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Life cycle assessment of coated abrasives and polishing agents

Case Mirka

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ABSTRACT:

This thesis presents and discusses the lifecycle assessment (LCA) of coated abrasives and polishing agents. The thesis was commissioned by Mirka Ltd. in 2020 and it's aims are to 1) establish the environmental impact (as carbon and water footprints) of coated abrasives and polishing agents throughout the products' life cycles and 2) compare the carbon footprint of three abrasives with the results from Henriksson's 2012 thesis. The LCA methodology is standardised through the ISO 14040 and ISO 14044 standards and the number of LCA studies commissioned by companies is increasing. However, in the sanding solutions industry specifically are there yet not many published LCA studies. For this study the standardised LCA methodology was used, with background data from the ecoinvent 3.6 database and foreground data collected through Mirka employees. Data collected for the establishment of the environmental impact was made up of a sample of four PAPER, two PLASTIC, two NET and one TEXTILE coated abrasive products and four polishing agents. Data collected for the comparison included the products PRODUCT 1, PRODUCT 2 and PRODUCT 3. The data was assessed in the OpenLCA 1.10.2 software with the ReCiPe Midpoint (H) V1.13 method. The results show that one major contributor to the environmental impact is the raw material, followed by production for coated abrasives and packaging for polishing agents. The large impact of air freight is highlighted in the assessment of the distribution. The discussion on the end-of-life stage finds waste-to-energy (WtE) to be the most suitable option for the coated abrasives, with recycling or reuse the preferred option for the packaging materials. In the comparative assessment it is found that Mirka's transition to WtE technology at the Jepua facility has zeroed the facility's production impact. With the biggest environmental impact areas identified, Mirka can now search for solutions to lower their impact and have a benchmark to track their progress against.

KEYWORDS: lifecycle assessment, environmental impact, carbon footprint, water footprint, coated abrasive, polishing agent

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ABSTRAKT:

Denna pro gradu avhandling presenterar och diskuterar livscykelanalysen (LCA) på sandpapper och polermedel. Avhandlingen som beställdes av Mirka Ltd. år 2020 har som mål att 1) etablera miljöpåverkan (koldioxid- och vattenfotavtryck) av sandpapper och polermedel under produkternas livscykel och 2) jämföra tre sandpappers koldioxidfotavtryck med resultaten från Henrikssons slutarbete från 2012. LCA metoden är standardiserad genom standarderna ISO 14040 och ISO 14044 och efterfrågan på LCA studier ökar bland företag. Inom slipmaterialsindustrin har det dock ännu inte publicerats någon större mängd LCA studier. I denna studie användes den standardiserade LCA metoden, med bakgrundsdata från ecoinvent 3.6 databasen och förgrundsdata som är insamlat i samarbete med anställda på Mirka. För etablering av produkternas miljöpåverkan samlades data ur ett stickprov på fem pappers- (PAPER), två plast- (PLASTIC) och två nätprodukter (NET), samt en textilprodukt (TEXTILE) ur sandpapperskategorin och fyra polermedel. Data för jämförelsen inkluderade produkterna PRODUCT 1, PRODUCT 2 och PRODUCT 3. Analysen gjordes i programvaran OpenLCA 1.10.2 med metoden ReCiPe Midpoint (H) V1.13. Enligt resultaten har råmaterialen den största inverkan på produkternas miljöpåverkan, med produktionen för sandpappren och förpackningsmaterialen för polermedlen på andra plats. Den höga påverkan av flygtransport synliggörs i analysen av distributionen. I diskussionen angående graven-delen av produkternas livscykel är slutsatsen att avfallsenergiprocesser är det bästa alternativet för sandpapper, medan återvinning eller återanvändning är att föredra för förpackningsmaterialen. I den jämförande delen synliggörs det att Mirkas övergång till avfallsförbränning som huvudsaklig energikälla vid fabriken i Jeppo har nollat fabrikens koldioxidfotavtryck för produktionen. När områden med den största miljöpåverkan nu identifierade kan Mirka hitta lösningar för att sänka deras påverkan och ha en baslinje att jämföra framstegen mot.

NYCKELORD: livscykelanalys, miljöpåverkan, koldioxidfotavtryck, vattenfotavtryck, sandpapper, polermedel

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Abbreviations

CFP	Carbon footprint of products
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
GHG	Greenhouse gas
GWP	Global warming potential
ISO	International Organization for Standardization
LCA	Life cycle assessment
LC	Life cycle
WFA	Water footprint assessment
WFN	Water footprint network
WtE	Waste-to-Energy

1 Introduction

Knowing the environmental footprint of products and production lines is becoming increasingly important for companies. Both company stakeholders and the environmental management system (ISO 14001) are increasingly asking whether assessments been done. Environmental footprints are becoming more of a focal point on political levels as well, with both the EU (European Green Deal) and the UN (The 17 Sustainable Development Goals) promoting knowing one's footprint. Actions are also being taken by national governments, such as the Finnish government's goal to achieve carbon neutrality by 2035 (Finnish Government, n.d.). Evaluating the environmental impact is therefore becoming more than just green marketing.

This thesis was commissioned by Mirka at the beginning of 2020 to be concluded by the end of the year. The study aims to 1) establish the environmental impact of coated abrasives and polishing agents throughout the products' life cycles and 2) compare the carbon footprint of three abrasives with the results from Henriksson's 2012 thesis. Included in the environmental impact is both carbon and water footprints, which are assessed through the life cycle assessment methodology. Establishing and comparing environmental impacts are important steps to develop more environmentally friendly products and processes.

Mirka Ltd. is a global company under the KWH Group Ltd, offering sanding solutions to their customers (Mirka, 2018). The company has trough their *clean commitments* pledged to "preserve the planet's resources" and to continuously reduce their environmental footprint (Mirka, n.d). This study is one of the steps the company is taking towards improving their manufacturing processes from an environmental viewpoint.

This thesis discusses the results by identifying major contributors to the environmental impact, suggesting options for the end-of-life stage, and comparing the different processes (both within the sample used for establishing a baseline and in the comparative study). The thesis closes by considering future steps for Mirka to take and providing suggestions for further research. On top of providing the company with results on their environmental impact, this thesis can also work as an incentive for other companies in the industry to conduct their own studies and evaluate their environmental impact.

2 Literature review

2.1 A brief history of LCA

The earliest studies to be considered as precursors to today's life cycle assessment (LCA) were conducted during the late 1960s and early 1970s (Curran, 2015; European Environmental Agency 1997; Hunt & Franklin, 1996). The first was conducted in 1969 by the Coca-Cola Company as an internal (and unpublished) study where they attempted to measure energy, material and environmental effects throughout the product's life cycle (LC) (Curran, 2015; Hunt & Franklin, 1996; Sonneveld, 2000). The first published studies to describe the methodology started to appear in 1972 (Hunt & Franklin, 1996). However, these early studies focused mostly on the emissions and consumption, rather than the environmental impact (Klöpffer & Grahl, 2014).

In Europe a similar concept, eco-balance, developed around the same time (European Environmental Agency, 1997). The European Environment Agency defines eco-balance as "the consumption of energy and resources and the pollution caused by the production cycle of a given product", considering a cradle-to-grave view of the product's LC ("Eco-balance", n.d.). Ian Boustead's eco-balance calculations for beverage containers in the UK in 1972 are considered as one of the first LCA studies conducted in Europe (European Environment Agency, 1997; Klöpffer & Grahl, 2014).

However, it wasn't until the late 1980s and 1990s the real interest for LCA grew (European Environment Agency, 1997; Finnveden et al., 2009). This was also when the first comprehensive LCA studies appeared in scientific publications and the full LCA methodology was published (Finnveden et al., 2009; Hunt & Franklin, 1996).

2.2 LCA today

Today LCA is the only method for assessing environmental impacts that is internationally accepted (Klöpffer & Grahl, 2014). The International Organization for Standardization (ISO) has standardised the LCA practices through ISO 14040 and ISO 14044, covering principles and framework, and requirements and guidelines respectively.

LCA is defined in the ISO 14040 standard as a "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (p. 23), with the product system containing all the processes included to model the life of a product or service (ISO, 2006a). The assessment of the product system is divided into four parts – the goal and scope definition, the life cycle inventory analysis (LCI), the life cycle impact analysis (LCIA), and the life cycle interpretation (ISO, 2006a) – and a complete LCA study covers the system from cradle to grave (Curran, 2012). A partial LCA study, such as Henriksson's 2012 bachelor thesis, would only consider the product system from e.g. cradle to factory gate (Finnveden et al., 2009).

There are quite a few identified direct applications of LCA. In the ISO 14040 standard are product development and improvement, strategic planning, public policy making, and marketing mentioned (ISO, 2006a). Modelling of future systems in combination with an LCA of the future system is added to the list of possible applications (Table 1) by Finnveden et al. (2009). Depending on the planned application, Curran (2015) has identified four different types of LCA studies, 1) single system – internal use of results, 2) single system – external use of results, 3) comparative analysis – internal use of results, and 4) comparative analysis – external use of results, all of which are suitable for different goals (Table 2). To note, however, is that despite the different application possibilities of an LCA, an LCA is not a substitute for Environmental Risk Assessments, since an LCA ignores emissions from other product systems and background pollution levels (Finnveden et al., 2009).

Table 1. Summary of types of future scenarios modelling and their application with LCA (Finnveden et al., 2009).

Scenario	*Predictive*	*Explorative*	*Normative*
Question	What will happen?	What can happen?	How can a specific target be reached?
Application with LCA	Forecasts of background processes	Energy and transportation	Environmental impact of various backcasting scenarios

Table 2. The four types of LCAs as defined by Curran (2015) and their respective goals.

	Internal use of results	*External use of results*
Single system	Establish product baseline	Environmental product declaration
Comparative analysis	Comparison of design option in order to make development decision	Defence of product's environmental performance compared to alternatives

Modern LCAs are very data-intensive and collecting the data can easily be one of the most time and labour consuming stage of an LCA (Finnveden et al., 2009) as well as very expensive (Steubing et al., 2016; Wernet et al., 2016), which has led to the development of databases containing background data. These databases are recognised as the foundation of any LCA since enough background data is essential for good quality results (Steubing et al., 2016; Wernet et al., 2016). For industry LCAs do databases also solve the problem of taking processes containing confidential information, such as the production of steel or electricity, into account in the assessment (Finnveden et al., 2009). In total can as much as 99 % of an LCA be made up of background data, with the collected foreground data only covering the "selected activities that reflect the immediate space for action" (Wernet et al., 2016, p. 1219).

Due to the amount of process data needed for a comprehensive LCA – there can be thousands of unit processes included in one LC (Steubing et al., 2016; Wernet et al., 2016) – different software packages have been developed to help with the allocation and calculation of environmental impacts. Some widely used commercial software packages are SimaPro, GaBi and COMPASS (Speck et al., 2015). When conducting an LCA it is due to be noted that the result can differ depending on the software used. Differences in reported impact categories and the impact itself can vary significantly depending on the software used and it can thus be difficult to compare products assessed by different software packages (Speck et al., 2015). The differences should, however, be minute no matter the software used if the same defined method, database version and cut-offs are used (Ciroth, 2020).

LCA is overall a useful tool to evaluate environmental impact and the results can be used for many different purposes, but the assessment method includes some flaws. One flaw concerns the environmental impact of a product, since the calculated impact does not take into consideration the sensitivity of the local environment (Finnveden et al., 2009). The real impact can, in other words, differ significantly from the calculated impact. Another flaw can be found in the background data. However, the risk of the data including hidden biases or lacking transparency can be somewhat avoided by using unit process data, which allows for reviewing and tailoring of the data (Finnveden et al., 2009). Allocating the environmental impacts to the right processes also offers a challenge, since one process can produce multiple products or have multiple inputs, or recycled waste is turned into another product e.g. through energy recovery (Finnveden et al., 2009). If the allocation of environmental impacts to processes is done carelessly, the results can be misleading.

2.3 How LCA has been used

A search on Google Scholar with the key word “*life cycle assessment”* provides close to 450 thousand results, including reviews on and developments of the methodology itself as well as studies conducted on different products and processes. In this chapter a few examples of studies showcasing how the LCA results have been used will be presented.

Product development and innovation is one of the fields where LCAs have been utilised. Da Silva (2012) highlights how LCAs provide the baseline for future development of products and how improvements can lead to sales and provide tools for marketing. Hanssen et al. (2012) brings a case of packaging optimisation forward as an example of how LCA has been used by the food industry to prevent food waste. In their 2017 article do Iraldo et al. compare the environmental and economic impacts of changing the durability of products and it was noted that benefits in both these categories were achieved only when the original production and end-of-life steps had high impacts.

LCAs have also been used for process development purposes. In the field of sustainable chemistry and engineering it helps provide holistic design solutions (Hunter et al., 2012). Together with cost analysis methods can LCA also be used to develop processes to be both cost and environmentally beneficial, as showcased by Vinci et al. (2019) in their study on Italian glass production.

LCA studies have also been used to show the impact cooperation between companies can have on the environment[1]. Weisbrod & Loftus (2012) showcase how LCA can be used to develop scorecards for environmental sustainability, which further can be used to build sustainable supply chains in cooperation with the suppliers. A more recent study evaluated the environmental benefits of cooperation between companies in SME clusters and concluded that the cooperation brought both climate change and terrestrial eutrophication benefits (Daddi et al., 2017).

2.4 Carbon footprint

Carbon footprint is a measurement of the amount of greenhouse gas (GHG) emissions produced by human activities and works along the business maxim “if you can’t measure it, you can’t manage it” (Matthew & Apul, 2012). Its standard unit is the carbon dioxide

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[1] Cooperation to minimise environmental impacts is becoming more of a focal point in the EU through the implementation of the European Green Deal (Smol, Marcinek, Duda, & Szoldrowska, 2020).

equivalent (CO_2eq), which expresses the thermal radiative force of GHG emissions over time, usually as the global warming potential (GWP) over 100 years (Committee on Methods for Estimating Greenhouse Gas Emissions, 2010; ISO, 2018; Matthew & Apul, 2012; Pfister et al., 2017). The thermal radiative force over time is then compared and normalised against carbon dioxide (CO_2) (ISO, 2018; Matthew & Apul, 2012). This allows for an easy comparison of the impacts of different GHG emissions across different activities. It is to be noted that when the CO_2eq is calculated, the most recent 100-year GWP should be used (ISO, 2018).

The quantification of the carbon footprint of products (CFP) has been standardised in the ISO 14067 standard (ISO, 2018). The standard allows for transparent communication of the carbon footprint (Wu et al., 2015) and supports the identification of GHG emission sources, prepares organisations for a post-carbon world and helps increase the competitiveness of businesses (Matthew & Apul, 2012). The standard can also help to create change in consumer behaviours, in which even a small change can have a meaningful impact on global GHG emissions (Wu et al., 2015). To be noted is that the CFP standardised method is very similar to the standardised LCA method but differs in only focusing on the climate change impact category (ISO, 2018).

