voltage[NL]	400	kilowatt hour	
	[G14891]	Concrete rubble	1.00E+05	kilogram	
	Economic outflows				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	[W2197]	refinery sludge_treatment of refinery sludge, sanitary landfill[Europe without Switzerland]	2.60E+03	kilogram	
	[W14892]	Sieve sand	4.45E+04	kilogram	
	[G14893]	REcycled concrete aggregate	5.29E+04	kilogram	Zhang et al. (2019)
	Environmental resources				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	Environmental emissions				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	Recycling concrete, Advanced dry recycling				
	Economic inflows				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	[G174]	diesel, burned in building machine_market for diesel, burned in building machine[GLO]	5.07E+04	megajoule	Zhang et al. (2019)
	[G1721]	transport, freight, lorry, unspecified_transport, freight, lorry, all sizes, EURO5 to generic market for transport, freight, lorry, unspecified[RER]	5.00E+03	ton kilometer	Zhang et al. (2019)
	[G3289]	tap water_market for tap water[Europe without Switzerland]	140	kilogram	Zhang et al. (2019)
	[G5435]	electricity, medium voltage_market for electricity, medium voltage[NL]	36.8	kilowatt hour	Zhang et al. (2019)
	[G14891]	Concrete rubble	1.00E+05	kilogram	Zhang et al. (2019)
	Economic outflows				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	[W14892]	Sieve sand	3.20E+04	kilogram	Zhang et al. (2019)
	[G14895]	Recycled concrete aggregate, crusher + ADR	6.80E+04	kilogram	Zhang et al. (2019)
	Environmental resources				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	Environmental emissions				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	Recycled concrete production, wet processing				
	Economic inflows				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	[G3289]	tap water_market for tap water[Europe without Switzerland]	175	kilogram	EcoInvent 3.4

	[G4653]	cement, alternative constituents 6-20%_market for cement, alternative constituents 6-20%[CH]	290	kilogram	EcoInvent 3.4
	[G5435]	electricity, medium voltage_market for electricity, medium voltage[NL]	4.3	kilowatt hour	EcoInvent 3.4
	[G6842]	concrete mixing factory_concrete mixing factory construction[CH]	4.17E-07	unit	EcoInvent 3.4
	[G7830]	sand_market for sand[GLO]	705	kilogram	EcoInvent 3.4
	[G11483]	gravel, round_market for gravel, round[CH]	625	kilogram	EcoInvent 3.4
	[G14893]	REcycled concrete aggregate	625	kilogram	EcoInvent 3.4
	Economic outflows				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	[W1816]	waste concrete_market for waste concrete[CH]	5.38	kilogram	EcoInvent 3.4
	[G14894]	Recycled concrete, high exacting requirements_concrete production, for building construction, with cement CEM II/A	1	cubic meter	EcoInvent 3.4
	Environmental resources				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	Environmental emissions				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	Recycled concrete production, advanced dry recycling				
	Economic inflows				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	[G3289]	tap water_market for tap water[Europe without Switzerland]	175	kilogram	EcoInvent 3.4
	[G4653]	cement, alternative constituents 6-20%_market for cement, alternative constituents 6-20%[CH]	290	kilogram	EcoInvent 3.4
	[G5435]	electricity, medium voltage_market for electricity, medium voltage[NL]	4.3	kilowatt hour	EcoInvent 3.4
	[G6842]	concrete mixing factory_concrete mixing factory construction[CH]	4.17E-07	unit	EcoInvent 3.4
	[G7830]	sand_market for sand[GLO]	705	kilogram	EcoInvent 3.4
	[G11483]	gravel, round_market for gravel, round[CH]	625	kilogram	EcoInvent 3.4
	[G14895]	Recycled concrete aggregate, crusher + ADR	625	kilogram	EcoInvent 3.4
	Economic outflows				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	[W1816]	waste concrete_market for waste concrete[CH]	5.38	kilogram	EcoInvent 3.4
	[G14896]	Recycled concrete, crusher + ADR, high exacting requirements_concrete production, for building construction, with cement CEM II/A	1	cubic meter	EcoInvent 3.4
	Environmental resources				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	Environmental emissions				
	Label	*Name*	*Value*	*Unit*	*Data Source*
Copper	**copper production, primary[RER]**				
	Economic inflows				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	[G1513]	anode, for metal electrolysis_market for anode, for metal electrolysis[GLO]	0.001	kilogram	EcoInvent 3.4
	[G6419]	lime, packed_market for lime, packed[CH]	0.25	kilogram	EcoInvent 3.4

	[G7183]	silica sand_market for silica sand[GLO]	0.75	kilogram	EcoInvent 3.4
	[G8219]	electricity, high voltage_market group for electricity, high voltage[RER]	0.219	kilowatt hour	EcoInvent 3.4
	[G8433]	electricity, high voltage_electricity production, hydro, run-of-river[RoW]	0.328	kilowatt hour	EcoInvent 3.4
	[G8510]	heat, district or industrial, other than natural gas_market group for heat, district or industrial, other than natural gas[RER]	4.3	megajoule	EcoInvent 3.4
	[G11689]	Transport, freight, sea, transoceanic tanker_ transport, freight, sea, transoceanic tanker [GLO]	49.7	Tonne kilometer	EcoInvent 3.4
	[G12399]	non-ferrous metal smelter_market for non-ferrous metal smelter[GLO]	1.14E-11	unit	EcoInvent 3.4
	[G12607]	copper concentrate, sulfide ore_copper mine operation, sulfide ore[RER]	4.14	kilogram	EcoInvent 3.4
	[G14480]	heat, district or industrial, natural gas_market group for heat, district or industrial, natural gas[RER]	3.55	megajoule	EcoInvent 3.4
	[G14786]	oxygen, liquid_market for oxygen, liquid[RER]	0.3	kilogram	EcoInvent 3.4
	Economic outflows				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	[W4860]	dross from Al electrolysis_market for dross from Al electrolysis[GLO]	10	kilogram	EcoInvent 3.4
	[G5796]	copper_copper production, primary[RER]	1	kilogram	EcoInvent 3.4
	[W12300]	nickel smelter slag_market for nickel smelter slag[GLO]	0.925	kilogram	EcoInvent 3.4
	[W13368]	wastewater, unpolluted_market for wastewater, unpolluted[RoW]	0.0058	cubic meter	EcoInvent 3.4
	Environmental resources				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	[E704]	Water, river[('natural resource', 'in water')]	0.0058	cubic meter	EcoInvent 3.4
	Environmental emissions				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	[E745]	Antimony[('air', 'non-urban air or from high stacks')]	5.50E-06	kilogram	EcoInvent 3.4
	[E751]	Arsenic[('air', 'non-urban air or from high stacks')]	3.25E-05	kilogram	EcoInvent 3.4
	[E784]	Cadmium[('air', 'non-urban air or from high stacks')]	6.50E-06	kilogram	EcoInvent 3.4
	[E793]	Carbon dioxide, fossil[('air', 'non-urban air or from high stacks')]	0.11	kilogram	EcoInvent 3.4
	[E800]	Carbon monoxide, fossil[('air', 'non-urban air or from high stacks')]	3.00E-05	kilogram	EcoInvent 3.4
	[E813]	Chromium[('air', 'non-urban air or from high stacks')]	5.00E-08	kilogram	EcoInvent 3.4
	[E825]	Copper[('air', 'non-urban air or from high stacks')]	0.00025	kilogram	EcoInvent 3.4
	[E840]	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin[('air', 'non-urban air or from high stacks')]	2.00E-12	kilogram	EcoInvent 3.4
	[E921]	Lead[('air', 'non-urban air or from high stacks')]	0.00015	kilogram	EcoInvent 3.4
	[E930]	Manganese[('air', 'non-urban air or from high stacks')]	1.50E-05	kilogram	EcoInvent 3.4
	[E934]	Mercury[('air', 'non-urban air or from high stacks')]	1.00E-07	kilogram	EcoInvent 3.4
	[E965]	Nickel[('air', 'non-urban air or from high stacks')]	5.50E-05	kilogram	EcoInvent 3.4
	[E977]	NMVOC, non-methane volatile organic compounds, unspecified origin[('air', 'non-urban air or from high stacks')]	1.50E-05	kilogram	EcoInvent 3.4
	[E986]	Particulates, < 2.5 um[('air', 'non-urban air or from high stacks')]	5.08E-07	kilogram	EcoInvent 3.4
	[E990]	Particulates, > 10 um[('air', 'non-urban air or from high stacks')]	0.000102	kilogram	EcoInvent 3.4