2.5 Water footprint

Water footprint assessment (WFA) is a relatively new concept, introduced in 1997 as *virtual water* before it was renamed as *water footprint* in 2002 (Pfister et al., 2017). It has since been developed into a methodology by two different players, the Water Footprint Network (WFN) and the LCA community, satisfying complementary goals (Boulay et al., 2013; Pfister et al., 2017). This has caused some confusion since the methodologies approach the WFA from slightly different directions.

WFN’s methodology focuses on the total amount of freshwater used and polluted in order to provide or produce goods and services (Pfister et al., 2017; Water Footprint Network, n.d. a). It aims to assess the freshwater balance between human activities and nature and to provide a base for environmentally sustainable solutions, which makes it good methodology for managing water (Boulay et al., 2013; Water Footprint Network, n.d. b). A methodology manual has been published and can be accessed for free through the Water Footprint Network’s webpages.

The LCA community’s methodology focuses on the environmental impacts related to water use rather than the volumes used (Boulay et al., 2013; Pfister et al., 2017). It is based on the LCA methodology and can support the identification of possible impact reductions in different parts of a product’s LC, as well as help improve water efficiency (International Organization for Standardization, 2014; Pfister et al., 2017). The methodology has been published as an ISO standard.

Both methodologies, despite their different approaches, try to assist companies and other actors to preserve water resources (Boulay et al., 2013). In this thesis, the LCA community’s methodology is used.

2.6 The manufacturing of coated abrasives and polishing agents

Coated abrasives and polishing agents are used for the finishing of different surfaces, such as glass, metal and wood, as well as the finishing of e.g. electronics in the precision industry. This requires them to perform varying degrees of material removal by the rubbing of grits – small grains – against a material. The importance of the ‘rubbing of grits’ is highlighted by Lewis and Schleicher (1976) with the following words: “without these small grits ours [society] might still largely be an agricultural society and the conquest of space merely a dream” (p. 3). In this chapter the manufacturing of coated abrasives and polishing agents will be covered.

Coated abrasives, or sandpapers, are made of a backing material, the make coating, the abrasive grit and the size coating (Linke, 2016). The backing material's purpose is to be the base that holds the grits and it is usually made of paper, cloth or vulcanised fibre (Carborundum, 2016; Linke, 2016). The make coating, also called bond or glue, fixes the grits to the backing material and for the coating usually glue, urea resin or phenolic resin is used (Carborundum, 2016; Linke, 2016). The abrasive grits, which can be e.g. garnet, silicon carbide or aluminium oxide, are distributed either by gravity scattering or electrostatic scattering during the so-called mineral coating (Carborundum, 2016; Linke, 2016). Lastly the size coating is added. It is a top layer of glue, urea resin or phenolic resin that anchors the grits and helps to achieve the wanted physical strength of the sandpaper (Carborundum, 2016). At this point the coated abrasive is too hard and brittle for customer use (Klingspor, n.d.).

Before the coated abrasive can be further processed it needs to go through flexing. The purpose of flexing is to soften the sandpaper by breaking it at different angels, which creates fine cracks in a regular pattern (Henriksson, 2012; Klingspor, n.d.). This is done by stretching the material across flex-shafts at different angels and speeds (Henriksson, 2012). After the flexing the coated abrasive is ready to be cut and packaged.

Polishing agents are basically a suspension of abrasive particles in a liquid. The particles can be e.g. emery or aluminium oxide and the grit size is often around 1 µm, which allows for a much finer material removal than achieved with coated abrasives (Linke, 2016).

2.7 Chapter summary

In this chapter the history and use of LCA, definitions of carbon and water footprints, and the manufacturing of coated abrasives and polishing agents are covered in order to provide a solid foundation for understanding the results of the thesis. LCA, with its 5 decades long history, is today an internationally accepted and standardised tool for assessing environmental impacts of products. It has a multitude of uses, including modelling the future, marketing a product, and as a tool to make development and design decisions. Carbon footprint is a measurement of the quantity of GHG emissions produced by human activity, while water footprint is a measurement of either the amount of freshwater polluted or water related environmental impacts, depending on the methodology used. In this thesis the latter methodology is used. The manufacturing of coated abrasives includes multiple steps, while polishing agent manufacturing basically is just mixing the materials together.

3 Methodology

In this chapter the methodology is outlined, based upon the ISO 14040 and ISO 14044 standards.

3.1 Goal and scope definition

This thesis aims to 1) establish the environmental impacts[2] of abrasives and polishing agents and 2) compare the carbon footprint of three abrasives with the results from Henriksson's 2012 study. In order to tackle the first aim, a single system cradle-to-warehouse LCA with the functional unit 1000 discs or 1000 litres is conducted, with an added discussion surrounding the end-of-life of the products. For the second aim, a comparative cradle-to-factory-gate LCA with the functional unit 100 discs is conducted.

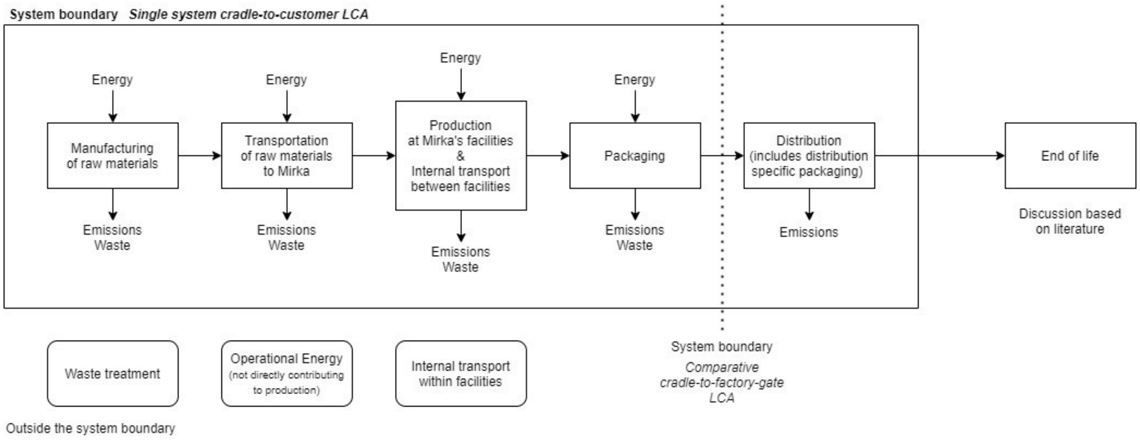

Figure 1. Flow chart of system and system boundary for abrasives and polishing agents.

The LCA focuses on the coated abrasives and polishing agents produced by Mirka at their facilities in Finland. The assessment starts from the manufacturing of raw materials and

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[2] The environmental impacts focused on in this thesis are carbon and water footprints.

their transportation to Mirka’s facilities, after which they are transformed into the desired products before they are packaged and shipped to the main warehouses. The system boundaries for both the single system and the comparative study are illustrated in Figure 1.

Waste treatment, operational energy and internal transport within facilities have all been excluded. Solid waste treatment for production waste is excluded from the system due to the difficulty of modelling it (note that wastewater treatment is included). Operational energy includes energy requirements for running the facilities, such as heating and lighting, and machinery production and upkeep. The operational energy is not considered due to it not being directly linked to the production of the products. Internal transports are neither included, due to difficulty of estimating distances per produced quantity.

3.2 Life cycle inventory analysis (LCI)

Due to Mirka’s broad product range, coated abrasives including 57 product names, all including different grit sizes and cuts, and polishing agents including 42 polishing products, a sample population was selected for data collection. The sample was chosen based upon the products’ large production quantities and/or different production methods and material composition.

Data collection is based on the identified inputs and outputs (Figure 2 and Figure 3) of the processes included in the LC. Most of the foreground data is secondary in nature, both due to the amount of data needed and the COVID-19 situation not allowing external personnel within the production facilities. For background data, the ecoinvent 3.6 database (hereinafter referred to as *background data*) was used. More on data collection in appendix 1.

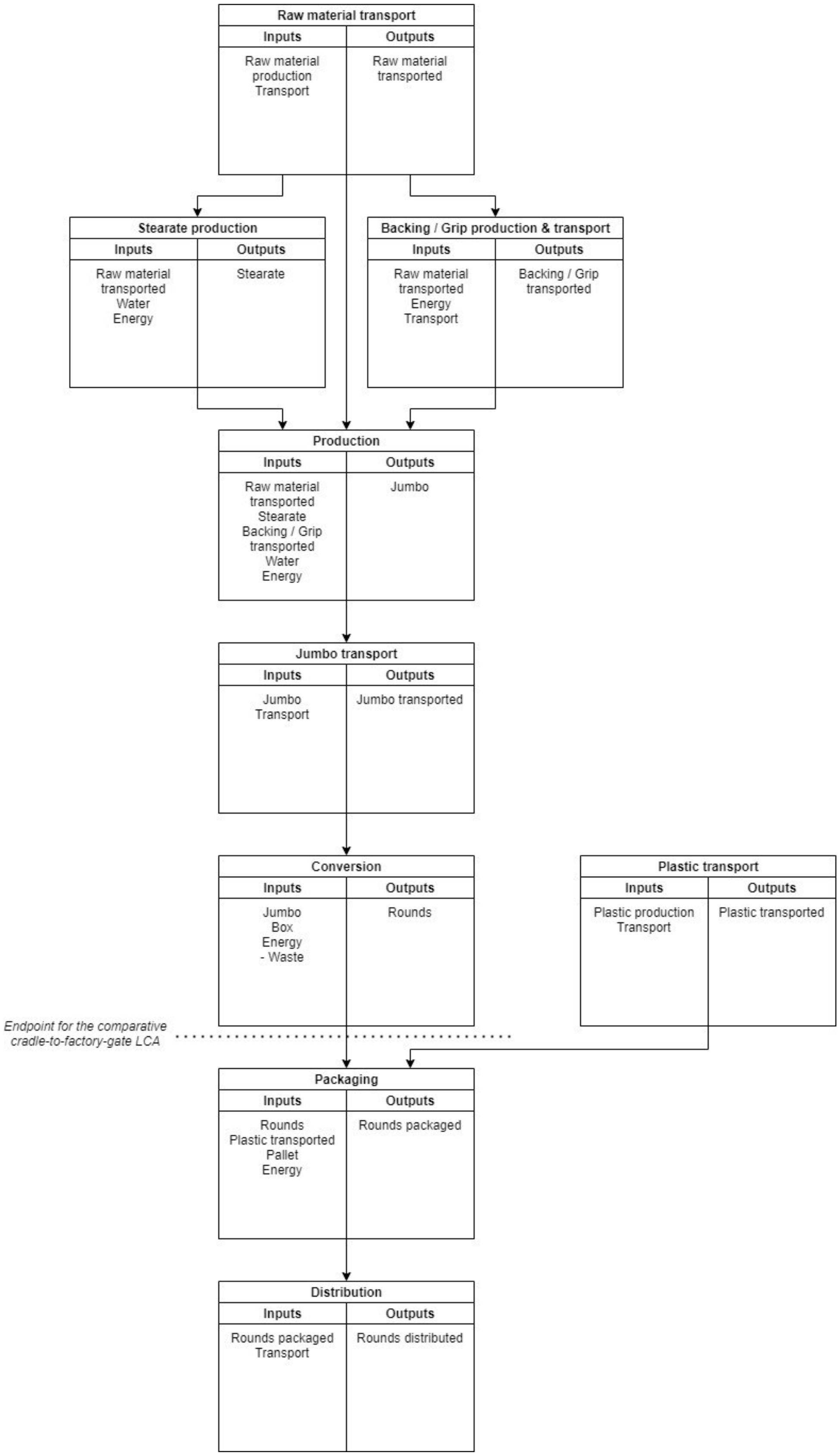

Figure 2. Allocation of flows (inputs and outputs) to processes for coated abrasives.

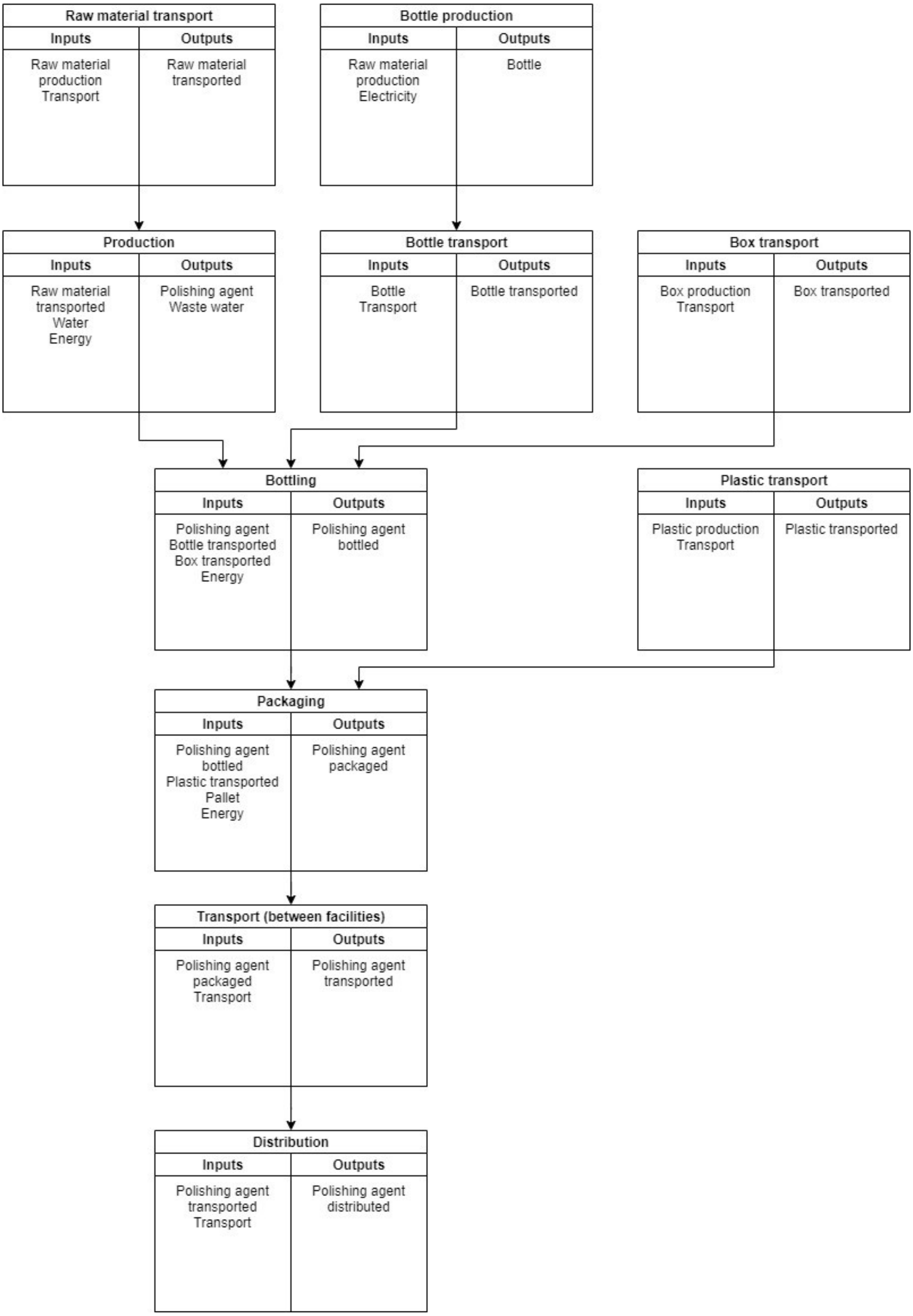

Figure 3. Allocation of flows (inputs and outputs) to processes for polishing agents.

3.3 Life cycle Impact assessment (LCIA)

The environmental impact of the single system LCA is assessed with the *ReCiPe Midpoint (H) V1.13* method, which is considered the default ReCiPe midpoint model (Golsteijn, 2012) and provides impacts for global warming potential (GWP), freshwater eutrophication, marine eutrophication, freshwater ecotoxicity, marine ecotoxicity and water depletion (Table 3), among others. For the comparative LCA the *IPCC 2013* method is used, since *IPCC 2007* was used in Henriksson's thesis. The assessment is done within the software *OpenLCA 1.10.2* (Figure 4).

Table 3. Impact categories and their respective indicators as provided by ReCiPe Midpoint (H) V1.13.

	Impact category	*Category indicator*
Carbon footprint	GWP100	kg CO_2eq
Water footprint	Freshwater eutrophication	kg Peq
	Marine eutrophication	kg Neq
	Freshwater ecotoxicity	kg 1,4-DCBeq
	Marine ecotoxicity	kg 1,4-DBeq
	Water depletion	m^3 water eq

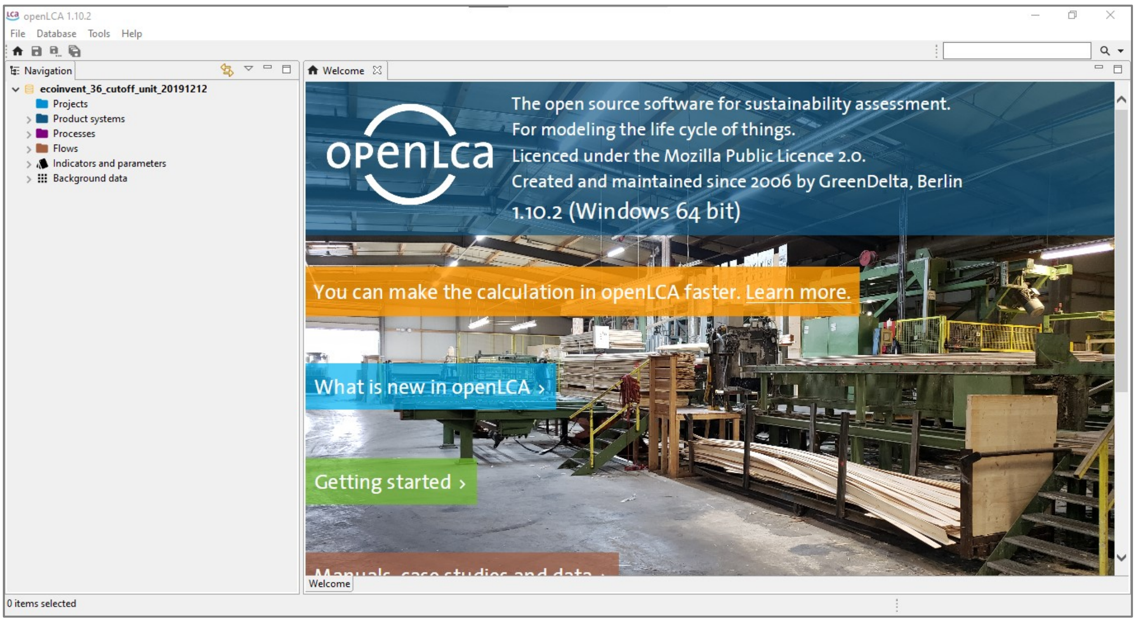

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Figure 4. Screenshot of OpenLCA 1.10.2.

4 Results

The carbon and water footprints will firstly be presented for each of the studied product groups – coated abrasives (PAPER, NET, PLASTIC and TEXTILE) and polishing agents – followed by the footprints for the distribution. Lastly the results are summarised to give an overview of the carbon and water footprints for coated abrasives and polishing agents.

4.1 Carbon footprint for production

In this chapter the carbon footprint results for the *cradle-to-factory gate* part of the LCA will be presented. In the cradle-to-factory gate part is divided into raw material production, raw material transport, packaging materials, backing/grip production, coated abrasives production, and internal transport for coated abrasives (Table 4). The division for polishing agents is into raw material production, raw material transport, packaging materials, polishing agent production and internal transport (Table 5).

Table 4. Carbon and water footprint categories for coated abrasives in the cradle-to-factory gate part of the LCA.

Category name	*Included in category*
Raw material production	Production of raw materials
Raw material transport	Distance transported Transport type
Packaging materials	Production of packaging materials (box, plastic film) Distance transported Transport type Pallet production
Backing/grip production	Energy for the production of the backing/grip material Tap water
Coated abrasives production	Energy for the production (jumbo production, conversion) Tap water Wastewater treatment
Internal transport	Distance transported between Mirka's facilities Transport type

Table 5. Carbon and water footprint categories for polishing agents in the cradle-to-factory gate part of the LCA.

Category name	*Included in category*
Raw material production	Production of raw materials
Raw material transport	Distance transported Transport type
Packaging materials	Production of packaging materials (bottle, box, plastic film) Distance transported Transport type Pallet production
Polishing agent production	Energy for the production, bottling and packing of the polishing agents Water Wastewater treatment
Internal transport	Distance transported between Mirka's facilities Transport type

4.1.1 Coated abrasive 1: PAPER

The carbon footprint for the studied PAPER products varies between 46 $kgCO_2eq/1000d$ and 74 $kgCO_2eq/1000d$ for the cradle-to-factory gate part of the LCA. PAPER 4 has the biggest carbon footprint, while PAPER 3 has the smallest (figure 6). The largest contributor to the footprint, making up between 72 and 78 % of the footprint, is raw material production.

If considering only production, around 6 $kgCO_2eq/1000d$ is produced in the Jepua and Oravainen facilities (*production*), while around 7 $kgCO_2eq/1000d$ is produced in the Karjaa facility (*backing production*). The raw material (including both its production and transport) used that contribute the most to the carbon footprint is the grip (around 20 $kgCO_2eq/1000d$).

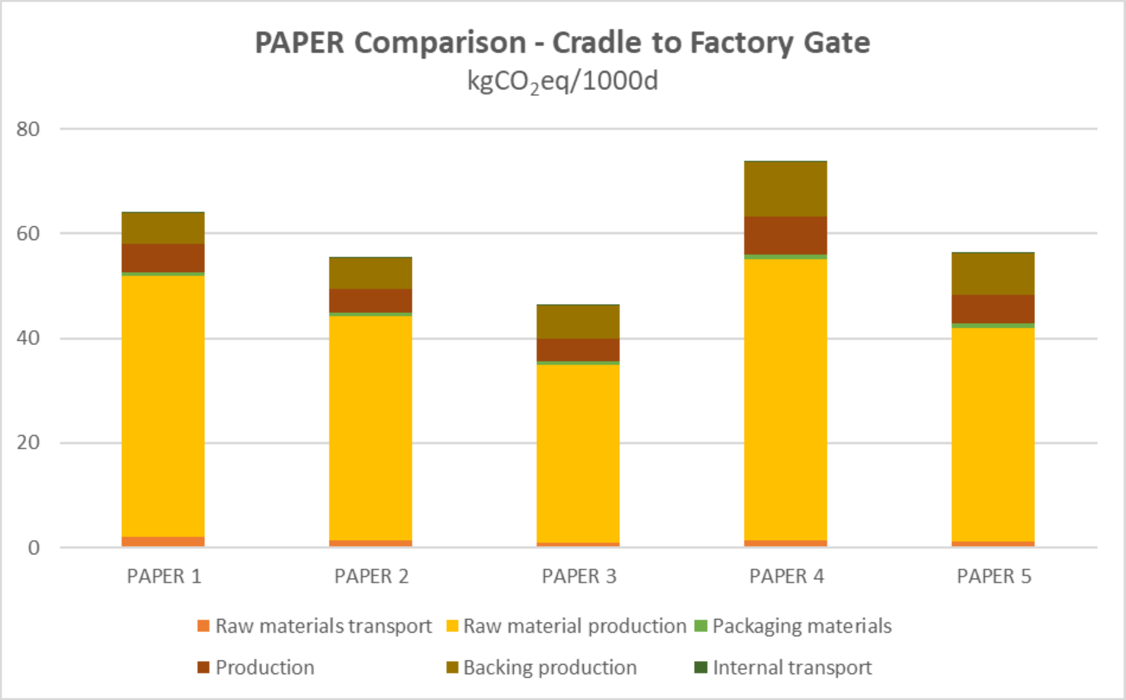

Figure 5. Division (kgCO2eq) of the carbon footprint per category for PAPER.

4.1.2 Coated abrasive 2: NET

The carbon footprint for the studied NET products equals to 54 $kgCO_2eq/1000d$ and 56 $kgCO_2eq/1000d$ for the cradle-to-factory gate part of the LCA. NET 2 has the bigger carbon footprint, while NET 1 has the smaller (figure 6). The largest contributor to the footprint, making up between 60 and 79 % of the footprint, is raw material production. The second largest contributor to the carbon footprint is backing production, making up between 17 and 37 % of the footprint.

If considering only production, around 0.07 $kgCO_2eq/1000d$ is produced in the Jepua and Oravainen facilities (*production*), while between 9 and 20 $kgCO_2eq/1000d$ is produced in the Karjaa facility (*backing production*). The large difference in the backing production is due to the energy need being approximately double for backing production for NET 2 compared to the backing production for NET 1. The raw materials (including both their production and transport) used that contribute the most to the carbon footprint is grip (around 25 $kgCO_2eq$/1000d) and resin (around 4 $kgCO_2eq$/1000d).

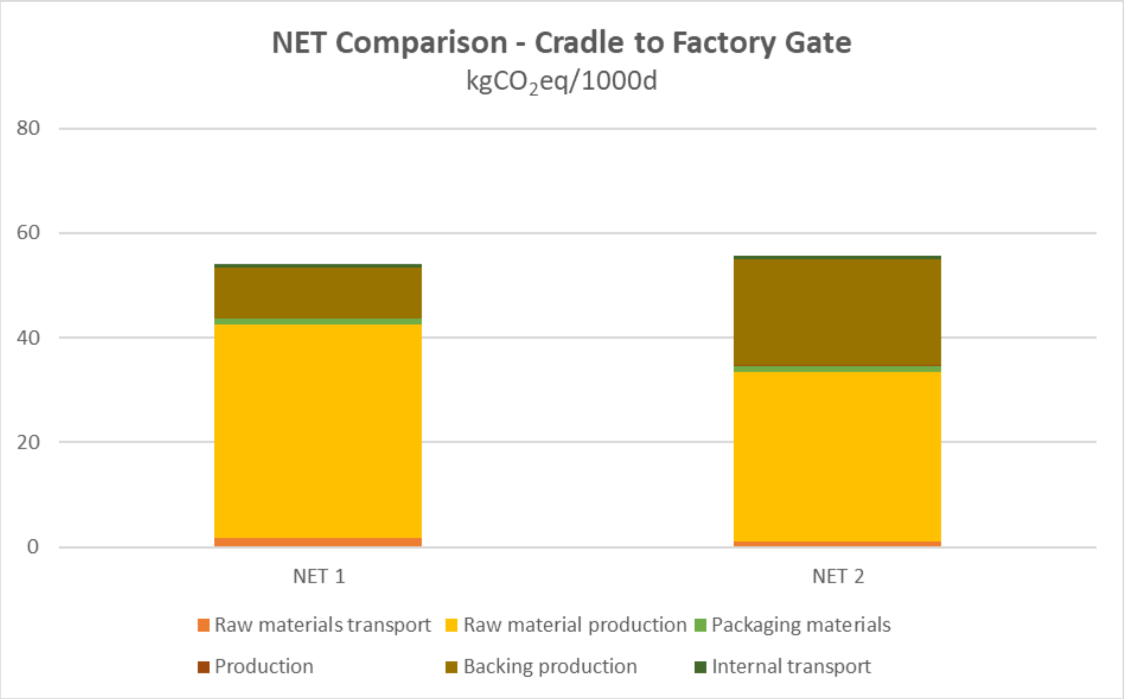

Figure 6. Division (kgCO2eq) of the carbon footprint per category for NET.

4.1.3 Coated abrasive 3: PLASTIC

The carbon footprint for the studied PLASTIC products is between 53 $kgCO_2eq$/1000d and 68 $kgCO_2eq$/1000d for the cradle-to-factory gate part of the LCA. PLASTIC 120 has the bigger carbon footprint, while PLASTIC 500 has the smaller (Figure 7). The largest contributor to the footprint, making up between 62 and 69 % of the footprint, is raw material production. The second largest contributor to the carbon footprint is production, contributing to 18–24 % of the footprint.

If considering only production, around 12 $kgCO_2eq$/1000d is produced in the Jepua and Oravainen facilities (*production*), while around 5 $kgCO_2eq$/1000d is produced in the Karjaa facility (*backing production*). The raw materials (including both their production and transport) used that contribute the most to the carbon footprint is grip (around 21 $kgCO_2eq/1000d$) and resin (around 5 $kgCO_2eq/1000d$).