	[E993]	Particulates, > 2.5 um, and < 10um[('air', 'non-urban air or from high stacks')]	0.000304	kilogram	EcoInvent 3.4
	[E1043]	Selenium[('air', 'non-urban air or from high stacks')]	5.50E-06	kilogram	EcoInvent 3.4
	[E1067]	Sulfur dioxide[('air', 'non-urban air or from high stacks')]	0.0357	kilogram	EcoInvent 3.4
	[E1085]	Tin[('air', 'non-urban air or from high stacks')]	6.25E-06	kilogram	EcoInvent 3.4
	[E1102]	Vanadium[('air', 'non-urban air or from high stacks')]	3.75E-07	kilogram	EcoInvent 3.4
	[E1114]	Zinc[('air', 'non-urban air or from high stacks')]	0.00015	kilogram	EcoInvent 3.4
	[E1261]	Arsenic, ion[('water', 'surface water')]	1.08E-07	kilogram	EcoInvent 3.4
	[E1310]	Cadmium, ion[('water', 'surface water')]	1.58E-08	kilogram	EcoInvent 3.4
	[E1353]	Chromium, ion[('water', 'surface water')]	1.66E-07	kilogram	EcoInvent 3.4
	[E1370]	Copper, ion[('water', 'surface water')]	3.05E-07	kilogram	EcoInvent 3.4
	[E1459]	Lead[('water', 'surface water')]	9.26E-08	kilogram	EcoInvent 3.4
	[E1481]	Mercury[('water', 'surface water')]	1.66E-09	kilogram	EcoInvent 3.4
	[E1503]	Nickel, ion[('water', 'surface water')]	1.23E-07	kilogram	EcoInvent 3.4
	[E1646]	Tin, ion[('water', 'surface water')]	1.66E-07	kilogram	EcoInvent 3.4
	[E1688]	Zinc, ion[('water', 'surface water')]	4.91E-07	kilogram	EcoInvent 3.4
	[E1797]	Water[('air',)]	0.00087	cubic meter	EcoInvent 3.4
	Recycled copper, electrolysis				
	Economic inflows				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	[G5174]	cotton seed, for sowing_cotton seed production, for sowing[US]	0.00133	kilogram	EcoInvent 3.8
	[G11313]	compost_market for compost[GLO]	1.75	kilogram	EcoInvent 3.8
	[W14902]	manure, solid, cattle	3.5	kilogram	EcoInvent 3.8
	Economic outflows				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	[G14890]	seed-cotton, organic	1	kilogram	EcoInvent 3.8
	Environmental resources				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	[E79]	Cadmium, 0.30% in sulfide, Cd 0.18%, Pb, Zn, Ag, In, in ground[('natural resource', 'in ground')]	2.53E-07	kilogram	EcoInvent 3.8
	[E91]	Carbon dioxide, in air[('natural resource', 'in air')]	1.5	kilogram	EcoInvent 3.8
	[E116]	Chromium, 25.5% in chromite, 11.6% in crude ore, in ground[('natural resource', 'in ground')]	5.76E-05	kilogram	EcoInvent 3.8
	[E139]	Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground[('natural resource', 'in ground')]	1.55E-05	kilogram	EcoInvent 3.8
	[E309]	Lead, 5.0% in sulfide, Pb 3.0%, Zn, Ag, Cd, In, in ground[('natural resource', 'in ground')]	1.09E-05	kilogram	EcoInvent 3.8
	[E386]	Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.76% in crude ore, in ground[('natural resource', 'in ground')]	4.18E-05	kilogram	EcoInvent 3.8
	[E401]	Occupation, annual crop, non-irrigated[('natural resource', 'land')]	6.99	square meter-year	EcoInvent 3.8
	[E601]	Transformation, from annual crop, non-irrigated[('natural resource', 'land')]	6.99	square meter	EcoInvent 3.8

	[E638]	Transformation, to annual crop, non-irrigated[('natural resource', 'land')]	6.99	square meter	EcoInvent 3.8
	[E716]	Zinc, 9.0% in sulfide, Zn 5.3%, Pb, Ag, Cd, In, in ground[('natural resource', 'in ground')]	3.28E-05	kilogram	EcoInvent 3.8
	[E1982]	Energy, gross calorific value, in biomass[('natural resource', 'biotic')]	17.3	megajoule	EcoInvent 3.8
	Environmental emissions				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	[E31]	Ammonia[('air', 'urban air close to ground')]	0.00456	kilogram	EcoInvent 3.8
	[E80]	Cadmium, ion[('water', 'ground-')]	1.37E-08	kilogram	EcoInvent 3.8
	[E117]	Chromium, ion[('water', 'ground-')]	1.31E-05	kilogram	EcoInvent 3.8
	[E144]	Copper, ion[('water', 'ground-')]	2.44E-06	kilogram	EcoInvent 3.8
	[E179]	Dinitrogen monoxide[('air', 'urban air close to ground')]	0.00101	kilogram	EcoInvent 3.8
	[E388]	Nickel, ion[('water', 'ground-')]	5.21E-05	kilogram	EcoInvent 3.8
	[E393]	Nitrogen oxides[('air', 'urban air close to ground')]	0.00814	kilogram	EcoInvent 3.8
	[E460]	Phosphate[('water', 'ground-')]	0.00015	kilogram	EcoInvent 3.8
	[E717]	Zinc, ion[('water', 'ground-')]	1.66E-05	kilogram	EcoInvent 3.8
Transport	**transport, freight, lorry, all sizes, EURO5 to generic market for transport, freight, lorry, unspecified[RoW]**				
	Economic inflows				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	[G2705]	transport, freight, lorry 7.5-16 metric ton, EURO5_market for transport, freight, lorry 7.5-16 metric ton, EURO5[GLO]	0.0321	ton kilometer	EcoInvent 3.4
	[G4519]	transport, freight, lorry 3.5-7.5 metric ton, EURO5_market for transport, freight, lorry 3.5-7.5 metric ton, EURO5[GLO]	0.0224	ton kilometer	EcoInvent 3.4
	[G13555]	transport, freight, lorry >32 metric ton, EURO5_market for transport, freight, lorry >32 metric ton, EURO5[GLO]	0.641	ton kilometer	EcoInvent 3.4
	[G14764]	transport, freight, lorry 16-32 metric ton, EURO5_market for transport, freight, lorry 16-32 metric ton, EURO5[GLO]	0.304	ton kilometer	EcoInvent 3.4
	Economic outflows				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	[G1721]	transport, freight, lorry, unspecified_transport, freight, lorry, all sizes, EURO5 to generic market for transport, freight, lorry, unspecified[RER]	1	ton kilometer	EcoInvent 3.4
	Environmental resources				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	Environmental emissions				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	Transpor transport, freight, lorry, all sizes, EURO4 to generic market for transport, freight, lorry, unspecified[RoW] truck EURO4				
	Economic inflows				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	[G4245]	transport, freight, lorry 3.5-7.5 metric ton, EURO4_market for transport, freight, lorry 3.5-7.5 metric ton, EURO4[GLO]	0.0246	ton kilometer	EcoInvent 3.4
	[G6752]	transport, freight, lorry 16-32 metric ton, EURO4_market for transport, freight, lorry 16-32 metric ton, EURO4[GLO]	0.318	ton kilometer	EcoInvent 3.4
	[G8601]	transport, freight, lorry >32 metric ton, EURO4_market for transport, freight, lorry >32 metric ton, EURO4[GLO]	0.625	ton kilometer	EcoInvent 3.4
	[G9327]	transport, freight, lorry 7.5-16 metric ton, EURO4_market for transport, freight, lorry 7.5-16 metric ton, EURO4[GLO]	0.0322	ton kilometer	EcoInvent 3.4
	Economic outflows				

	Label	*Name*	*Value*	*Unit*	*Data Source*
	[G4395]	transport, freight, lorry, unspecified_transport, freight, lorry, all sizes, EURO4 to generic market for transport, freight, lorry, unspecified[RoW]	1	ton kilometer	EcoInvent 3.4
	Environmental resources				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	Environmental emissions				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	Transport, freight, inland waterways, barge [RER]				
	Economic inflows				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	[G1757]	diesel_market group for diesel[RER]	0.00939	kilogram	EcoInvent 3.4
	[G3636]	port facilities_market for port facilities[GLO]	2.54E-14	unit	EcoInvent 3.4
	[G12136]	canal_market for canal[GLO]	0.000116	meter-year	EcoInvent 3.4
	[G12199]	barge_market for barge[GLO]	1.05E-09	unit	EcoInvent 3.4
	[G14608]	maintenance, barge_market for maintenance, barge[GLO]	1.05E-09	unit	EcoInvent 3.4
	Economic outflows				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	[W5989]	bilge oil_market for bilge oil[Europe without Switzerland]	4.58E-05	kilogram	EcoInvent 3.4
	[W8474]	bilge oil_market for bilge oil[CH]	1.20E-06	kilogram	EcoInvent 3.4
	[G13653]	transport, freight, inland waterways, barge_transport, freight, inland waterways, barge[RER]	1	ton kilometer	EcoInvent 3.4
	Environmental resources				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	Environmental emissions				
	Label	*Name*	*Value*	*Unit*	*Data Source*
	[E742]	Ammonia[('air', 'non-urban air or from high stacks')]	4.87E-07	kilogram	EcoInvent 3.4
	[E761]	Benzene[('air', 'non-urban air or from high stacks')]	1.78E-07	kilogram	EcoInvent 3.4
	[E768]	Benzo(a)pyrene[('air', 'non-urban air or from high stacks')]	7.24E-14	kilogram	EcoInvent 3.4
	[E784]	Cadmium[('air', 'non-urban air or from high stacks')]	9.39E-11	kilogram	EcoInvent 3.4
	[E793]	Carbon dioxide, fossil[('air', 'non-urban air or from high stacks')]	0.0296	kilogram	EcoInvent 3.4
	[E800]	Carbon monoxide, fossil[('air', 'non-urban air or from high stacks')]	2.54E-05	kilogram	EcoInvent 3.4
	[E813]	Chromium[('air', 'non-urban air or from high stacks')]	4.70E-10	kilogram	EcoInvent 3.4
	[E825]	Copper[('air', 'non-urban air or from high stacks')]	1.60E-08	kilogram	EcoInvent 3.4
	[E836]	Dinitrogen monoxide[('air', 'non-urban air or from high stacks')]	3.11E-06	kilogram	EcoInvent 3.4
	[E896]	Hydrogen chloride[('air', 'non-urban air or from high stacks')]	9.95E-09	kilogram	EcoInvent 3.4
	[E921]	Lead[('air', 'non-urban air or from high stacks')]	1.88E-10	kilogram	EcoInvent 3.4
	[E934]	Mercury[('air', 'non-urban air or from high stacks')]	6.58E-13	kilogram	EcoInvent 3.4
	[E949]	Methane, fossil[('air', 'non-urban air or from high stacks')]	2.25E-07	kilogram	EcoInvent 3.4

	[E965]	Nickel[('air', 'non-urban air or from high stacks')]	6.58E-10	kilogram	EcoInvent 3.4
	[E973]	Nitrogen oxides[('air', 'non-urban air or from high stacks')]	0.00047	kilogram	EcoInvent 3.4
	[E977]	NMVOC, non-methane volatile organic compounds, unspecified origin[('air', 'non-urban air or from high stacks')]	9.39E-06	kilogram	EcoInvent 3.4
	[E986]	Particulates, < 2.5 um[('air', 'non-urban air or from high stacks')]	8.67E-06	kilogram	EcoInvent 3.4
	[E990]	Particulates, > 10 um[('air', 'non-urban air or from high stacks')]	3.71E-07	kilogram	EcoInvent 3.4
	[E993]	Particulates, > 2.5 um, and < 10um[('air', 'non-urban air or from high stacks')]	7.23E-07	kilogram	EcoInvent 3.4
	[E1043]	Selenium[('air', 'non-urban air or from high stacks')]	9.39E-11	kilogram	EcoInvent 3.4
	[E1067]	Sulfur dioxide[('air', 'non-urban air or from high stacks')]	5.64E-06	kilogram	EcoInvent 3.4
	[E1091]	Toluene[('air', 'non-urban air or from high stacks')]	7.52E-08	kilogram	EcoInvent 3.4
	[E1112]	Xylene[('air', 'non-urban air or from high stacks')]	7.52E-08	kilogram	EcoInvent 3.4
	[E1114]	Zinc[('air', 'non-urban air or from high stacks')]	9.39E-09	kilogram	EcoInvent 3.4