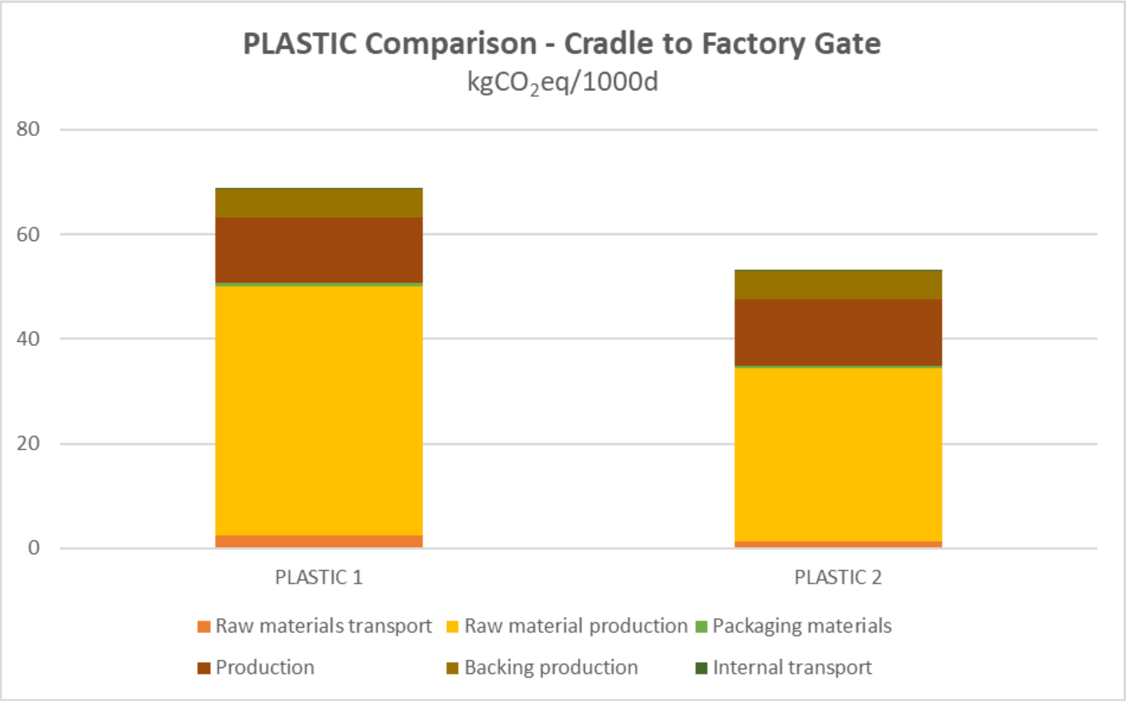

Figure 7. Division (kgCO2eq) of the carbon footprint per category for PLASTIC.

4.1.4 Coated abrasive 4: TEXTILE

The carbon footprint for the studied TEXTILE product equals to 118 $kgCO_2eq/1000d$ for the cradle-to-factory gate part of the LCA (Figure 8). The largest contributor to the footprint is raw material production, making up 73 % of the footprint, followed by backing production, contributing to 22 % of the footprint.

If considering only production, around 0.0005 $kgCO_2eq/1000d$ is produced in the Jepua facility (*production*), while around 27 $kgCO_2eq/1000d$ is produced in the Karjaa facility (*backing production*). The raw materials (including both their production and transport) used that contribute the most to the carbon footprint are grip (45 $kgCO_2eq/1000d$) and flexible foam (32 $kgCO_2eq/1000d$).

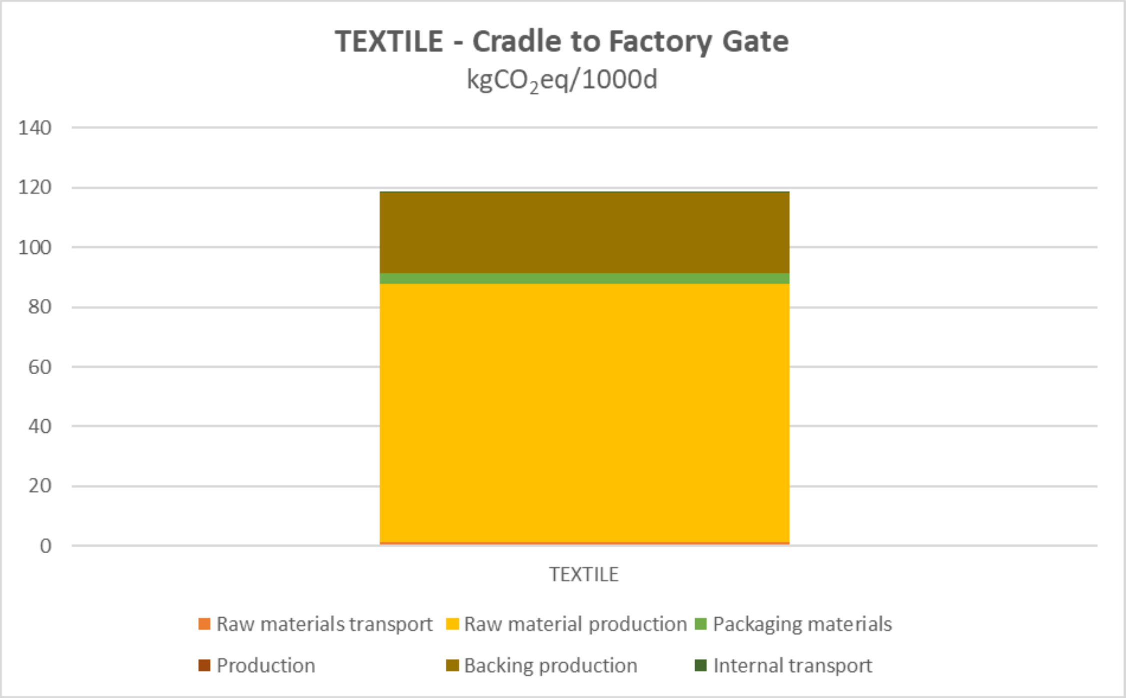

Figure 8. Division (kgCO2eq) of the carbon footprint per category for TEXTILE.

4.1.5 Polishing agent

The carbon footprint for the studied polishing agents equals to between 2500 kgCO2eq/1000L and 3000 kgCO2eq/1000L for the cradle-to-factory gate part of the LCA (Figure 9). The largest contributor to the footprint is raw material production, making up between 40 and 58 % of the footprint, followed by the packaging materials, which contribution to the carbon footprint is between 31 and 37 %.

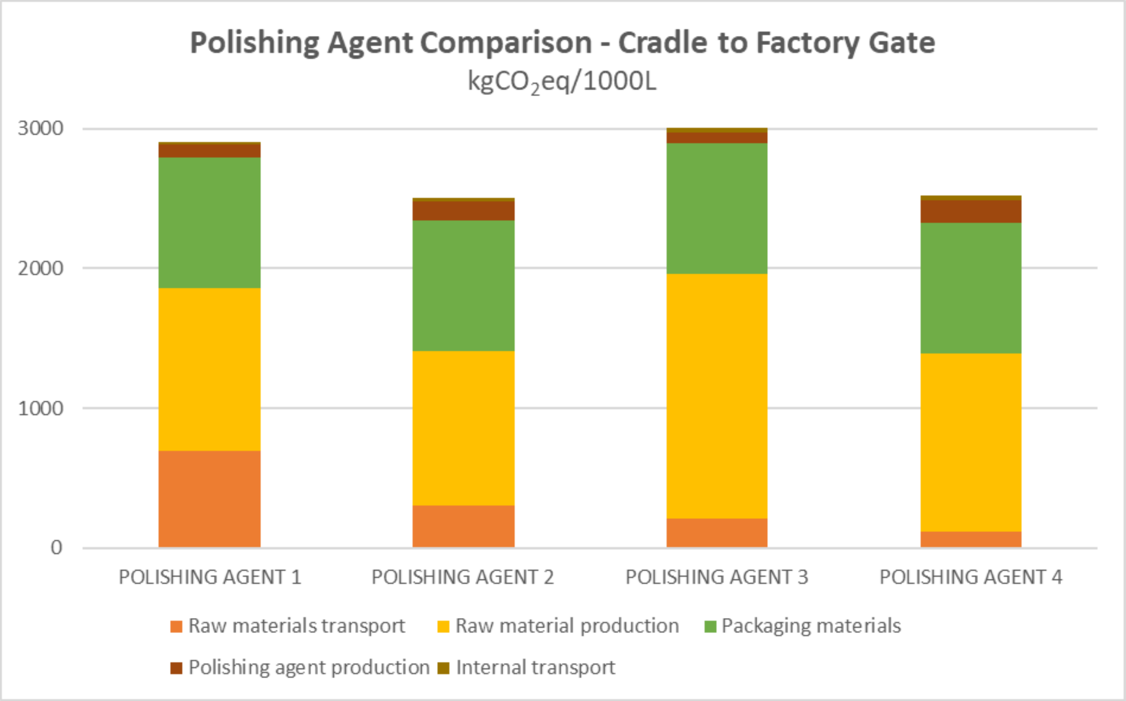

Figure 9. Division (kgCO2eq) of the carbon footprint per category for each polishing agent.

The second largest total carbon footprint of the polishing agents analysed is produced by polishing agent 1. The footprint is 2909 kgCO2eq/1000L for cradle-to-factory gate, of which roughly 64 % originate from raw materials production and transport, 32 % from packaging material production and transport, and the last 4 % from the production of the polishing agent and internal transport.

Polishing agent 2 has the lowest carbon footprint of the analysed polishing agents in the cradle-to-factory gate part. Its footprint is 2502 kgCO2eq/1000L, of which around 56 % originate from raw materials production and transport, 37 % from packaging material production and transport, and the last 6 % from the production of the polishing agent and internal transport.

Polishing agent 3 production has the highest carbon footprint of the analysed polishing agents. Its footprint is 3003 kgCO2eq/1000L in the cradle-to-factory gate part, of which around 65 % originate from raw materials production and transport, 31 % from packaging material production and transport, and the last 4 % from the production of the polishing agent and internal transport.

Lastly, polishing agent 4 is the polishing agent with the second to lowest carbon footprint in the cradle-to-factory gate part of the analysed polishing agents. Its footprint is 2518 kgCO2eq/1000L, of which around 55 % originate from raw materials production and transport, 37 % from packaging material production and transport, and the last 8 % from the production of the polishing agent and internal transport.

4.2 Water footprint for production

In this chapter the water footprint results for the *cradle-to-factory gate* part of the LCA will be presented. Due to be noted is that the water footprint is divided into five categories – freshwater eutrophication, marine eutrophication, freshwater ecotoxicity, marine ecotoxicity, and water depletion – which cannot be compared between each other.

4.2.1 Coated abrasive 1: PAPER

The water footprint for the studied PAPER abrasives is between 0.010 and 0.020 kgPeq/1000d for freshwater eutrophication, 0.020 and 0.042 kgNeq/1000d for marine eutrophication, 0.84 and 1.70 kg 1,4-DCBeq/1000d for freshwater ecotoxicity, 0.76 and 1.39 kg 1,4-DBeq/1000d for marine ecotoxicity, and between 0.80 and 1.41 m^3 water eq/1000d for water depletion (Figure 10). The largest footprints (in all categories) are produced by *raw material production*, followed by *production* (includes all Mirka facilities).

4.2.2 Coated abrasive 2: NET

The water footprint for the studied NET abrasives is between 0.009 and 0.013 kgPeq/1000d for freshwater eutrophication, 0.017 and 0.019 kgNeq/1000d for marine eutrophication, 1.05 and 1.16 kg 1,4-DCBeq/1000d for freshwater ecotoxicity, 0.95 and 0.97 kg 1,4-DBeq/1000d for marine ecotoxicity, and between 0.82 and 0.90 m^3 water eq/1000d for water depletion (Figure 11). The largest footprints (in all categories) are produced by *raw material production* and *production* (includes all Mirka facilities), with raw material production being the bigger contributor in NET 120 and production being the larger one in NET 500.

4.2.3 Coated abrasive 3: PLASTIC

The water footprint for the studied PLASTIC abrasives is between 0.012 and 0.017 kgPeq/1000d for freshwater eutrophication, 0.022 and 0.028 kgNeq/1000d for marine eutrophication, 0.95 and 1.39 kg 1,4-DCBeq/1000d for freshwater ecotoxicity, 0.86 and 1.27 kg 1,4-DBeq/1000d for marine ecotoxicity, and between 0.83 and 1.05 m^3 water eq/1000d for water depletion (Figure 12). The largest footprints (in all categories) are produced by *raw material production* and *production* (includes all Mirka facilities), with raw material production being the larger contributor in all categories for NET 120 and in marine eutrophication and water depletion for NET 500.

4.2.4 Coated abrasive 4: TEXTILE

The water footprint for the studied TEXTILE abrasive is 0.020 kgPeq/1000d for freshwater eutrophication, 0.065 kgNeq/1000d for marine eutrophication, 1.406 kg 1,4-

DCBeq/1000d for freshwater ecotoxicity, 1.270 kg 1,4-DBeq/1000d for marine ecotoxicity, and 1.769 m^3 water eq/1000d for water depletion (Figure 13). The largest footprints (in all categories) are produced by *raw material production*, followed by *production* (includes all Mirka facilities).

4.2.5 Polishing agent

The water footprint for the studied polishing agent products is between 1.248 and 1.372 kgPeq/1000L for freshwater eutrophication, 0.698 and 1.946 kgNeq/1000L for marine eutrophication, 63.091 and 78.324 kg 1,4-DCBeq/1000L for freshwater ecotoxicity, 56.624 and 72.149 kg 1,4-DBeq/1000L for marine ecotoxicity, and between 23.017 and 26.317 m^3 water eq/1000L for water depletion (Figure 14). The largest footprints (in all categories) are produced by *raw material production* and *packaging materials*. Raw material production contributes more to the water footprint in all categories except for freshwater eutrophication, where packaging materials contribute the most.

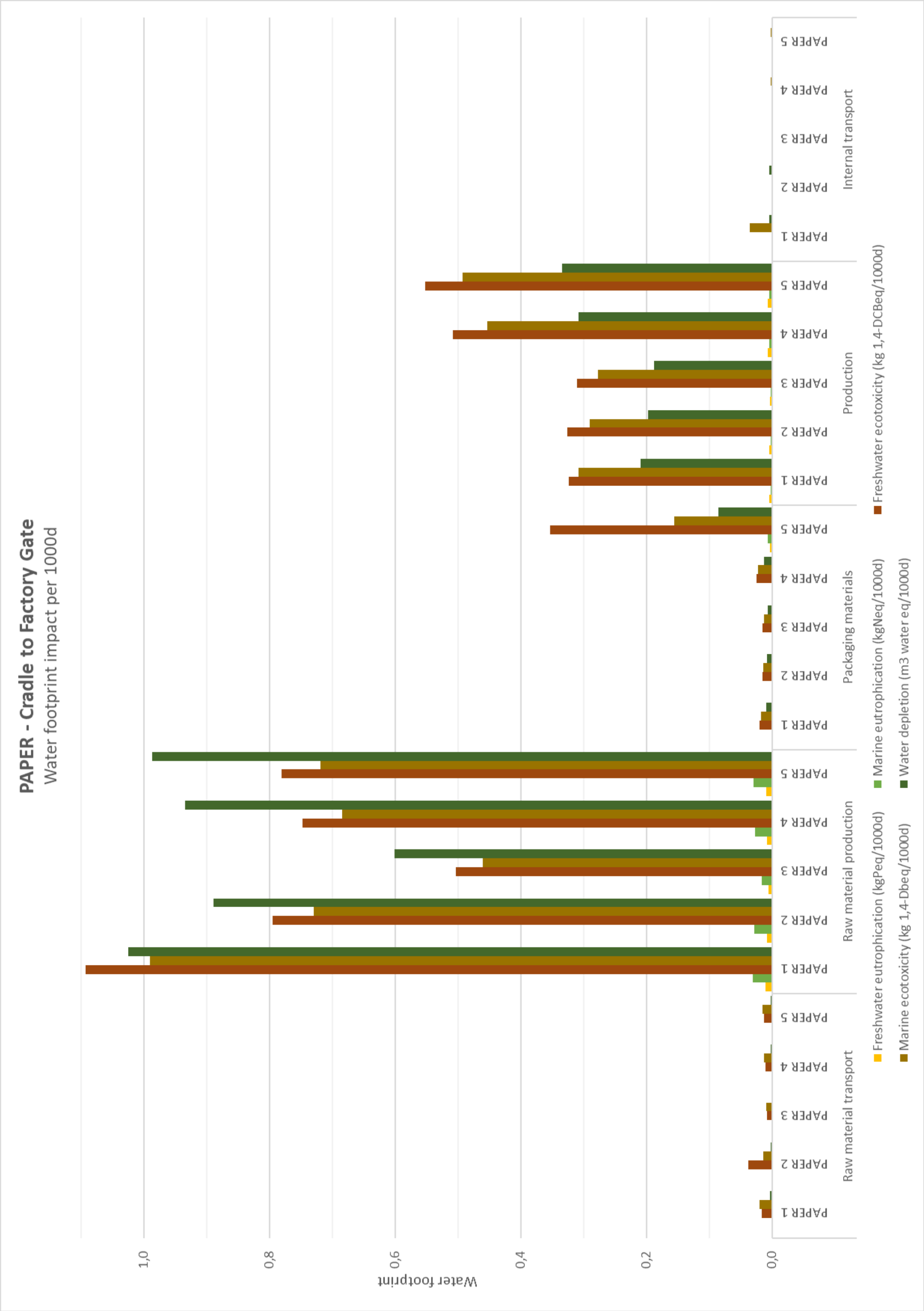

Figure 10. Water footprint for 1000 discs PAPER.

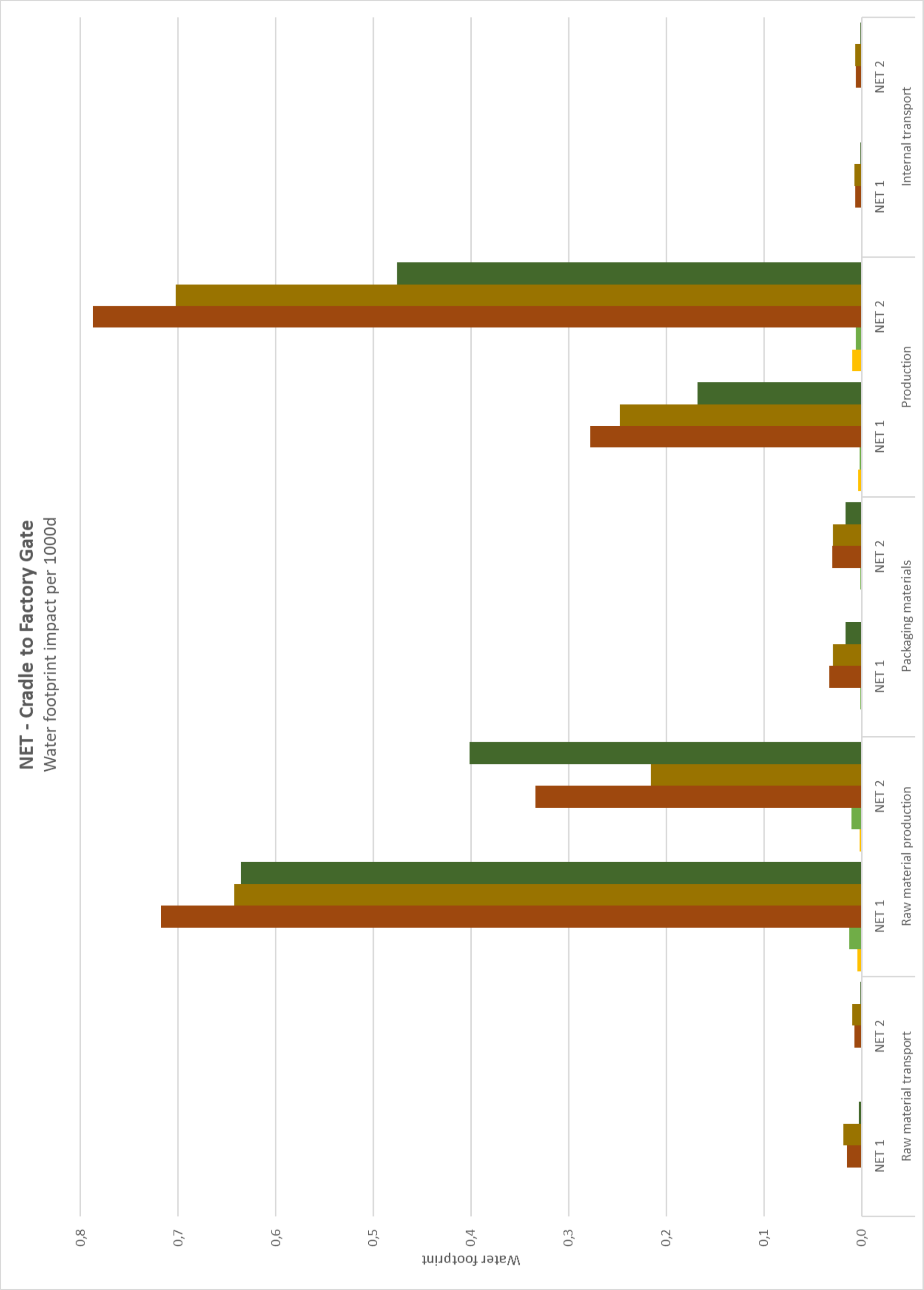

Figure 11. Water footprint for 1000 discs NET.

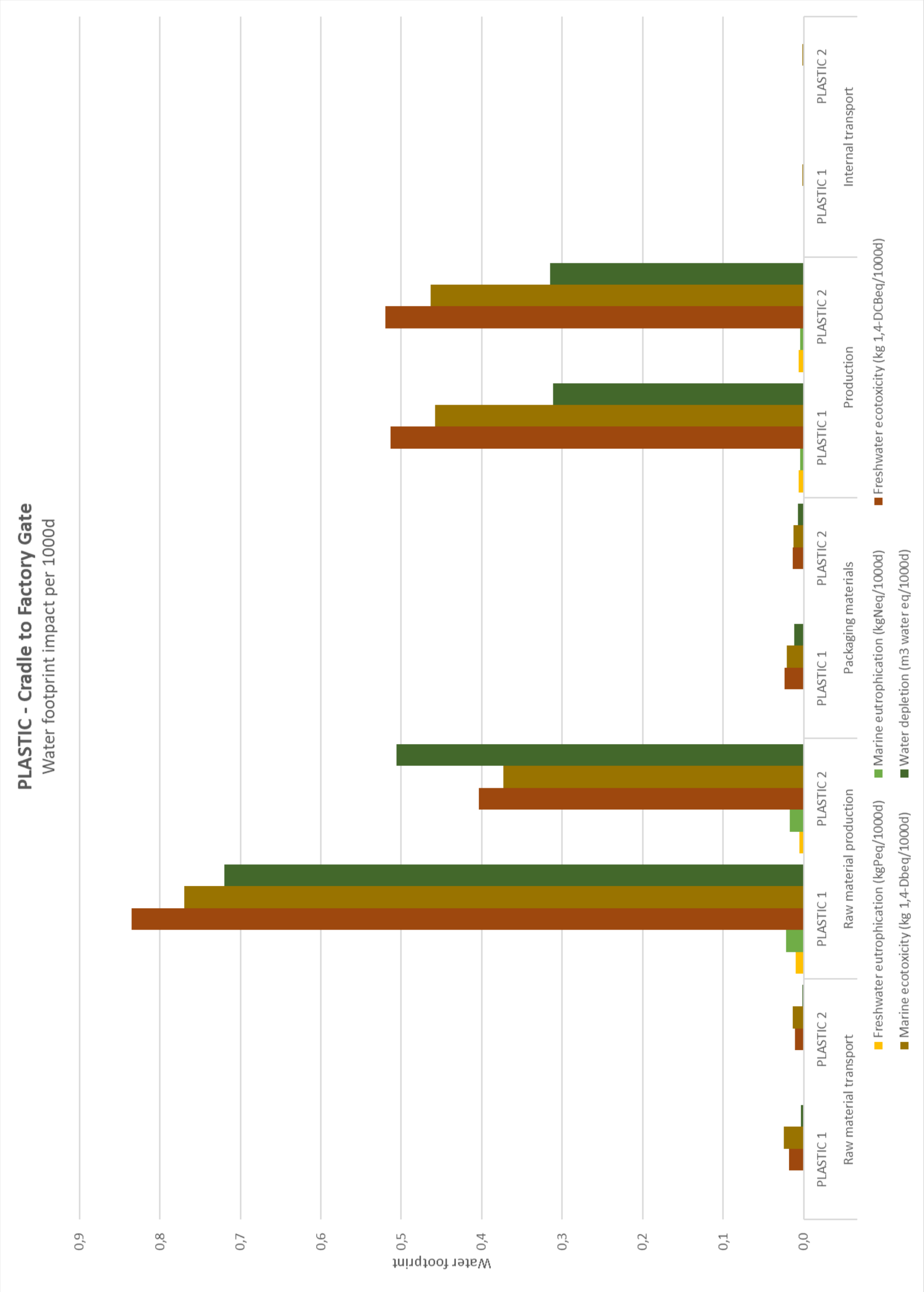

Figure 12. Water footprint for 1000 discs PLASTIC.

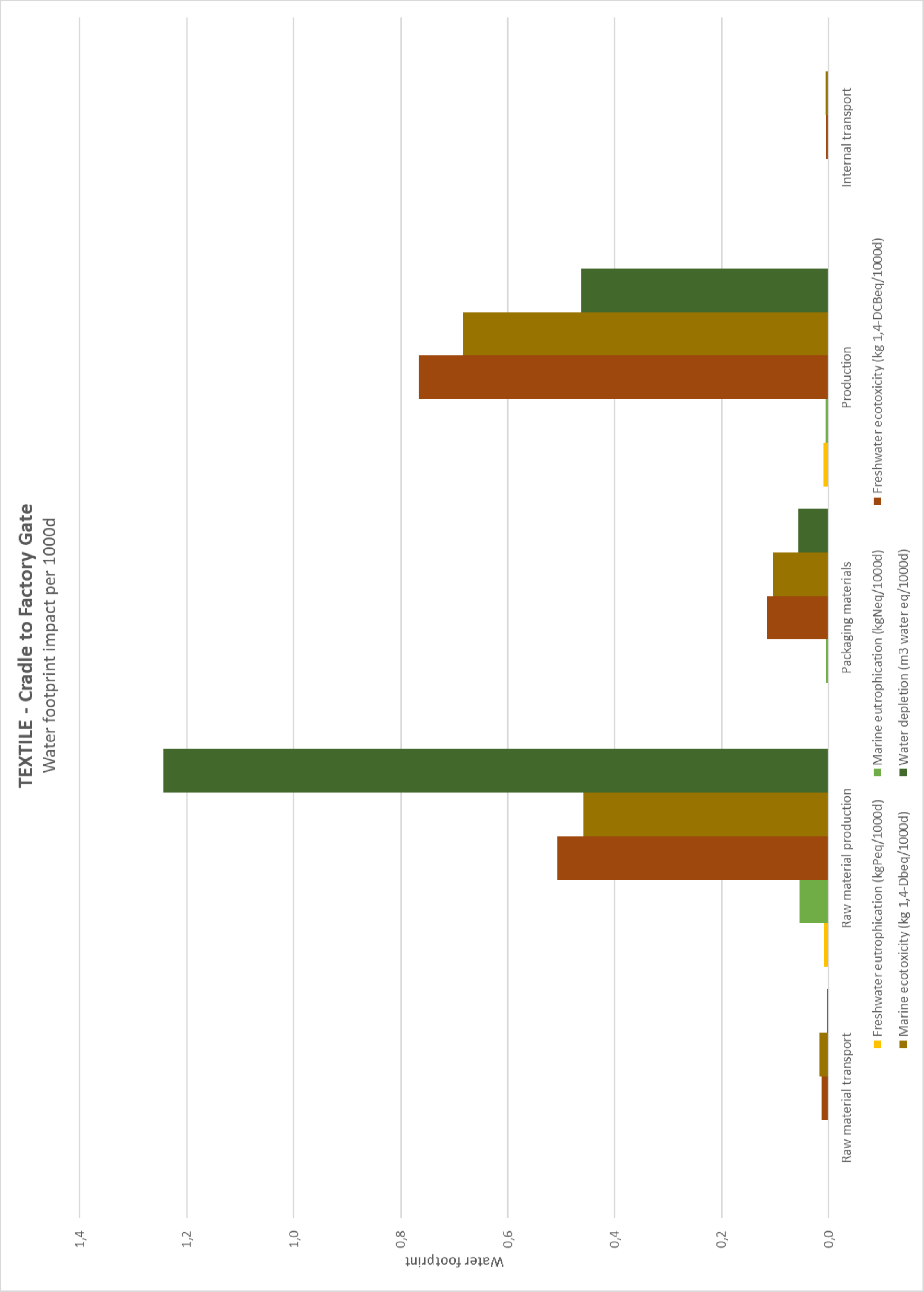

Figure 13. Water footprint for 1000 discs TEXTILE.