Appendix III – Concrete results

A. Complete LCA results for primary and recycled concrete

	LCA results				Normalised LCA results			
Name	Primairy concrete	Recycled concrete, wet processing	Recycled concrete, advanced dry recycling	Unit	Primary concrete	Recycled concrete, wet processing	Recycled concrete, Advanced dry rec.	Unit
GWP	244	237	255	kg CO2-Eq	5.69E-12	5.52E-12	5.94E-12	year
FTA	0.67	0.556	0.979	mol H+-Eq	2.21E-12	1.84E-12	3.23E-12	year
FET	686	1.76E+03	546	CTUh.m3.yr	2.30E-11	5.88E-11	1.83E-11	year
FE	0.0292	0.0279	0.0282	kg P-Eq	1.95E-12	1.86E-12	1.88E-12	year
IR	6.52E-05	5.08E-05	6.75E-05	mol N-Eq	0.00E+00	0.00E+00	0.00E+00	year
ME	0.182	0.174	0.336	kg N-Eq	2.56E-12	2.45E-12	4.73E-12	year
TE	2.17E+00	1.81E+00	3.85E+00	mol N-Eq	3.09E-12	2.58E-12	5.49E-12	year
CE	5.16E-06	4.41E-06	5.19E-06	CTUh	1.28E-11	1.09E-11	1.28E-11	year
NCE	2.84E-05	5.75E-05	2.28E-05	CTUh	9.56E-13	1.94E-12	7.68E-13	year
OLD	1.18E-05	6.61E-06	1.36E-05	kg CFC-11-Eq	9.85E-14	5.51E-14	1.13E-13	year
POC	0.534	0.429	0.979	kg ethylene-Eq	1.80E-12	1.44E-12	3.29E-12	year
REI	0.0498	0.0354	0.0883	kg PM2.5-Eq	1.27E-12	9.02E-13	2.25E-12	year
LU	1.12E+03	756	831	kg Soil Organic Carbon	0	0	0	year
MFR	0.00588	0.00325	0.00329	kg Sb-Eq	1.67E-11	9.22E-12	9.34E-12	year

B. Distance calculations based on LCA

Indicator	**difference**		**transport impact**		**Unit**	**# additional km/m^3 concrete**			
						truck		barge	
	wet processed	Advanced dry rec.	truck	barge		wet processed	Advanced dry rec.	wet processed	Advanced dry rec.
GWP	7.00E+00	-1.10E+01	3.06E-01	1.15E-01	kg CO2-Eq	2.29E+01	-3.59E+01	6.09E+01	-9.57E+01
FTA	1.14E-01	-3.09E-01	1.28E-03	1.15E-03	mol H+-Eq	8.91E+01	-2.41E+02	9.91E+01	-2.69E+02
FET	-1.07E+03	1.40E+02	1.77E+00	2.89E-01	CTUh.m3.yr	-6.07E+02	7.91E+01	-3.72E+03	4.84E+02
FE	1.30E-03	1.00E-03	2.46E-05	1.37E-05	kg P-Eq	5.28E+01	4.07E+01	9.49E+01	7.30E+01
IR	1.44E-05	-2.30E-06	1.45E-07	4.70E-08	mol N-Eq	9.93E+01	-1.59E+01	3.06E+02	-4.89E+01
ME	8.00E-03	-1.54E-01	3.66E-04	4.83E-04	kg N-Eq	2.19E+01	-4.21E+02	1.66E+01	-3.19E+02
TE	3.60E-01	-1.68E+00	4.02E-03	5.31E-03	mol N-Eq	8.96E+01	-4.18E+02	6.78E+01	-3.16E+02
CE	7.50E-07	-3.00E-08	9.36E-09	5.30E-09	CTUh	8.01E+01	-3.21E+00	1.42E+02	-5.66E+00
NCE	-2.91E-05	5.60E-06	7.20E-08	1.10E-08	CTUh	-4.04E+02	7.78E+01	-2.65E+03	5.09E+02
OLD	5.19E-06	-1.80E-06	5.61E-08	1.70E-08	kg CFC-11-Eq	9.25E+01	-3.21E+01	3.05E+02	-1.06E+02
POC	1.05E-01	-4.45E-01	1.23E-03	1.36E-03	kg ethylene-Eq	8.54E+01	-3.62E+02	7.72E+01	-3.27E+02
REI	1.44E-02	-3.85E-02	1.56E-04	4.95E-05	kg PM2.5-Eq	9.23E+01	-2.47E+02	2.91E+02	-7.78E+02
LU	3.64E+02	2.89E+02	1.61E+00	1.02E+00	kg Soil Organic Carbon	2.26E+02	1.80E+02	3.57E+02	2.83E+02
MFR	2.63E-03	2.59E-03	2.11E-05	8.71E-07	kg Sb-Eq	1.25E+02	1.23E+02	3.02E+03	2.97E+03

C. Sensitivity analysis concrete - transport mode

Indicator	difference		transport impact			# additional km/m^3 concrete				diff. EURO5 EURO4	
						EURO5		EURO4			
	wet processed	Advanced dry rec.	EURO5	EURO4	Unit	wet processed	Advanced dry rec.	wet processed	Advanced dry rec.	wet processed	Advanced dry rec.
GWP	7.00E+00	-1.10E+01	3.06E-01	3.08E-01	kg CO2-Eq	2.29E+01	-3.59E+01	2.27E+01	-3.57E+01	0.65%	0.65%
FTA	1.14E-01	-3.09E-01	1.28E-03	1.58E-03	mol H+-Eq	8.91E+01	-2.41E+02	7.22E+01	-1.96E+02	18.99%	18.99%
FET	-1.07E+03	1.40E+02	1.77E+00	1.80E+00	CTUh.m3.yr	-6.07E+02	7.91E+01	-5.97E+02	7.78E+01	1.67%	1.67%
FE	1.30E-03	1.00E-03	2.46E-05	2.51E-05	kg P-Eq	5.28E+01	4.07E+01	5.18E+01	3.98E+01	1.99%	1.99%
IR	1.44E-05	-2.30E-06	1.45E-07	1.47E-07	mol N-Eq	9.93E+01	-1.59E+01	9.80E+01	-1.56E+01	1.36%	1.36%
ME	8.00E-03	-1.54E-01	3.66E-04	5.19E-04	kg N-Eq	2.19E+01	-4.21E+02	1.54E+01	-2.97E+02	29.48%	29.48%
TE	3.60E-01	-1.68E+00	4.02E-03	5.69E-03	mol N-Eq	8.96E+01	-4.18E+02	6.33E+01	-2.95E+02	29.35%	29.35%
CE	7.50E-07	-3.00E-08	9.36E-09	9.56E-09	CTUh	8.01E+01	-3.21E+00	7.85E+01	-3.14E+00	2.09%	2.09%
NCE	-2.91E-05	5.60E-06	7.20E-08	7.32E-08	CTUh	-4.04E+02	7.78E+01	-3.98E+02	7.65E+01	1.64%	1.64%
OLD	5.19E-06	-1.80E-06	5.61E-08	5.69E-08	kg CFC-11-Eq	9.25E+01	-3.21E+01	9.12E+01	-3.16E+01	1.41%	1.41%
POC	1.05E-01	-4.45E-01	1.23E-03	1.63E-03	kg ethylene-Eq	8.54E+01	-3.62E+02	6.44E+01	-2.73E+02	24.54%	24.54%
REI	1.44E-02	-3.85E-02	1.56E-04	1.61E-04	kg PM2.5-Eq	9.23E+01	-2.47E+02	8.94E+01	-2.39E+02	3.11%	3.11%
LU	3.64E+02	2.89E+02	1.61E+00	1.63E+00	kg Soil Organic Carbon	2.26E+02	1.80E+02	2.23E+02	1.77E+02	1.23%	1.23%
MFR	2.63E-03	2.59E-03	2.11E-05	2.17E-05	kg Sb-Eq	1.25E+02	1.23E+02	1.21E+02	1.19E+02	2.76%	2.76%

D. Sensitivity analysis concrete - recycled content

Results for 30% recycled content versus 50%

Indicator	50% RCA					30% RCA					transport impact	Unit	additional km/m^3 concrete				difference 50% vs 30%	
	LCA results			difference		LCA results			difference				50%		30%			
	Primary concrete	Recycled concrete, wet processing	Recycled concrete, advanced dry rec.	wet processing	advanced dry rec.	Primary concrete	Wet processing	advanced dry rec.	wet processing	advanced dry rec.	EURO5 truck		wet processing	advanced dry rec.	wet processing	advanced dry rec.	wet processing	advanced dry rec.

GWP	2.44E+02	2.37E+02	2.55E+02	7.00E+00	-1.10E+01	2.44E+02	2.26E+02	2.37E+02	1.08E+00	1.03E+00	3.06E-01	kg CO2-Eq	2.29E+01	-3.59E+01	3.53E+00	3.36E+00	84.58%	109.36%
FTA	6.70E-01	5.56E-01	9.79E-01	1.14E-01	-3.09E-01	6.70E-01	5.43E-01	7.97E-01	1.23E+00	8.41E-01	1.28E-03	mol H+-Eq	8.91E+01	-2.41E+02	9.64E+02	6.57E+02	-982.36%	372.06%
FET	6.86E+02	1.76E+03	5.46E+02	-1.07E+03	1.40E+02	6.86E+02	1.25E+03	5.21E+02	5.49E-01	1.32E+00	1.77E+00	CTUh.m3.yr	-6.07E+02	7.91E+01	3.10E-01	7.44E-01	100.05%	99.06%
FE	2.92E-02	2.79E-02	2.82E-02	1.30E-03	1.00E-03	2.92E-02	2.73E-02	2.75E-02	1.07E+00	1.06E+00	2.46E-05	kg P-Eq	5.28E+01	4.07E+01	4.35E+04	4.32E+04	-82176.70%	-106081.82%
IR	6.52E-05	5.08E-05	6.75E-05	1.44E-05	-2.30E-06	6.52E-05	4.99E-05	5.99E-05	1.31E+00	1.09E+00	1.45E-07	mol N-Eq	9.93E+01	-1.59E+01	9.01E+06	7.51E+06	-9073602.96%	47325352.23%
ME	1.82E-01	1.74E-01	3.36E-01	8.00E-03	-1.54E-01	1.82E-01	1.61E-01	2.58E-01	1.13E+00	7.05E-01	3.66E-04	kg N-Eq	2.19E+01	-4.21E+02	3.09E+03	1.93E+03	-14030.43%	558.07%
TE	2.17E+00	1.81E+00	3.85E+00	3.60E-01	-1.68E+00	2.17E+00	1.77E+00	3.00E+00	1.23E+00	7.23E-01	4.02E-03	mol N-Eq	8.96E+01	-4.18E+02	3.05E+02	1.80E+02	-240.55%	143.06%
CE	5.16E-06	4.41E-06	5.19E-06	7.50E-07	-3.00E-08	5.16E-06	4.29E-06	4.75E-06	1.20E+00	1.09E+00	9.36E-09	CTUh	8.01E+01	-3.21E+00	1.29E+08	1.16E+08	-160372860.37%	3621052731.58%
NCE	2.84E-05	5.75E-05	2.28E-05	-2.91E-05	5.60E-06	2.84E-05	4.26E-05	2.18E-05	6.67E-01	1.30E+00	7.20E-08	CTUh	-4.04E+02	7.78E+01	9.26E+06	1.81E+07	2291050.74%	-23263333.81%
OLD	1.18E-05	6.61E-06	1.36E-05	5.19E-06	-1.80E-06	1.18E-05	6.10E-06	1.03E-05	1.93E+00	1.15E+00	5.61E-08	kg CFC-11-Eq	9.25E+01	-3.21E+01	3.45E+07	2.04E+07	-37272081.69%	63646270.44%
POC	5.34E-01	4.29E-01	9.79E-01	1.05E-01	-4.45E-01	5.34E-01	4.15E-01	7.45E-01	1.29E+00	7.17E-01	1.23E-03	kg ethylene-Eq	8.54E+01	-3.62E+02	1.05E+03	5.83E+02	-1125.47%	261.07%
REI	4.98E-02	3.54E-02	8.83E-02	1.44E-02	-3.85E-02	4.98E-02	3.40E-02	6.57E-02	1.46E+00	7.58E-01	1.56E-04	kg PM2.5-Eq	9.23E+01	-2.47E+02	9.39E+03	4.86E+03	-10071.57%	2068.81%
LU	1.12E+03	7.56E+02	8.31E+02	3.64E+02	2.89E+02	1.12E+03	8.28E+02	8.73E+02	1.35E+00	1.28E+00	1.61E+00	kg Soil Organic Carbon	2.26E+02	1.80E+02	8.40E-01	7.97E-01	99.63%	99.56%
MFR	5.88E-03	3.25E-03	3.29E-03	2.63E-03	2.59E-03	5.88E-03	3.23E-03	3.26E-03	1.82E+00	1.80E+00	2.11E-05	kg Sb-Eq	1.25E+02	1.23E+02	8.63E+04	8.55E+04	-69118.00%	-69540.19%

Results for 45% recycled content versus 50%

	RCA 45%							RCA 50%		Difference 50% vs 45% RCA	
	LCA results			transport impact	Unit	additional km		additional km			
indicator	primary	wet	Advanced dry rec.	truck EURO5		wet	Advanced dry rec.	wet	Advanced dry rec.	wet	Advanced dry rec.
GWP	2.44E+02	2.34E+02	2.51E+02	3.06E-01	kg CO2-Eq	3.27E+01	-2.29E+01	2.29E+01	-3.59E+01	-42.86%	36.36%
FTA	6.70E-01	5.53E-01	9.34E-01	1.28E-03	mol H+-Eq	9.14E+01	-2.06E+02	8.91E+01	-2.41E+02	-2.63%	14.56%
FET	6.86E+02	1.63E+03	5.40E+02	1.77E+00	CTUh.m3.yr	-5.33E+02	8.25E+01	-6.07E+02	7.91E+01	12.10%	-4.29%
FE	2.92E-02	2.78E-02	2.80E-02	2.46E-05	kg P-Eq	5.69E+01	4.88E+01	5.28E+01	4.07E+01	-7.69%	-20.00%
IR	6.52E-05	5.05E-05	6.56E-05	1.45E-07	mol N-Eq	1.01E+02	-2.76E+00	9.93E+01	-1.59E+01	-2.08%	82.61%
ME	1.82E-01	1.71E-01	3.16E-01	3.66E-04	kg N-Eq	3.01E+01	-3.66E+02	2.19E+01	-4.21E+02	-37.50%	12.99%
TE	2.17E+00	1.80E+00	3.64E+00	4.02E-03	mol N-Eq	9.20E+01	-3.66E+02	8.96E+01	-4.18E+02	-2.78%	12.50%
CE	5.16E-06	4.38E-06	5.08E-06	9.36E-09	CTUh	8.33E+01	8.55E+00	8.01E+01	-3.21E+00	-4.00%	366.67%
NCE	2.84E-05	5.38E-05	2.26E-05	7.20E-08	CTUh	-3.53E+02	8.06E+01	-4.04E+02	7.78E+01	12.71%	-3.57%
OLD	1.18E-05	6.48E-06	1.28E-05	5.61E-08	kg CFC-11-Eq	9.48E+01	-1.78E+01	9.25E+01	-3.21E+01	-2.50%	44.44%
POC	5.34E-01	4.25E-01	9.21E-01	1.23E-03	kg ethylene-Eq	8.86E+01	-3.15E+02	8.54E+01	-3.62E+02	-3.81%	13.03%
REI	4.98E-02	3.51E-02	8.27E-02	1.56E-04	kg PM2.5-Eq	9.42E+01	-2.11E+02	9.23E+01	-2.47E+02	-2.08%	14.55%
LU	1.12E+03	7.74E+02	8.42E+02	1.61E+00	kg Soil Organic Carbon	2.15E+02	1.73E+02	2.26E+02	1.80E+02	4.95%	3.81%
MFR	5.88E-03	3.25E-03	3.28E-03	2.11E-05	kg Sb-Eq	1.25E+02	1.23E+02	1.25E+02	1.23E+02	0.00%	-0.39%

Appendix IV – Copper results

A. Complete results for primary and recycled copper

	LCA results			**normalised results**		
	Primary copper	Recycled copper	Unit	primary copper	recycled copper	Unit
GWP	2.13	1.58	kg CO2-Eq	4.96E-14	3.68E-14	year
FTA	0.0824	0.0253	mol H+-Eq	2.72E-13	8.37E-14	year
FET	919	520	CTUh.m3.yr	3.08E-11	1.74E-11	year
FE	0.023	0.0134	kg P-Eq	1.53E-12	8.90E-13	year
IR	9.66E-07	8.51E-07	mol N-Eq	0.00E+00	0.00E+00	year
ME	0.214	0.00382	kg N-Eq	3.01E-12	5.37E-14	year
TE	0.117	0.0443	mol N-Eq	1.66E-13	6.32E-14	year
CE	1.55E-06	8.49E-07	CTUh	3.84E-12	2.10E-12	year
NCE	4.10E-05	2.81E-05	CTUh	1.38E-12	9.45E-13	year
OLD	2.09E-07	1.11E-07	kg CFC-11-Eq	1.75E-15	9.28E-16	year
POC	0.0257	0.00963	kg ethylene-Eq	8.63E-14	3.24E-14	year
REI	0.00753	0.00266	kg PM2.5-Eq	1.92E-13	6.77E-14	year
LU	22.2	7.31	kg Soil Organic Carbon	0	0	year
MFR	0.00406	0.000574	kg Sb-Eq	1.15E-11	1.63E-12	year

B. Distance calculations based on LCA

Indicator	**Difference**	**Transport impact**		**Unit**	**# additional km/kg copper**	
		truck	barge		truck	barge
GWP	5.50E-01	0.000127	4.80E-05	kg CO2-Eq	4.33E+03	1.15E+04
FTA	5.71E-02	5.33E-07	4.79E-07	mol H+-Eq	1.07E+05	1.19E+05
FET	3.99E+02	0.000738	0.00012	CTUh.m3.yr	5.41E+05	3.33E+06
FE	9.60E-03	1.02E-08	5.70E-09	kg P-Eq	9.41E+05	1.68E+06
IR	1.15E-07	6.03E-11	1.96E-11	mol N-Eq	1.91E+03	5.87E+03
ME	2.10E-01	1.52E-07	2.01E-07	kg N-Eq	1.38E+06	1.05E+06
TE	7.27E-02	1.67E-06	2.21E-06	mol N-Eq	4.35E+04	3.29E+04
CE	7.01E-07	3.90E-12	2.21E-12	CTUh	1.80E+05	3.17E+05
NCE	1.29E-05	3.00E-11	4.59E-12	CTUh	4.30E+05	2.81E+06
OLD	9.80E-08	2.34E-11	7.08E-12	kg CFC-11-Eq	4.19E+03	1.38E+04
POC	1.61E-02	5.12E-07	5.65E-07	kg ethylene-Eq	3.14E+04	2.84E+04
REI	4.87E-03	6.52E-08	2.06E-08	kg PM2.5-Eq	7.47E+04	2.36E+05
LU	1.49E+01	0.000672	0.000425	kg Soil Organic Carbon	2.22E+04	3.50E+04
MFR	3.49E-03	8.77E-09	3.63E-10	kg Sb-Eq	3.97E+05	9.60E+06