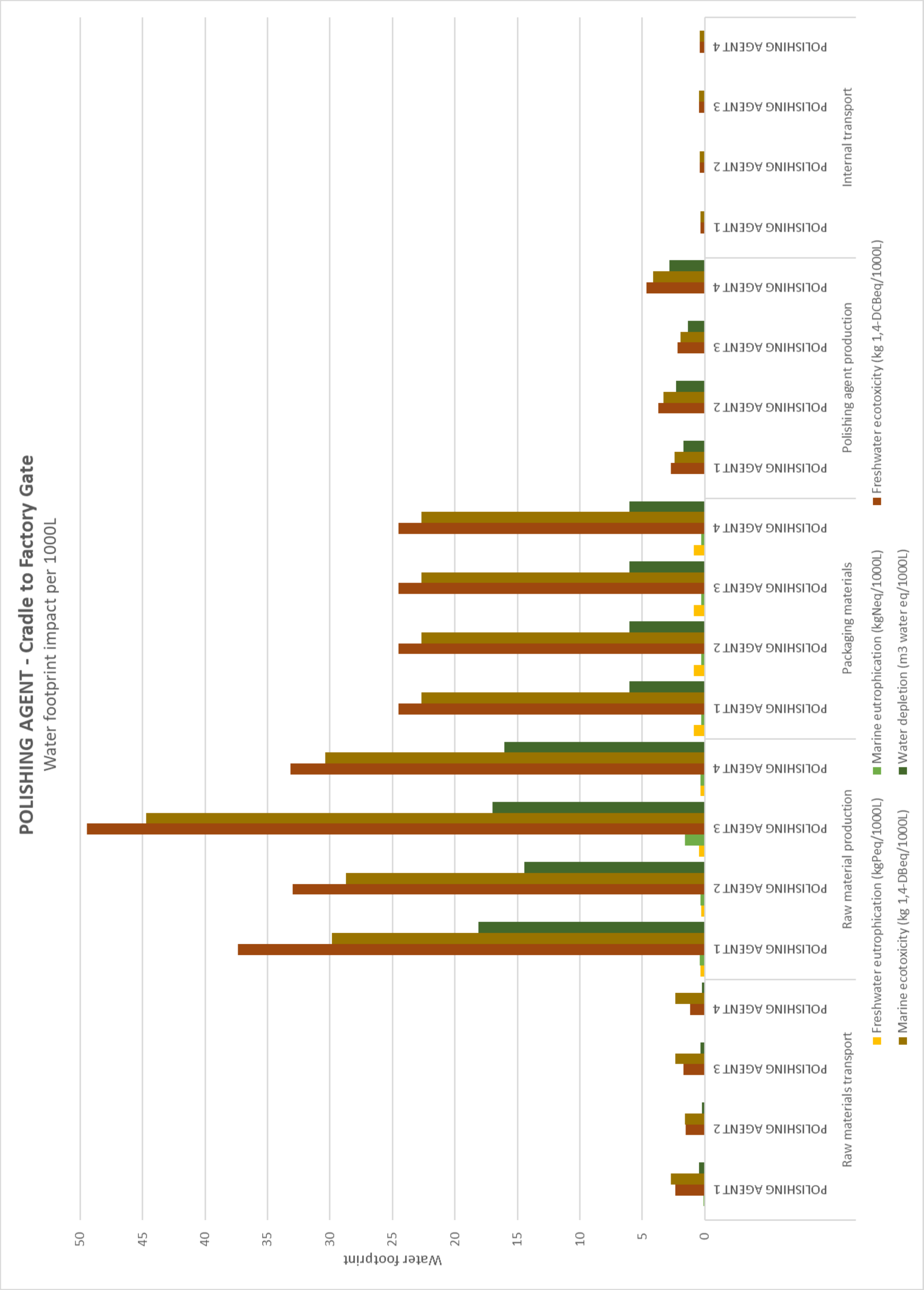

Figure 14. Water footprint for 1000 litre POLISHING AGENT.

4.3 Carbon and water footprint for distribution

In this chapter both the carbon and water footprint results for the *distribution* part of the LCA will be presented. The carbon and water footprints have been calculated for the distribution from Jepua, Finland, to ten of Mirka's warehouses worldwide. In the footprint assessment the transportation type – lorry (including ferry connections), container ship and air freight – and the corresponding distances are considered (Table 6) and the results presented as footprint per 1000 discs or litres. The footprint is also evaluated according to the real distribution (%) of the production of 1000 discs or litres.

Table 6. Warehouses considered, transportation type and total transportation distance.

Warehouse	*Transport type*	*Transport distance (km)*
W1	Lorry	2 777
W2	Lorry	428
W3	Lorry + Container ship	10 294
W4	Lorry + Container ship	17 936
W5	Lorry + Air freight	8 336
W6	Lorry	670
W7	Lorry + Container ship	12 392
W8	Lorry	3 135
W9	Lorry + Container ship	12 643
W10	Lorry + Air freight	10 891

Distribution contributes with between 0.6 $kgCO_2eq/1000d$ and 73.2 $kgCO_2eq/1000d$ to the total carbon footprint for coated abrasive (Figure 15). The largest carbon footprints for distribution are produced by the transport to W5 and W10. The smallest carbon footprint is produced by the distribution to W2.

When considering the carbon footprint according to the real distribution of 1000 discs coated abrasives (Figure 16), the biggest carbon footprints are produced by the distribution to W10 and W1, with 4.21 $kgCO_2eq$ and 2.21 $kgCO_2eq$ respectively.

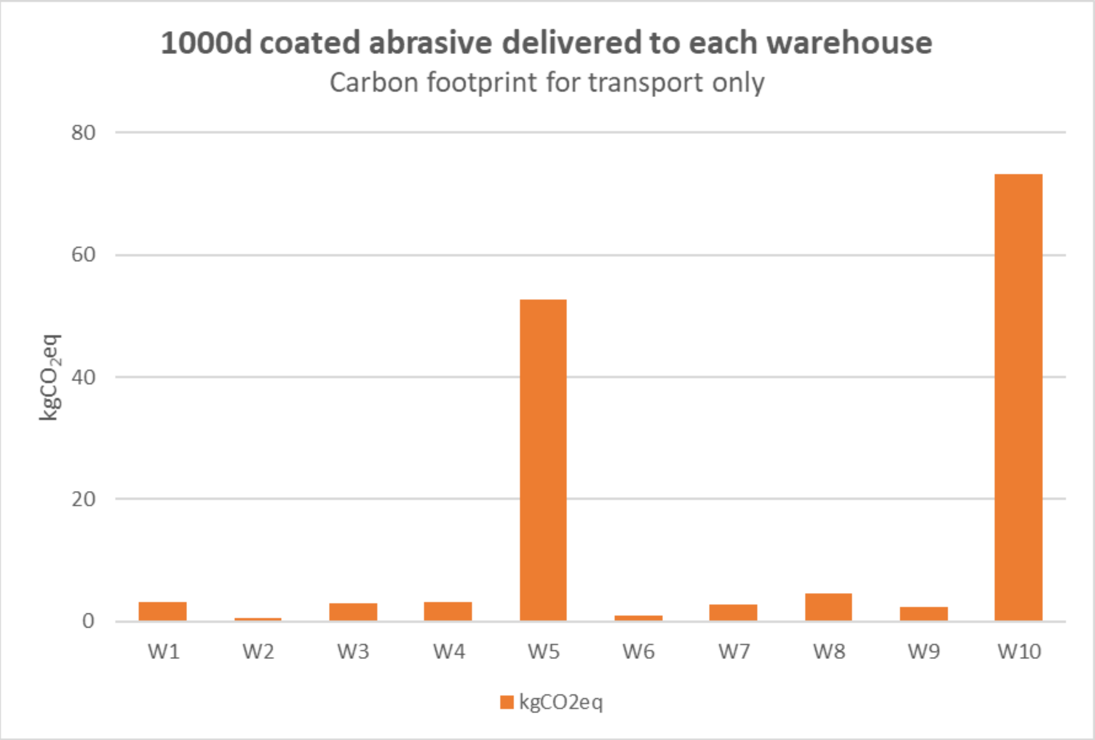

Figure 15. Carbon footprint for distribution of 1000d coated abrasive to each warehouse.

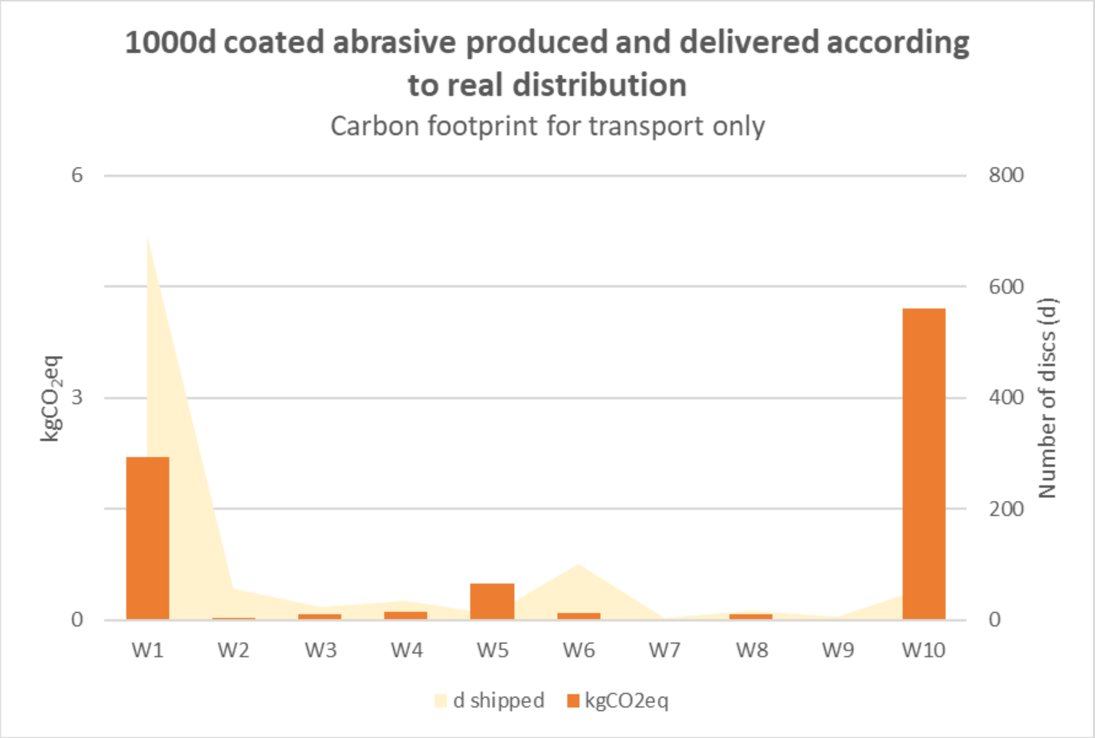

Figure 16. Carbon footprint for real distribution of 1000d coated abrasive to warehouses.

The water footprint for distribution adds between 4×10^{-5} and 133×10^{-5} kgPeq/1000d for freshwater eutrophication, between 0.0001 and 0.0142 kgNeq/1000d for marine eutrophication, between 0.005 and 0.185 kg 1,4-DCBeq/1000d for freshwater ecotoxicity, between 0.007 and 0.183 kg 1,4-DBeq/1000d for marine ecotoxicity, and between 0.001 and 0.038 m^3 water eq/1000d for water depletion (Figure 17). The largest water footprints (in all subcategories) are produced by distribution to W10 and W5, both of which have a significantly larger footprint compared to the other warehouses. The smallest water footprints (in all subcategories) are produced by the distribution to W2 and W6.

When considering the water footprint according to the real distribution of 1000 discs coated abrasives (Figure 18), the largest water footprint (in all subcategories) is produced by the distribution to W1 and W10. W1 has a bigger water footprint for freshwater eutrophication and ecotoxicity, marine ecotoxicity, and water depletion. W10’s water footprint is bigger for marine eutrophication.

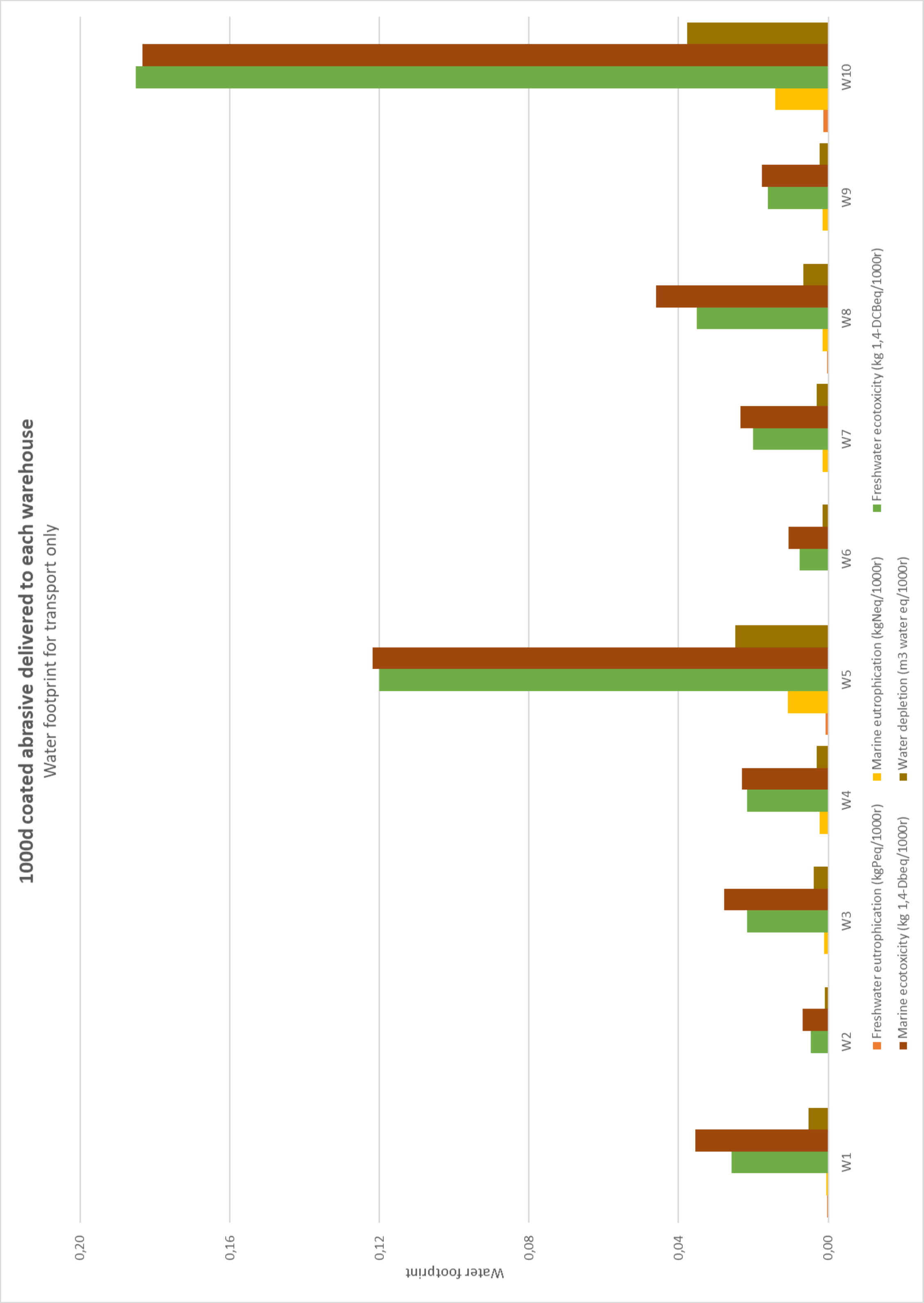

Figure 17. Water footprint for distribution of 1000 discs coated abrasives to each warehouse.