C. Sensitivity analysis copper – transport

Indicator	LCA results			transport impact		Unit	# additional km/kg copper		Difference EURO 5 vs EURO 4
	Primary	Recycled	Difference	EURO5	EURO4		EURO5	EURO4	
GWP	2.13E+00	1.58E+00	5.50E-01	1.27E-04	1.28E-04	kg CO2-Eq	4.33E+03	4.30E+03	0.78%
FTA	8.24E-02	2.53E-02	5.71E-02	5.33E-07	6.58E-07	mol H+-Eq	1.07E+05	8.68E+04	19.00%
FET	9.19E+02	5.20E+02	3.99E+02	7.38E-04	7.50E-04	CTUh.m3.yr	5.41E+05	5.32E+05	1.60%
FE	2.30E-02	1.34E-02	9.60E-03	1.02E-08	1.04E-08	kg P-Eq	9.41E+05	9.23E+05	1.92%
IR	9.66E-07	8.51E-07	1.15E-07	6.03E-11	6.11E-11	mol N-Eq	1.91E+03	1.88E+03	1.31%
ME	2.14E-01	3.82E-03	2.10E-01	1.52E-07	2.16E-07	kg N-Eq	1.38E+06	9.73E+05	29.63%
TE	1.17E-01	4.43E-02	7.27E-02	1.67E-06	2.37E-06	mol N-Eq	4.35E+04	3.07E+04	29.54%
CE	1.55E-06	8.49E-07	7.01E-07	3.90E-12	3.98E-12	CTUh	1.80E+05	1.76E+05	2.01%
NCE	4.10E-05	2.81E-05	1.29E-05	3.00E-11	3.05E-11	CTUh	4.30E+05	4.23E+05	1.64%
OLD	2.09E-07	1.11E-07	9.80E-08	2.34E-11	2.37E-11	kg CFC-11-Eq	4.19E+03	4.14E+03	1.27%
POC	2.57E-02	9.63E-03	1.61E-02	5.12E-07	6.77E-07	kg ethylene-Eq	3.14E+04	2.37E+04	24.37%
REI	7.53E-03	2.66E-03	4.87E-03	6.52E-08	6.71E-08	kg PM2.5-Eq	7.47E+04	7.26E+04	2.83%
LU	2.22E+01	7.31E+00	1.49E+01	6.72E-04	6.78E-04	kg Soil Organic Carbon	2.22E+04	2.20E+04	0.88%
MFR	4.06E-03	5.74E-04	3.49E-03	8.77E-09	9.03E-09	kg Sb-Eq	3.97E+05	3.86E+05	2.88%

D. Sensitivity analysis copper – recycled content

Indicator	LCA results			Difference		impact transport	Unit	# additional km/kg copper		difference 92 vs 87
	primary	recycled 92%	Recycled 87%	92%	87%	truck EURO5		92%	87%	
GWP	2.13E+00	1.58E+00	1.81E+00	5.50E-01	3.20E-01	1.27E-04	kg CO2-Eq	4.33E+03	2.52E+03	41.82%
FTA	8.24E-02	2.53E-02	3.26E-02	5.71E-02	4.98E-02	5.33E-07	mol H+-Eq	1.07E+05	9.34E+04	12.78%
FET	9.19E+02	5.20E+02	8.33E+02	3.99E+02	8.60E+01	7.38E-04	CTUh.m3.yr	5.41E+05	1.17E+05	78.45%
FE	2.30E-02	1.34E-02	2.12E-02	9.60E-03	1.80E-03	1.02E-08	kg P-Eq	9.41E+05	1.76E+05	81.25%
IR	9.66E-07	8.51E-07	9.19E-07	1.15E-07	4.70E-08	6.03E-11	mol N-Eq	1.91E+03	7.79E+02	59.13%

ME	2.14E-01	3.82E-03	5.17E-03	2.10E-01	2.09E-01	1.52E-07	kg N-Eq	1.38E+06	1.37E+06	0.64%
TE	1.17E-01	4.43E-02	5.99E-02	7.27E-02	5.71E-02	1.67E-06	mol N-Eq	4.35E+04	3.42E+04	21.46%
CE	1.55E-06	8.49E-07	1.32E-06	7.01E-07	2.30E-07	3.90E-12	CTUh	1.80E+05	5.90E+04	67.19%
NCE	4.10E-05	2.81E-05	4.09E-05	1.29E-05	1.00E-07	3.00E-11	CTUh	4.30E+05	3.33E+03	99.22%
OLD	2.09E-07	1.11E-07	1.18E-07	9.80E-08	9.10E-08	2.34E-11	kg CFC-11-Eq	4.19E+03	3.89E+03	7.14%
POC	2.57E-02	9.63E-03	1.27E-02	1.61E-02	1.30E-02	5.12E-07	kg ethylene-Eq	3.14E+04	2.54E+04	19.10%
REI	7.53E-03	2.66E-03	3.62E-03	4.87E-03	3.91E-03	6.52E-08	kg PM2.5-Eq	7.47E+04	6.00E+04	19.71%
LU	2.22E+01	7.31E+00	9.40E+00	1.49E+01	1.28E+01	6.72E-04	kg Soil Organic Carbon	2.22E+04	1.90E+04	14.04%
MFR	4.06E-03	5.74E-04	8.93E-04	3.49E-03	3.17E-03	8.77E-09	kg Sb-Eq	3.97E+05	3.61E+05	9.15%

E. Methods different transport modes – oceanic tanker, aircraft & train

For the calculation of transport distance by transoceanic tanker, aircraft and train the same methods are used as for truck and barge. Also the same reference flows and units are used as presented in Table 6.

Data unit processes used to calculate distances

Transport, freight, sea, transoceanic tanker[GLO]				
Economic inflows				
Label	*Name*	*Value*	*Unit*	*Data Source*
[G26]	maintenance, freight ship, transoceanic_market for maintenance, freight ship, transoceanic[GLO]	3.58E-12	unit	EcoInvent 3.4
[G1288]	heavy fuel oil_market for heavy fuel oil[RoW]	0.00108	kilogram	EcoInvent 3.4
[G3636]	port facilities_market for port facilities[GLO]	7.23E-15	unit	EcoInvent 3.4
[G3712]	heavy fuel oil_market group for heavy fuel oil[RER]	0.000222	kilogram	EcoInvent 3.4
[G7371]	tanker, transoceanic_market for tanker, transoceanic[GLO]	3.58E-12	unit	EcoInvent 3.4
Economic outflows				
Label	*Name*	*Value*	*Unit*	*Data Source*
[W1530]	bilge oil_market for bilge oil[RoW]	4.35E-06	kilogram	EcoInvent 3.4
[W5989]	bilge oil_market for bilge oil[Europe without Switzerland]	2.09E-06	kilogram	EcoInvent 3.4
[W8474]	bilge oil_market for bilge oil[CH]	5.47E-08	kilogram	EcoInvent 3.4
[G11689]	transport, freight, sea, transoceanic tanker_transport, freight, sea, transoceanic tanker[GLO]	1	ton kilometer	EcoInvent 3.4
Environmental resources				
Label	*Name*	*Value*	*Unit*	*Data Source*
Environmental emissions				
Label	*Name*	*Value*	*Unit*	*Data Source*
[E742]	Ammonia[('air', 'non-urban air or from high stacks')]	5.20E-07	kilogram	EcoInvent 3.4
[E751]	Arsenic[('air', 'non-urban air or from high stacks')]	4.89E-10	kilogram	EcoInvent 3.4
[E761]	Benzene[('air', 'non-urban air or from high stacks')]	2.86E-08	kilogram	EcoInvent 3.4
[E784]	Cadmium[('air', 'non-urban air or from high stacks')]	3.18E-11	kilogram	EcoInvent 3.4
[E793]	Carbon dioxide, fossil[('air', 'non-urban air or from high stacks')]	0.004	kilogram	EcoInvent 3.4
[E800]	Carbon monoxide, fossil[('air', 'non-urban air or from high stacks')]	4.02E-06	kilogram	EcoInvent 3.4
[E813]	Chromium[('air', 'non-urban air or from high stacks')]	2.03E-10	kilogram	EcoInvent 3.4
[E825]	Copper[('air', 'non-urban air or from high stacks')]	4.89E-10	kilogram	EcoInvent 3.4
[E836]	Dinitrogen monoxide[('air', 'non-urban air or from high stacks')]	1.04E-07	kilogram	EcoInvent 3.4
[E840]	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin[('air', 'non-urban air or from high stacks')]	1.30E-15	kilogram	EcoInvent 3.4
[E896]	Hydrogen chloride[('air', 'non-urban air or from high stacks')]	7.71E-08	kilogram	EcoInvent 3.4
[E899]	Hydrogen fluoride[('air', 'non-urban air or from high stacks')]	7.71E-09	kilogram	EcoInvent 3.4
[E921]	Lead[('air', 'non-urban air or from high stacks')]	2.24E-10	kilogram	EcoInvent 3.4
[E934]	Mercury[('air', 'non-urban air or from high stacks')]	3.67E-11	kilogram	EcoInvent 3.4

[E949]	Methane, fossil[('air', 'non-urban air or from high stacks')]	3.61E-08	kilogram	EcoInvent 3.4
[E965]	Nickel[('air', 'non-urban air or from high stacks')]	2.83E-08	kilogram	EcoInvent 3.4
[E973]	Nitrogen oxides[('air', 'non-urban air or from high stacks')]	3.30E-05	kilogram	EcoInvent 3.4
[E977]	NMVOC, non-methane volatile organic compounds, unspecified origin[('air', 'non-urban air or from high stacks')]	1.50E-06	kilogram	EcoInvent 3.4
[E983]	PAH, polycyclic aromatic hydrocarbons[('air', 'non-urban air or from high stacks')]	2.60E-09	kilogram	EcoInvent 3.4
[E986]	Particulates, < 2.5 um[('air', 'non-urban air or from high stacks')]	1.87E-06	kilogram	EcoInvent 3.4
[E990]	Particulates, > 10 um[('air', 'non-urban air or from high stacks')]	2.68E-06	kilogram	EcoInvent 3.4
[E993]	Particulates, > 2.5 um, and < 10um[('air', 'non-urban air or from high stacks')]	2.14E-06	kilogram	EcoInvent 3.4
[E1043]	Selenium[('air', 'non-urban air or from high stacks')]	4.48E-10	kilogram	EcoInvent 3.4
[E1067]	Sulfur dioxide[('air', 'non-urban air or from high stacks')]	9.10E-05	kilogram	EcoInvent 3.4
[E1091]	Toluene[('air', 'non-urban air or from high stacks')]	1.20E-08	kilogram	EcoInvent 3.4
[E1112]	Xylene[('air', 'non-urban air or from high stacks')]	1.20E-08	kilogram	EcoInvent 3.4
[E1114]	Zinc[('air', 'non-urban air or from high stacks')]	1.03E-09	kilogram	EcoInvent 3.4
[E1285]	BOD5, Biological Oxygen Demand[('water', 'ocean')]	0.000286	kilogram	EcoInvent 3.4
[E1365]	COD, Chemical Oxygen Demand[('water', 'ocean')]	0.000286	kilogram	EcoInvent 3.4
[E1391]	DOC, Dissolved Organic Carbon[('water', 'ocean')]	7.87E-05	kilogram	EcoInvent 3.4
[E1524]	Oils, unspecified[('water', 'ocean')]	9.09E-05	kilogram	EcoInvent 3.4
[E1653]	TOC, Total Organic Carbon[('water', 'ocean')]	7.87E-05	kilogram	EcoInvent 3.4
[E1660]	Tributyltin compounds[('water', 'ocean')]	1.00E-08	kilogram	EcoInvent 3.4
Transport, freight, aircraft, intracontinental[RER]				
Economic inflows				
Label	*Name*	*Value*	*Unit*	*Data Source*
[G2525]	kerosene_market for kerosene[Europe without Switzerland]	0.435	kilogram	EcoInvent 3.4
[G3809]	airport_market for airport[GLO]	2.35E-14	unit	EcoInvent 3.4
[G5932]	aircraft, medium haul_market for aircraft, medium haul[GLO]	2.39E-09	unit	EcoInvent 3.4
[G11992]	kerosene_market for kerosene[CH]	0.0181	kilogram	EcoInvent 3.4
Economic outflows				
Label	*Name*	*Value*	*Unit*	*Data Source*
[G4134]	transport, freight, aircraft_transport, freight, aircraft, intracontinental[RER]	1	ton kilometer	EcoInvent 3.4
Environmental resources				
Label	*Name*	*Value*	*Unit*	*Data Source*
Environmental emissions				
Label	*Name*	*Value*	*Unit*	*Data Source*
[E761]	Benzene[('air', 'non-urban air or from high stacks')]	3.71E-06	kilogram	EcoInvent 3.4
[E762]	Benzene[('air', 'lower stratosphere + upper troposphere')]	1.60E-06	kilogram	EcoInvent 3.4
[E763]	Benzene[('air',)]	3.73E-06	kilogram	EcoInvent 3.4

[E778]	Butadiene[('air', 'non-urban air or from high stacks')]	3.51E-06	kilogram	EcoInvent 3.4
[E779]	Butadiene[('air', 'lower stratosphere + upper troposphere')]	1.52E-06	kilogram	EcoInvent 3.4
[E780]	Butadiene[('air',)]	3.54E-06	kilogram	EcoInvent 3.4
[E784]	Cadmium[('air', 'non-urban air or from high stacks')]	1.86E-09	kilogram	EcoInvent 3.4
[E786]	Cadmium[('air', 'lower stratosphere + upper troposphere')]	8.02E-10	kilogram	EcoInvent 3.4
[E787]	Cadmium[('air',)]	1.87E-09	kilogram	EcoInvent 3.4
[E793]	Carbon dioxide, fossil[('air', 'non-urban air or from high stacks')]	0.585	kilogram	EcoInvent 3.4
[E794]	Carbon dioxide, fossil[('air', 'lower stratosphere + upper troposphere')]	0.253	kilogram	EcoInvent 3.4
[E795]	Carbon dioxide, fossil[('air',)]	0.589	kilogram	EcoInvent 3.4
[E800]	Carbon monoxide, fossil[('air', 'non-urban air or from high stacks')]	0.000687	kilogram	EcoInvent 3.4
[E801]	Carbon monoxide, fossil[('air', 'lower stratosphere + upper troposphere')]	0.000297	kilogram	EcoInvent 3.4
[E802]	Carbon monoxide, fossil[('air',)]	0.000692	kilogram	EcoInvent 3.4
[E813]	Chromium[('air', 'non-urban air or from high stacks')]	9.29E-09	kilogram	EcoInvent 3.4
[E814]	Chromium[('air', 'lower stratosphere + upper troposphere')]	4.01E-09	kilogram	EcoInvent 3.4
[E815]	Chromium[('air',)]	9.35E-09	kilogram	EcoInvent 3.4
[E825]	Copper[('air', 'non-urban air or from high stacks')]	3.16E-07	kilogram	EcoInvent 3.4
[E827]	Copper[('air', 'lower stratosphere + upper troposphere')]	1.36E-07	kilogram	EcoInvent 3.4
[E828]	Copper[('air',)]	3.18E-07	kilogram	EcoInvent 3.4
[E836]	Dinitrogen monoxide[('air', 'non-urban air or from high stacks')]	5.57E-06	kilogram	EcoInvent 3.4
[E838]	Dinitrogen monoxide[('air', 'lower stratosphere + upper troposphere')]	2.41E-06	kilogram	EcoInvent 3.4
[E839]	Dinitrogen monoxide[('air',)]	5.61E-06	kilogram	EcoInvent 3.4
[E865]	Ethylene oxide[('air', 'non-urban air or from high stacks')]	3.39E-05	kilogram	EcoInvent 3.4
[E866]	Ethylene oxide[('air', 'lower stratosphere + upper troposphere')]	1.46E-05	kilogram	EcoInvent 3.4
[E867]	Ethylene oxide[('air',)]	3.42E-05	kilogram	EcoInvent 3.4
[E873]	Formaldehyde[('air', 'non-urban air or from high stacks')]	2.93E-05	kilogram	EcoInvent 3.4
[E874]	Formaldehyde[('air', 'lower stratosphere + upper troposphere')]	1.26E-05	kilogram	EcoInvent 3.4
[E875]	Formaldehyde[('air',)]	2.95E-05	kilogram	EcoInvent 3.4
[E896]	Hydrogen chloride[('air', 'non-urban air or from high stacks')]	1.60E-07	kilogram	EcoInvent 3.4
[E897]	Hydrogen chloride[('air', 'lower stratosphere + upper troposphere')]	6.89E-08	kilogram	EcoInvent 3.4
[E898]	Hydrogen chloride[('air',)]	1.61E-07	kilogram	EcoInvent 3.4
[E921]	Lead[('air', 'non-urban air or from high stacks')]	3.72E-09	kilogram	EcoInvent 3.4
[E923]	Lead[('air', 'lower stratosphere + upper troposphere')]	1.60E-09	kilogram	EcoInvent 3.4
[E924]	Lead[('air',)]	3.74E-09	kilogram	EcoInvent 3.4
[E934]	Mercury[('air', 'non-urban air or from high stacks')]	1.30E-11	kilogram	EcoInvent 3.4

[E936]	Mercury[('air', 'lower stratosphere + upper troposphere')]	5.61E-12	kilogram	EcoInvent 3.4
[E937]	Mercury[('air',)]	1.31E-11	kilogram	EcoInvent 3.4
[E949]	Methane, fossil[('air', 'non-urban air or from high stacks')]	9.29E-06	kilogram	EcoInvent 3.4
[E950]	Methane, fossil[('air', 'lower stratosphere + upper troposphere')]	4.01E-06	kilogram	EcoInvent 3.4
[E951]	Methane, fossil[('air',)]	9.35E-06	kilogram	EcoInvent 3.4
[E965]	Nickel[('air', 'non-urban air or from high stacks')]	1.30E-08	kilogram	EcoInvent 3.4
[E967]	Nickel[('air', 'lower stratosphere + upper troposphere')]	5.61E-09	kilogram	EcoInvent 3.4
[E968]	Nickel[('air',)]	1.31E-08	kilogram	EcoInvent 3.4
[E973]	Nitrogen oxides[('air', 'non-urban air or from high stacks')]	0.0026	kilogram	EcoInvent 3.4
[E975]	Nitrogen oxides[('air', 'lower stratosphere + upper troposphere')]	0.00112	kilogram	EcoInvent 3.4
[E976]	Nitrogen oxides[('air',)]	0.00262	kilogram	EcoInvent 3.4
[E977]	NMVOC, non-methane volatile organic compounds, unspecified origin[('air', 'non-urban air or from high stacks')]	0.000125	kilogram	EcoInvent 3.4
[E978]	NMVOC, non-methane volatile organic compounds, unspecified origin[('air', 'lower stratosphere + upper troposphere')]	5.38E-05	kilogram	EcoInvent 3.4
[E979]	NMVOC, non-methane volatile organic compounds, unspecified origin[('air',)]	0.000126	kilogram	EcoInvent 3.4
[E986]	Particulates, < 2.5 um[('air', 'non-urban air or from high stacks')]	7.06E-06	kilogram	EcoInvent 3.4
[E988]	Particulates, < 2.5 um[('air', 'lower stratosphere + upper troposphere')]	3.05E-06	kilogram	EcoInvent 3.4
[E989]	Particulates, < 2.5 um[('air',)]	7.11E-06	kilogram	EcoInvent 3.4
[E1043]	Selenium[('air', 'non-urban air or from high stacks')]	1.86E-09	kilogram	EcoInvent 3.4
[E1045]	Selenium[('air', 'lower stratosphere + upper troposphere')]	8.02E-10	kilogram	EcoInvent 3.4
[E1046]	Selenium[('air',)]	1.87E-09	kilogram	EcoInvent 3.4
[E1067]	Sulfur dioxide[('air', 'non-urban air or from high stacks')]	0.000186	kilogram	EcoInvent 3.4
[E1068]	Sulfur dioxide[('air', 'lower stratosphere + upper troposphere')]	8.02E-05	kilogram	EcoInvent 3.4
[E1069]	Sulfur dioxide[('air',)]	0.000187	kilogram	EcoInvent 3.4
[E1114]	Zinc[('air', 'non-urban air or from high stacks')]	1.86E-07	kilogram	EcoInvent 3.4
[E1116]	Zinc[('air', 'lower stratosphere + upper troposphere')]	8.02E-08	kilogram	EcoInvent 3.4
[E1117]	Zinc[('air',)]	1.87E-07	kilogram	EcoInvent 3.4
[E1797]	Water[('air',)]	0.000232	cubic meter	EcoInvent 3.4
[E1799]	Water[('air', 'lower stratosphere + upper troposphere')]	9.94E-05	cubic meter	EcoInvent 3.4
[E1800]	Water[('air', 'non-urban air or from high stacks')]	0.00023	cubic meter	EcoInvent 3.4