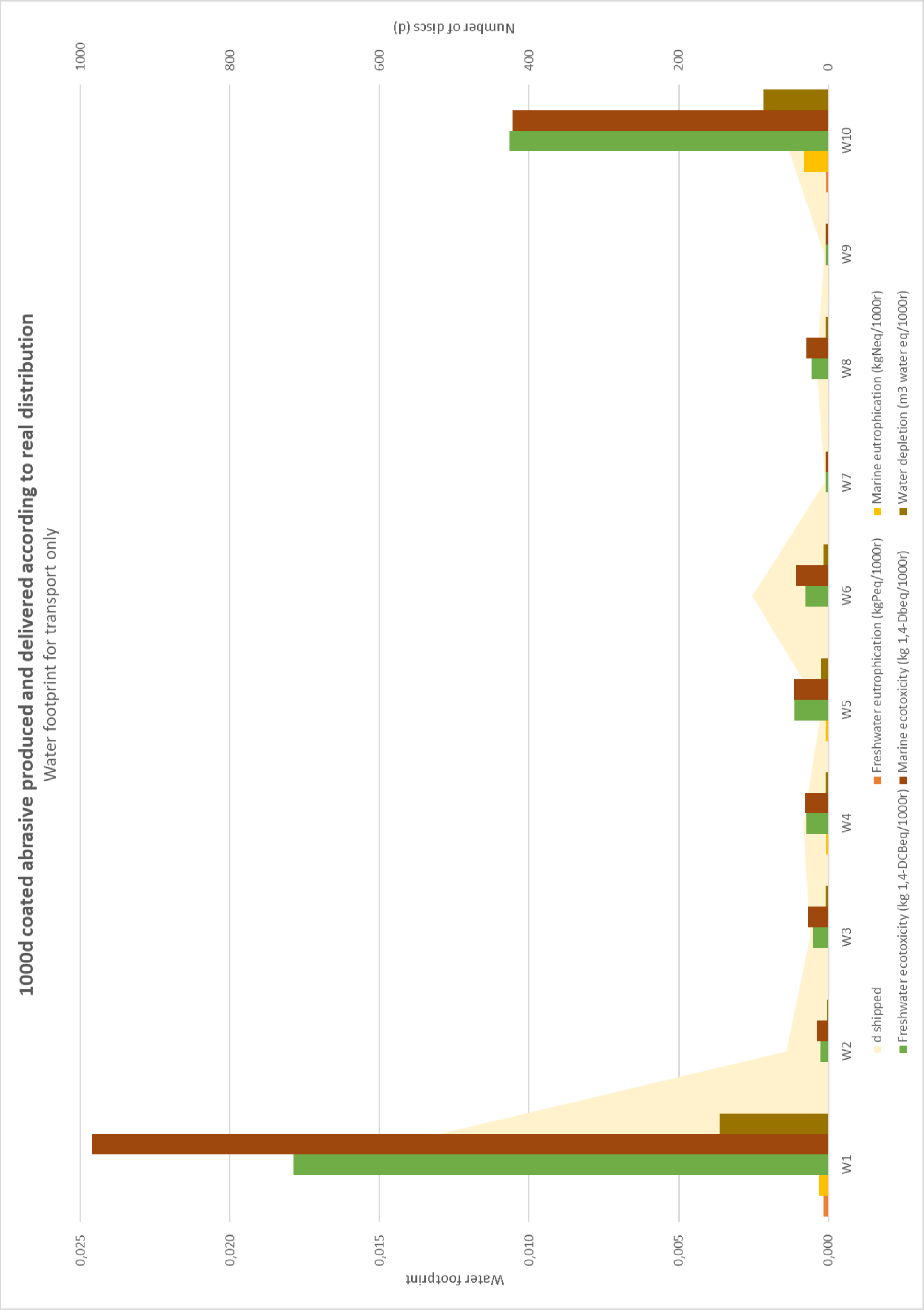

Figure 18. Water footprint for distribution of 1000 discs coated abrasives, according to real distribution.

For the polishing agents contributes distribution with between 48 $kgCO_2eq/1000L$ and 5 882 $kgCO_2eq/1000L$ to the total carbon footprint (Figure 19). The largest carbon footprint for distribution of polishing agents, between 4 231 $kgCO_2eq/1000L$ and 5 882 $kgCO_2eq/1000L$, is produced by the transport to W5 and W10. The smallest carbon footprint, 48 $kgCO_2eq/1000L$, is produced by the distribution to W2.

When considering the carbon footprint according to the real distribution of 1000L polishing agents (Figure 20), the biggest carbon footprints are produced by the distribution to W5 and W1, contributing 252 $kgCO_2eq$ and 86 $kgCO_2eq$ respectively.

Figure 19. Carbon footprint for distribution of 1000L polishing agent to each warehouse.

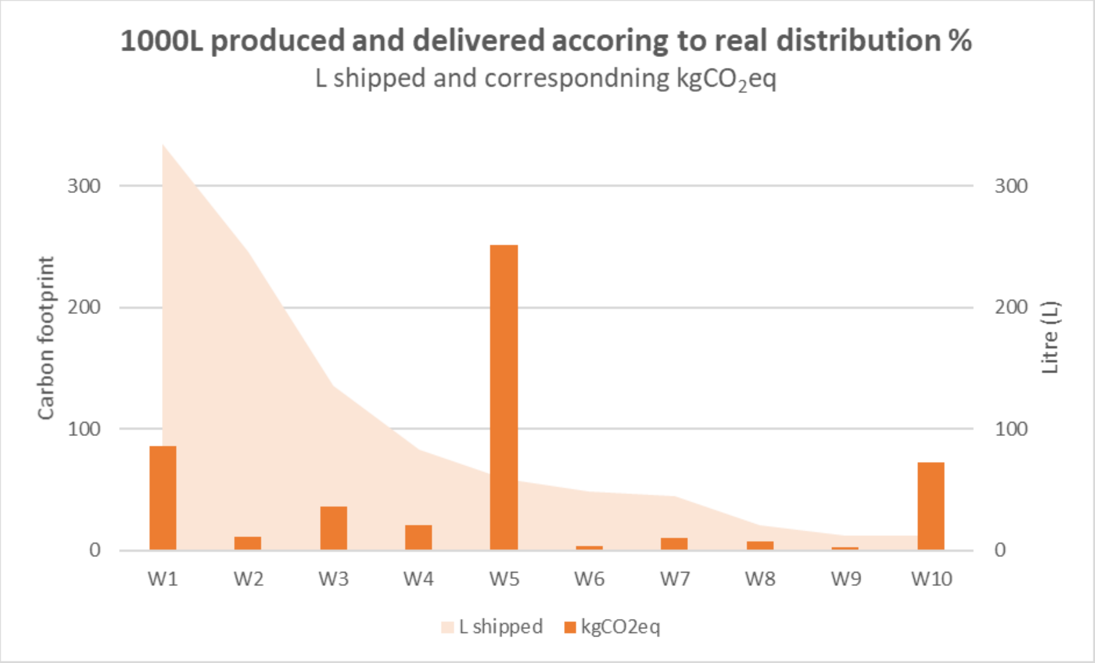

Figure 20. Carbon footprint for real distribution of 1000L polishing agent to warehouses.

The water footprint for distribution adds between 0.004 and 0.107 kgPeq/1000L for freshwater eutrophication, between 0.005 and 1.139 kgNeq/1000L for marine eutrophication, between 0.388 and 14.879 kg 1,4-DCBeq/1000L for freshwater ecotoxicity, between 0.545 and 14.820 kg 1,4-DBeq/1000L for marine ecotoxicity, and between 0.081 and 3.024 m^3 water eq/1000L for water depletion (Figure 21). The largest water footprints (in all subcategories) are produced by distribution to W10 and W5, both of which have a significantly larger footprint compared to the other warehouses. The smallest water footprints (in all subcategories) are produced by the distribution to W2 and W6.

When considering the water footprint according to the real distribution of 1000L polishing agent (Figure 22), the largest water footprint (in all subcategories) is produced by the distribution to W1 and W5. W1 has a bigger water footprint for freshwater eutrophication and ecotoxicity, marine ecotoxicity, and water depletion. W5's water footprint is bigger for marine eutrophication.

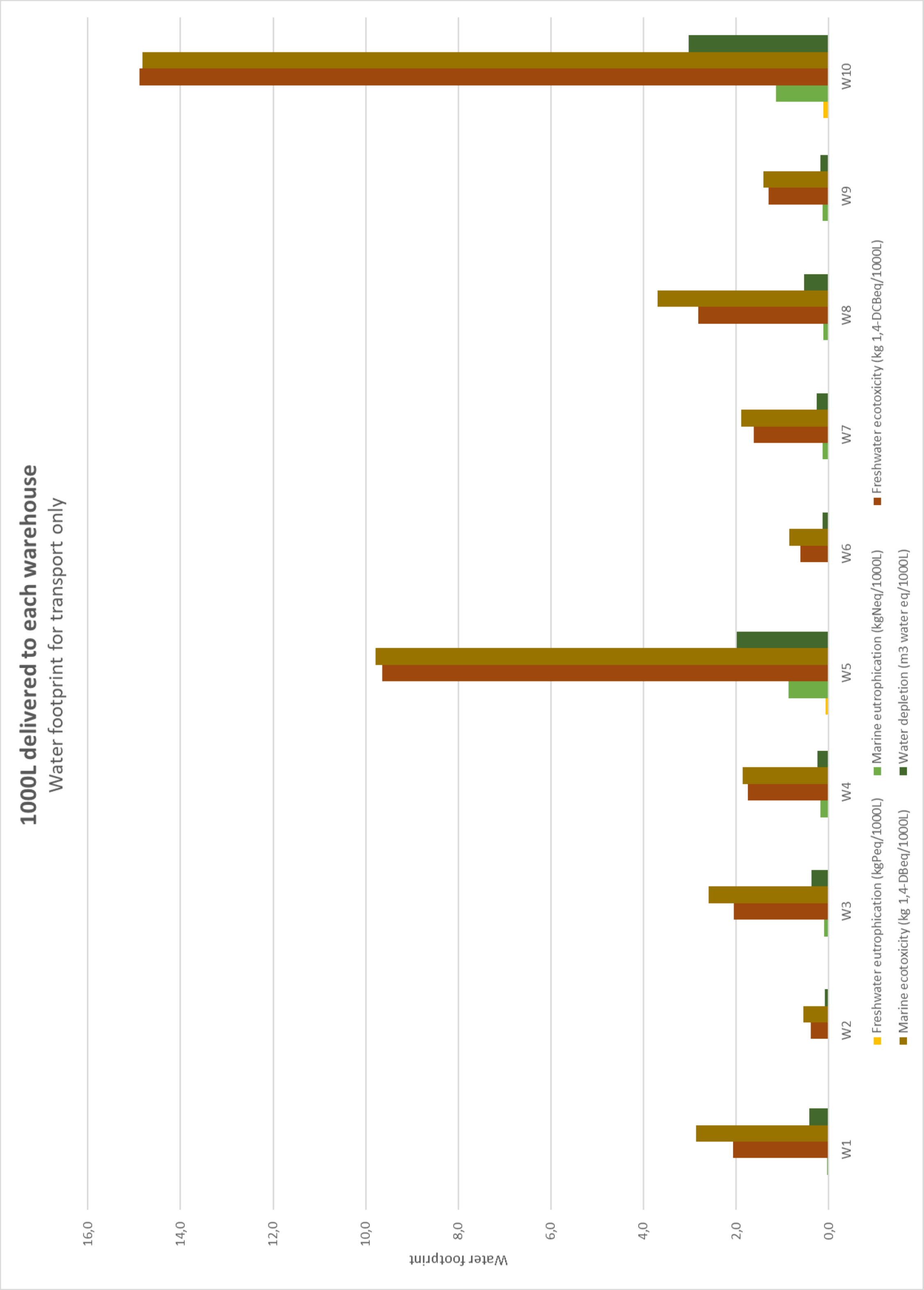

Figure 21. Water footprint for distribution of 1000L polishing agent to each warehouse.

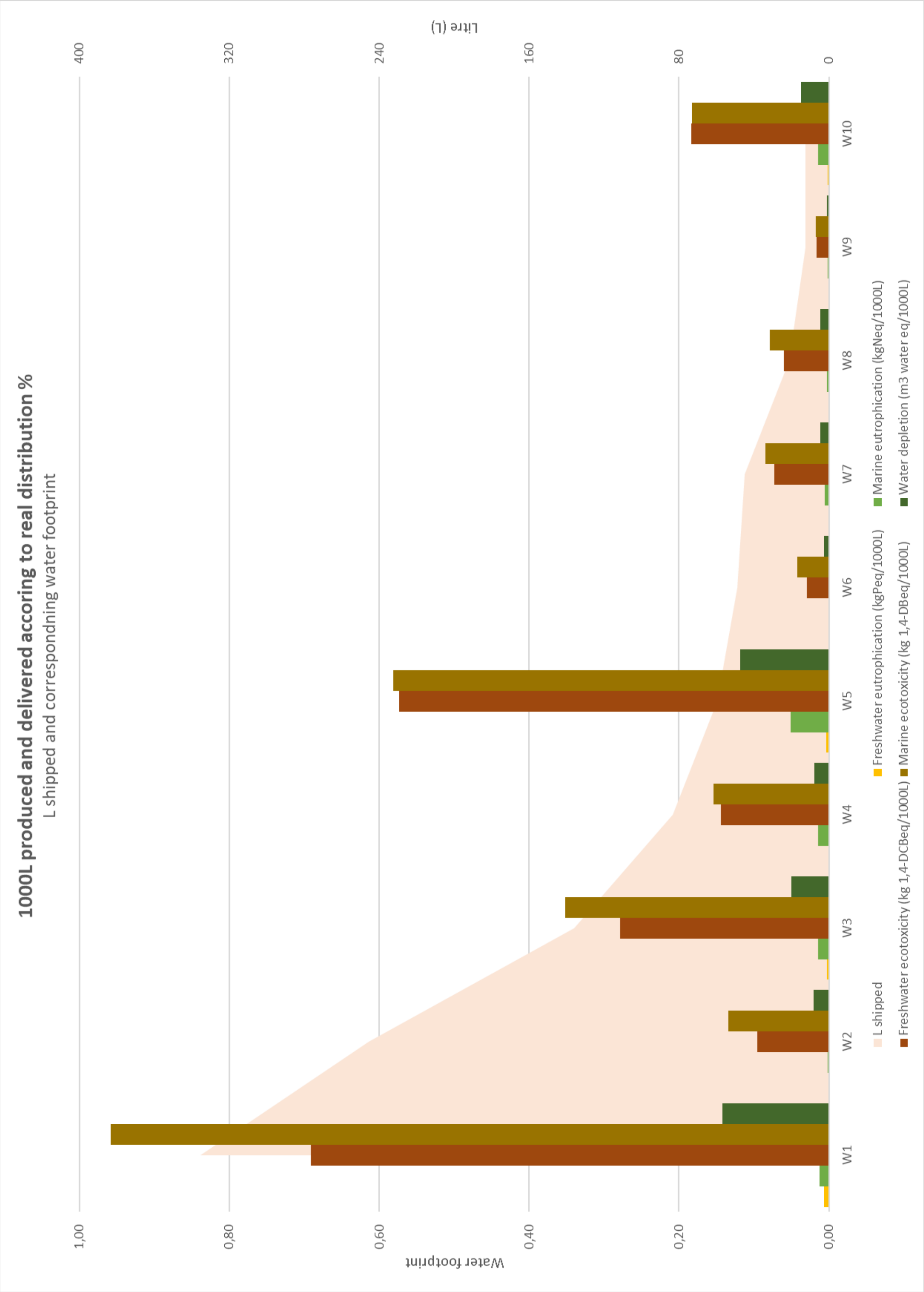

Figure 22. Water footprint for distribution of 1000L polishing agent, according to real distribution.