Transport, freight, aircraft, intercontinental[RER]

Economic inflows

Label	*Name*	*Value*	*Unit*	*Data Source*
[G205]	aircraft, long haul_market for aircraft, long haul[GLO]	3.16E-10	unit	EcoInvent 3.4
[G2525]	kerosene_market for kerosene[Europe without Switzerland]	0.277	kilogram	EcoInvent 3.4
[G3809]	airport_market for airport[GLO]	8.24E-13	unit	EcoInvent 3.4

[G11992]	kerosene_market for kerosene[CH]	0.0115	kilogram	EcoInvent 3.4
Economic outflows				
Label	*Name*	*Value*	*Unit*	*Data Source*
[G12997]	transport, freight, aircraft_transport, freight, aircraft, intercontinental[RER]	1	ton kilometer	EcoInvent 3.4
Environmental resources				
Label	*Name*	*Value*	*Unit*	*Data Source*
Environmental emissions				
Label	*Name*	*Value*	*Unit*	*Data Source*
[E761]	Benzene[('air', 'non-urban air or from high stacks')]	2.58E-07	kilogram	EcoInvent 3.4
[E762]	Benzene[('air', 'lower stratosphere + upper troposphere')]	1.65E-06	kilogram	EcoInvent 3.4
[E763]	Benzene[('air',)]	3.84E-06	kilogram	EcoInvent 3.4
[E778]	Butadiene[('air', 'non-urban air or from high stacks')]	2.44E-07	kilogram	EcoInvent 3.4
[E779]	Butadiene[('air', 'lower stratosphere + upper troposphere')]	1.56E-06	kilogram	EcoInvent 3.4
[E780]	Butadiene[('air',)]	3.64E-06	kilogram	EcoInvent 3.4
[E784]	Cadmium[('air', 'non-urban air or from high stacks')]	1.29E-10	kilogram	EcoInvent 3.4
[E786]	Cadmium[('air', 'lower stratosphere + upper troposphere')]	8.25E-10	kilogram	EcoInvent 3.4
[E787]	Cadmium[('air',)]	1.93E-09	kilogram	EcoInvent 3.4
[E793]	Carbon dioxide, fossil[('air', 'non-urban air or from high stacks')]	0.0407	kilogram	EcoInvent 3.4
[E794]	Carbon dioxide, fossil[('air', 'lower stratosphere + upper troposphere')]	0.26	kilogram	EcoInvent 3.4
[E795]	Carbon dioxide, fossil[('air',)]	0.607	kilogram	EcoInvent 3.4
[E800]	Carbon monoxide, fossil[('air', 'non-urban air or from high stacks')]	4.78E-05	kilogram	EcoInvent 3.4
[E801]	Carbon monoxide, fossil[('air', 'lower stratosphere + upper troposphere')]	0.000305	kilogram	EcoInvent 3.4
[E802]	Carbon monoxide, fossil[('air',)]	0.000712	kilogram	EcoInvent 3.4
[E813]	Chromium[('air', 'non-urban air or from high stacks')]	6.47E-10	kilogram	EcoInvent 3.4
[E814]	Chromium[('air', 'lower stratosphere + upper troposphere')]	4.13E-09	kilogram	EcoInvent 3.4
[E815]	Chromium[('air',)]	9.63E-09	kilogram	EcoInvent 3.4
[E825]	Copper[('air', 'non-urban air or from high stacks')]	2.20E-08	kilogram	EcoInvent 3.4
[E827]	Copper[('air', 'lower stratosphere + upper troposphere')]	1.40E-07	kilogram	EcoInvent 3.4
[E828]	Copper[('air',)]	3.27E-07	kilogram	EcoInvent 3.4
[E836]	Dinitrogen monoxide[('air', 'non-urban air or from high stacks')]	3.88E-07	kilogram	EcoInvent 3.4
[E838]	Dinitrogen monoxide[('air', 'lower stratosphere + upper troposphere')]	2.48E-06	kilogram	EcoInvent 3.4
[E839]	Dinitrogen monoxide[('air',)]	5.78E-06	kilogram	EcoInvent 3.4
[E865]	Ethylene oxide[('air', 'non-urban air or from high stacks')]	2.36E-06	kilogram	EcoInvent 3.4
[E866]	Ethylene oxide[('air', 'lower stratosphere + upper troposphere')]	1.51E-05	kilogram	EcoInvent 3.4
[E867]	Ethylene oxide[('air',)]	3.52E-05	kilogram	EcoInvent 3.4

[E873]	Formaldehyde[('air', 'non-urban air or from high stacks')]	2.04E-06	kilogram	EcoInvent 3.4
[E874]	Formaldehyde[('air', 'lower stratosphere + upper troposphere')]	1.30E-05	kilogram	EcoInvent 3.4
[E875]	Formaldehyde[('air',)]	3.03E-05	kilogram	EcoInvent 3.4
[E896]	Hydrogen chloride[('air', 'non-urban air or from high stacks')]	1.11E-08	kilogram	EcoInvent 3.4
[E897]	Hydrogen chloride[('air', 'lower stratosphere + upper troposphere')]	7.10E-08	kilogram	EcoInvent 3.4
[E898]	Hydrogen chloride[('air',)]	1.66E-07	kilogram	EcoInvent 3.4
[E921]	Lead[('air', 'non-urban air or from high stacks')]	2.59E-10	kilogram	EcoInvent 3.4
[E923]	Lead[('air', 'lower stratosphere + upper troposphere')]	1.65E-09	kilogram	EcoInvent 3.4
[E924]	Lead[('air',)]	3.85E-09	kilogram	EcoInvent 3.4
[E934]	Mercury[('air', 'non-urban air or from high stacks')]	9.05E-13	kilogram	EcoInvent 3.4
[E936]	Mercury[('air', 'lower stratosphere + upper troposphere')]	5.78E-12	kilogram	EcoInvent 3.4
[E937]	Mercury[('air',)]	1.35E-11	kilogram	EcoInvent 3.4
[E949]	Methane, fossil[('air', 'non-urban air or from high stacks')]	6.47E-07	kilogram	EcoInvent 3.4
[E950]	Methane, fossil[('air', 'lower stratosphere + upper troposphere')]	4.13E-06	kilogram	EcoInvent 3.4
[E951]	Methane, fossil[('air',)]	9.63E-06	kilogram	EcoInvent 3.4
[E965]	Nickel[('air', 'non-urban air or from high stacks')]	9.05E-10	kilogram	EcoInvent 3.4
[E967]	Nickel[('air', 'lower stratosphere + upper troposphere')]	5.78E-09	kilogram	EcoInvent 3.4
[E968]	Nickel[('air',)]	1.35E-08	kilogram	EcoInvent 3.4
[E973]	Nitrogen oxides[('air', 'non-urban air or from high stacks')]	0.000181	kilogram	EcoInvent 3.4
[E975]	Nitrogen oxides[('air', 'lower stratosphere + upper troposphere')]	0.00116	kilogram	EcoInvent 3.4
[E976]	Nitrogen oxides[('air',)]	0.0027	kilogram	EcoInvent 3.4
[E977]	NMVOC, non-methane volatile organic compounds, unspecified origin[('air', 'non-urban air or from high stacks')]	8.68E-06	kilogram	EcoInvent 3.4
[E978]	NMVOC, non-methane volatile organic compounds, unspecified origin[('air', 'lower stratosphere + upper troposphere')]	5.54E-05	kilogram	EcoInvent 3.4
[E979]	NMVOC, non-methane volatile organic compounds, unspecified origin[('air',)]	0.000129	kilogram	EcoInvent 3.4
[E986]	Particulates, < 2.5 um[('air', 'non-urban air or from high stacks')]	4.91E-07	kilogram	EcoInvent 3.4
[E988]	Particulates, < 2.5 um[('air', 'lower stratosphere + upper troposphere')]	3.14E-06	kilogram	EcoInvent 3.4
[E989]	Particulates, < 2.5 um[('air',)]	7.32E-06	kilogram	EcoInvent 3.4
[E1043]	Selenium[('air', 'non-urban air or from high stacks')]	1.29E-10	kilogram	EcoInvent 3.4
[E1045]	Selenium[('air', 'lower stratosphere + upper troposphere')]	8.25E-10	kilogram	EcoInvent 3.4
[E1046]	Selenium[('air',)]	1.93E-09	kilogram	EcoInvent 3.4
[E1067]	Sulfur dioxide[('air', 'non-urban air or from high stacks')]	1.29E-05	kilogram	EcoInvent 3.4
[E1068]	Sulfur dioxide[('air', 'lower stratosphere + upper troposphere')]	8.25E-05	kilogram	EcoInvent 3.4
[E1069]	Sulfur dioxide[('air',)]	0.000193	kilogram	EcoInvent 3.4
[E1114]	Zinc[('air', 'non-urban air or from high stacks')]	1.29E-08	kilogram	EcoInvent 3.4

[E1116]	Zinc[('air', 'lower stratosphere + upper troposphere')]	8.25E-08	kilogram	EcoInvent 3.4
[E1117]	Zinc[('air',)]	1.93E-07	kilogram	EcoInvent 3.4
[E1797]	Water[('air',)]	0.000239	cubic meter	EcoInvent 3.4
[E1799]	Water[('air', 'lower stratosphere + upper troposphere')]	0.000102	cubic meter	EcoInvent 3.4
[E1800]	Water[('air', 'non-urban air or from high stacks')]	1.60E-05	cubic meter	EcoInvent 3.4
Transport, freight train, electricity[Europe without Switzerland]				
Economic inflows				
Label	*Name*	*Value*	*Unit*	*Data Source*
[G1389]	maintenance, locomotive_market for maintenance, locomotive[GLO]	7.11E-10	unit	EcoInvent 3.4
[G5792]	goods wagon_market for goods wagon[GLO]	4.59E-08	unit	EcoInvent 3.4
[G7829]	locomotive_market for locomotive[GLO]	7.11E-10	unit	EcoInvent 3.4
[G11839]	electricity, high voltage_market group for electricity, high voltage[Europe without Switzerland]	0.0478	kilowatt hour	EcoInvent 3.4
[G12099]	diesel_market for diesel[Europe without Switzerland]	0.000677	kilogram	EcoInvent 3.4
[G12222]	railway track_market for railway track[RoW]	9.30E-05	meter-year	EcoInvent 3.4
[G12647]	maintenance, goods wagon_market for maintenance, goods wagon[GLO]	4.59E-08	unit	EcoInvent 3.4
Economic outflows				
Label	*Name*	*Value*	*Unit*	*Data Source*
[G1705]	transport, freight train_transport, freight train, electricity[Europe without Switzerland]	1	ton kilometer	EcoInvent 3.4
Environmental resources				
Label	*Name*	*Value*	*Unit*	*Data Source*
Environmental emissions				
Label	*Name*	*Value*	*Unit*	*Data Source*
[E744]	Ammonia[('air',)]	1.35E-08	kilogram	EcoInvent 3.4
[E763]	Benzene[('air',)]	6.77E-08	kilogram	EcoInvent 3.4
[E787]	Cadmium[('air',)]	6.77E-12	kilogram	EcoInvent 3.4
[E795]	Carbon dioxide, fossil[('air',)]	0.00213	kilogram	EcoInvent 3.4
[E802]	Carbon monoxide, fossil[('air',)]	1.07E-05	kilogram	EcoInvent 3.4
[E815]	Chromium[('air',)]	3.39E-11	kilogram	EcoInvent 3.4
[E828]	Copper[('air',)]	1.15E-09	kilogram	EcoInvent 3.4
[E839]	Dinitrogen monoxide[('air',)]	6.77E-08	kilogram	EcoInvent 3.4
[E924]	Lead[('air',)]	7.45E-14	kilogram	EcoInvent 3.4
[E937]	Mercury[('air',)]	1.35E-14	kilogram	EcoInvent 3.4
[E951]	Methane, fossil[('air',)]	8.80E-08	kilogram	EcoInvent 3.4
[E968]	Nickel[('air',)]	4.74E-11	kilogram	EcoInvent 3.4
[E976]	Nitrogen oxides[('air',)]	3.72E-05	kilogram	EcoInvent 3.4
[E979]	NMVOC, non-methane volatile organic compounds, unspecified origin[('air',)]	3.43E-06	kilogram	EcoInvent 3.4

[E989]	Particulates, < 2.5 um[('air',)]	8.69E-07	kilogram	EcoInvent 3.4
[E992]	Particulates, > 10 um[('air',)]	1.58E-05	kilogram	EcoInvent 3.4
[E995]	Particulates, > 2.5 um, and < 10um[('air',)]	6.91E-06	kilogram	EcoInvent 3.4
[E1046]	Selenium[('air',)]	6.77E-12	kilogram	EcoInvent 3.4
[E1069]	Sulfur dioxide[('air',)]	4.06E-07	kilogram	EcoInvent 3.4
[E1071]	Sulfur hexafluoride[('air',)]	2.10E-09	kilogram	EcoInvent 3.4
[E1092]	Toluene[('air',)]	2.71E-08	kilogram	EcoInvent 3.4
[E1113]	Xylene[('air',)]	2.71E-08	kilogram	EcoInvent 3.4
[E1117]	Zinc[('air',)]	6.77E-10	kilogram	EcoInvent 3.4
[E1160]	Iron[('soil',)]	6.02E-05	kilogram	EcoInvent 3.4
Transport, freight train, diesel[Europe without Switzerland]				
Economic inflows				
Label	*Name*	*Value*	*Unit*	*Data Source*
[G1389]	maintenance, locomotive_market for maintenance, locomotive[GLO]	7.11E-10	unit	EcoInvent 3.4
[G5792]	goods wagon_market for goods wagon[GLO]	4.59E-08	unit	EcoInvent 3.4
[G7829]	locomotive_market for locomotive[GLO]	7.11E-10	unit	EcoInvent 3.4
[G12099]	diesel_market for diesel[Europe without Switzerland]	0.0107	kilogram	EcoInvent 3.4
[G12222]	railway track_market for railway track[RoW]	9.30E-05	meter-year	EcoInvent 3.4
[G12647]	maintenance, goods wagon_market for maintenance, goods wagon[GLO]	4.59E-08	unit	EcoInvent 3.4
Economic outflows				
Label	*Name*	*Value*	*Unit*	*Data Source*
[G4216]	transport, freight train_transport, freight train, diesel[Europe without Switzerland]	1	ton kilometer	EcoInvent 3.4
Environmental resources				
Label	*Name*	*Value*	*Unit*	*Data Source*
Environmental emissions				
Label	*Name*	*Value*	*Unit*	*Data Source*
[E744]	Ammonia[('air',)]	2.14E-07	kilogram	EcoInvent 3.4
[E763]	Benzene[('air',)]	1.07E-06	kilogram	EcoInvent 3.4
[E787]	Cadmium[('air',)]	1.07E-10	kilogram	EcoInvent 3.4
[E795]	Carbon dioxide, fossil[('air',)]	0.0336	kilogram	EcoInvent 3.4
[E802]	Carbon monoxide, fossil[('air',)]	0.000169	kilogram	EcoInvent 3.4
[E815]	Chromium[('air',)]	5.34E-10	kilogram	EcoInvent 3.4
[E828]	Copper[('air',)]	1.82E-08	kilogram	EcoInvent 3.4
[E839]	Dinitrogen monoxide[('air',)]	1.07E-06	kilogram	EcoInvent 3.4
[E924]	Lead[('air',)]	1.17E-12	kilogram	EcoInvent 3.4
[E937]	Mercury[('air',)]	2.14E-13	kilogram	EcoInvent 3.4

[E951]	Methane, fossil[('air',)]	1.39E-06	kilogram	EcoInvent 3.4
[E968]	Nickel[('air',)]	7.47E-10	kilogram	EcoInvent 3.4
[E976]	Nitrogen oxides[('air',)]	0.000587	kilogram	EcoInvent 3.4
[E979]	NMVOC, non-methane volatile organic compounds, unspecified origin[('air',)]	5.41E-05	kilogram	EcoInvent 3.4
[E989]	Particulates, < 2.5 um[('air',)]	1.37E-05	kilogram	EcoInvent 3.4
[E992]	Particulates, > 10 um[('air',)]	1.63E-05	kilogram	EcoInvent 3.4
[E995]	Particulates, > 2.5 um, and < 10um[('air',)]	7.44E-06	kilogram	EcoInvent 3.4
[E1046]	Selenium[('air',)]	1.07E-10	kilogram	EcoInvent 3.4
[E1069]	Sulfur dioxide[('air',)]	6.41E-06	kilogram	EcoInvent 3.4
[E1092]	Toluene[('air',)]	4.27E-07	kilogram	EcoInvent 3.4
[E1113]	Xylene[('air',)]	4.27E-07	kilogram	EcoInvent 3.4
[E1117]	Zinc[('air',)]	1.07E-08	kilogram	EcoInvent 3.4
[E1160]	Iron[('soil',)]	6.02E-05	kilogram	EcoInvent 3.4

Distance calculations full results

Indicator	**Difference**	**Transport impact/ 0.001 tkm**					**Unit**	**# additional km/kg copper**				
		transoceanic tanker	intracontinental flight	intercontinental flight	electric train	diesel train		transoceanic tanker	intracontinental flight	intercontinental flight	electric train	diesel train
GWP	5.50E-01	6.03E-06	0.00168	0.00108	4.23E-05	5.83E-05	kg CO2-Eq	9.12E+04	3.27E+02	5.09E+02	1.30E+04	9.43E+03
FTA	5.71E-02	1.61E-07	8.25E-06	5.32E-06	2.83E-07	6.23E-07	mol H+-Eq	3.55E+05	6.92E+03	1.07E+04	2.02E+05	9.17E+04
FET	3.99E+02	1.36E-05	0.000749	0.000588	0.000412	0.000265	CTUh.m3.yr	2.93E+07	5.33E+05	6.79E+05	9.68E+05	1.51E+06
FE	9.60E-03	8.53E-10	3.14E-08	2.66E-08	2.92E-08	9.52E-09	kg P-Eq	1.13E+07	3.06E+05	3.61E+05	3.29E+05	1.01E+06
IR	1.15E-07	2.80E-12	7.60E-10	4.89E-10	3.16E-11	2.32E-11	mol N-Eq	4.11E+04	1.51E+02	2.35E+02	3.64E+03	4.96E+03
ME	2.10E-01	1.50E-08	2.78E-06	1.78E-06	5.47E-08	2.57E-07	kg N-Eq	1.40E+07	7.56E+04	1.18E+05	3.84E+06	8.18E+05
TE	7.27E-02	1.70E-07	3.05E-05	1.95E-05	6.46E-07	2.81E-06	mol N-Eq	4.28E+05	2.38E+03	3.73E+03	1.13E+05	2.59E+04
CE	7.01E-07	1.90E-13	8.95E-12	6.55E-12	6.95E-12	5.46E-12	CTUh	3.69E+06	7.83E+04	1.07E+05	1.01E+05	1.28E+05
NCE	1.29E-05	5.08E-13	3.75E-11	2.80E-11	1.58E-11	1.04E-11	CTUh	2.54E+07	3.44E+05	4.61E+05	8.16E+05	1.24E+06
OLD	9.80E-08	9.42E-13	3.10E-10	1.98E-10	3.78E-12	8.51E-12	kg CFC-11-Eq	1.04E+05	3.16E+02	4.95E+02	2.59E+04	1.15E+04
POC	1.61E-02	4.94E-08	8.22E-06	5.28E-06	1.52E-07	7.43E-07	kg ethylene-Eq	3.25E+05	1.95E+03	3.04E+03	1.06E+05	2.16E+04
REI	4.87E-03	8.29E-09	3.26E-07	2.21E-07	2.75E-08	4.09E-08	kg PM2.5-Eq	5.87E+05	1.49E+04	2.20E+04	1.77E+05	1.19E+05
LU	1.49E+01	1.62E-05	0.00427	0.00281	0.000155	0.000224	kg Soil Organic Carbon	9.19E+05	3.49E+03	5.30E+03	9.61E+04	6.65E+04
MFR	3.49E-03	1.85E-11	2.67E-09	2.07E-09	9.39E-10	8.87E-10	kg Sb-Eq	1.88E+08	1.31E+06	1.68E+06	3.71E+06	3.93E+06