4.4 Summary of carbon and water footprint

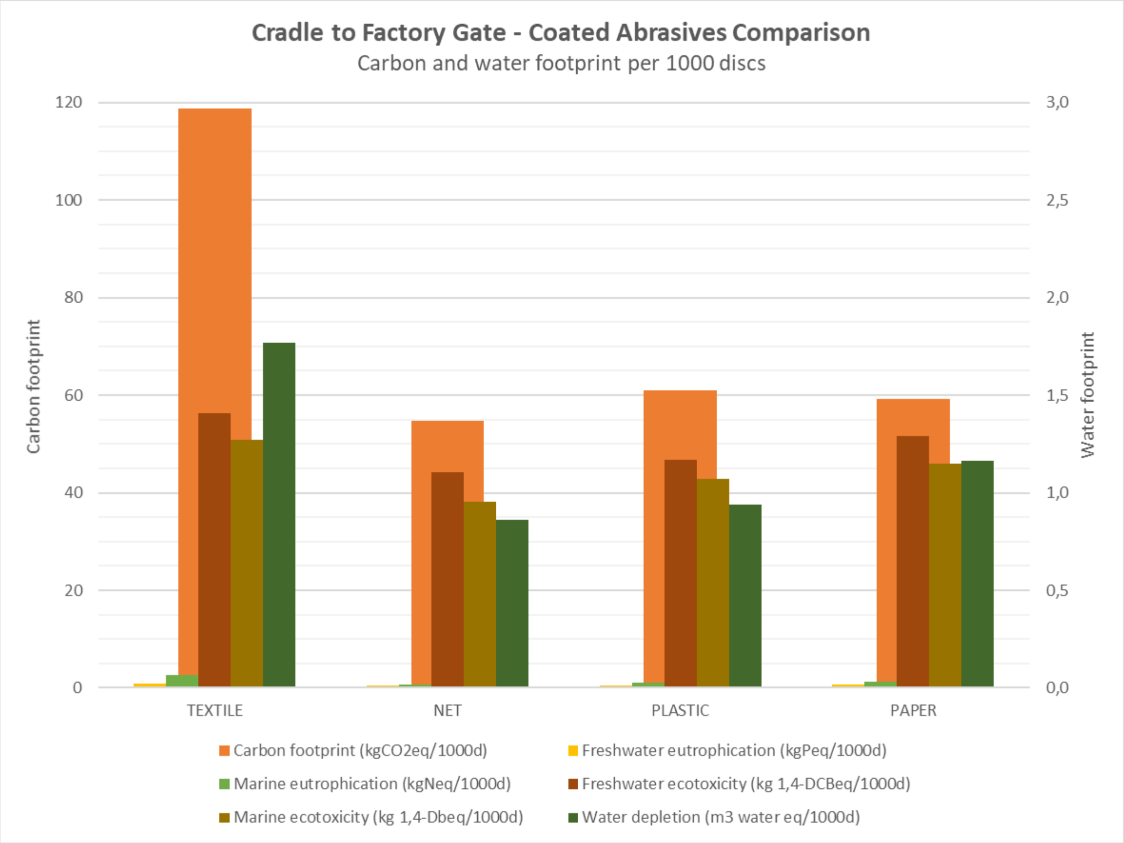

Figure 23. Summary of the carbon and water footprints for coated abrasives.

Coated abrasives (cradle-to-factory-gate) have an average carbon footprint varying between 55 kgCO_2eq/1000d and 119 kgCO_2eq/1000d (Figure 23), assuming equal amounts of each grit size is produced under a product name. For coated abrasives are the largest average carbon footprint is produced by TEXTILE and its footprint is significantly larger than the other coated abrasives. The second largest average carbon footprint is produced by PLASTIC (61 kgCO_2eq/1000d), followed by PAPER (59 kgCO_2eq/1000d). NET has the smallest average carbon footprint of the studied coated abrasives.

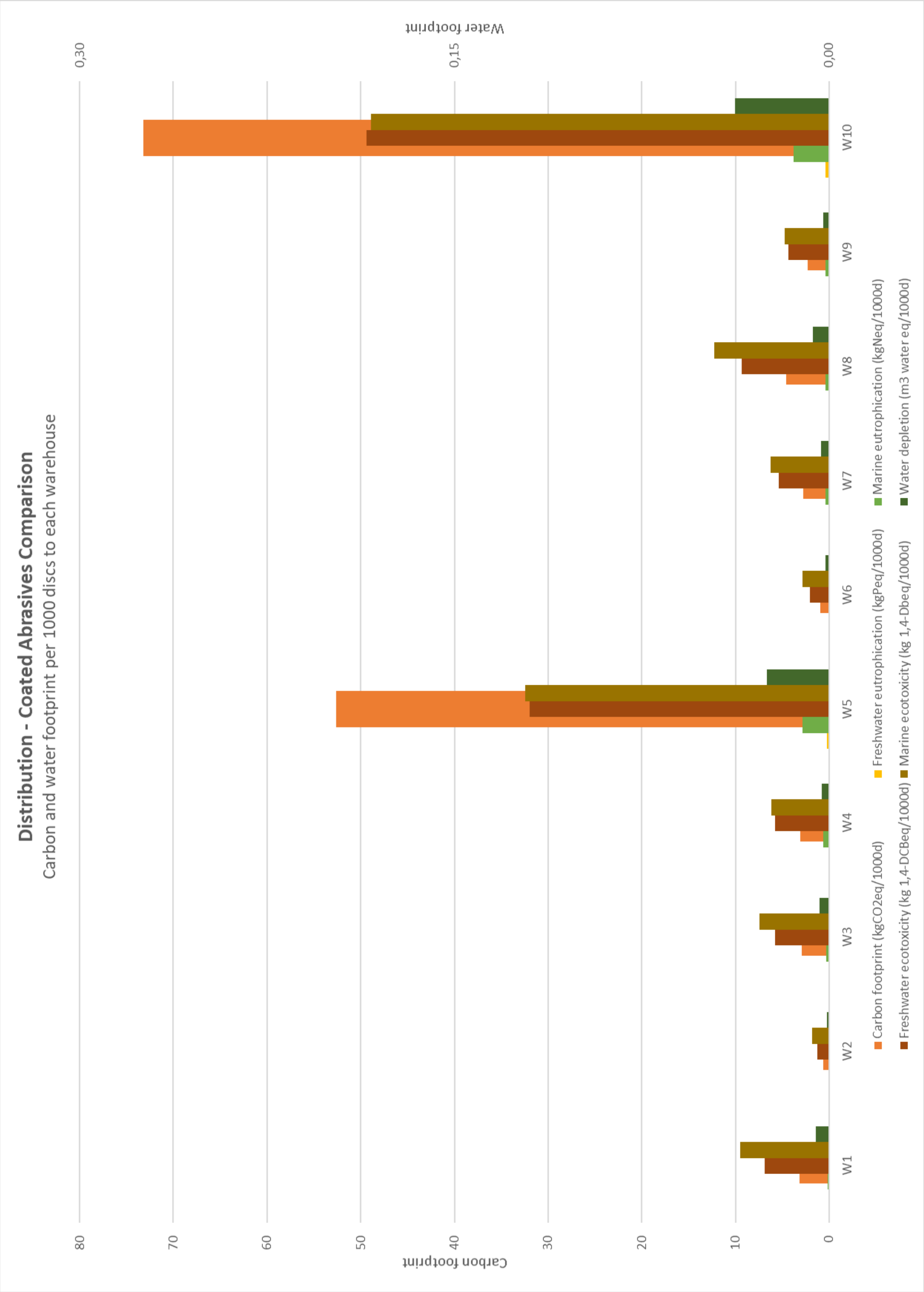

Figure 24. Summary of the carbon and water footprints for the distribution of coated abrasives.

The average water footprints for coated abrasives vary between 0.011 and 0.020 kgPeq/1000d for freshwater eutrophication, 0.017 and 0.065 kgNeq/1000d for marine eutrophication, 1.017 and 1.406 kg 1,4-DCBeq/1000d for freshwater ecotoxicity, 0.955 and 1.269 kg 1,4-DBeq/1000d for marine ecotoxicity, and between 0.860 and 1.769 m^3 water eq/1000d for water depletion (Figure 23), assuming equal amounts of each grit size is produced under a product name. The largest water footprints (in all categories) are produced by TEXTILE, followed by PLASTIC and PAPER. NET has the smallest average water footprints.

Distribution of coated abrasives have an average carbon footprint varying between 0.6 and 73.2 $kgCO_2eq$/1000d (Figure 24), assuming equal amounts of each grit size from all product names is produced. The largest average carbon footprints are produced by the distribution to W10, followed by W5 (52.7 $kgCO_2eq$/1000d). The smallest footprint is produced by the distribution to W2.

The average water footprints for the distribution of coated abrasives vary between 4×10^{-5} and 133×10^{-5} kgPeq/1000d for freshwater eutrophication, 1×10^{-4} and 142×10^{-4} kgNeq/1000d for marine eutrophication, 0.005 and 0.185 kg 1,4-DCBeq/1000d for freshwater ecotoxicity, 0.007 and 0.183 kg 1,4-DBeq/1000d for marine ecotoxicity, and between 0.001 and 0.038 m^3 water eq/1000d for water depletion (Figure 24), assuming equal amounts of each grit size is produced under a product name. For the distribution of coated abrasives are the largest average water footprints (in all categories) produced by distribution to W10. The second largest average water footprints (in all categories) is produced by distribution to W5. Distribution to W6 has the second smallest average water footprints (in all categories), with distribution to W2 having the smallest associated footprints.

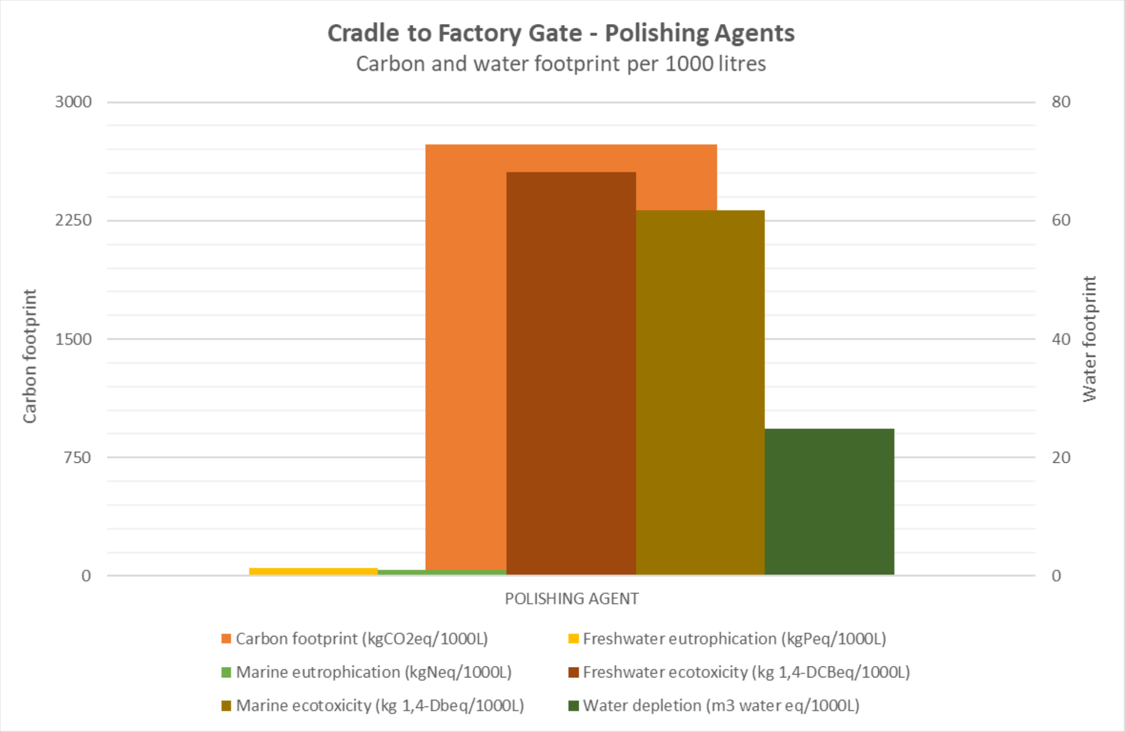

Figure 25. Summary of the carbon and water footprints for polishing agents.

Polishing agents (cradle-to-factory-gate) have an average carbon footprint of 2 733 $kgCO_2eq/1000L$ and the average water footprints are 1.290 kgPeq/1000L for freshwater eutrophication, 1.053 kgNeq/1000L for marine eutrophication, 68.134 kg 1,4-DCBeq/1000L for freshwater ecotoxicity, 61.682 kg 1,4-DBeq/1000L for marine ecotoxicity, and 24.812 m^3 water eq/1000d for water depletion (Figure 25), assuming equal amounts of each polishing grade is produced.

Distribution of polishing agents have an average carbon footprint varying between 47 and 5882 $kgCO_2eq/1000L$ (Figure 26), assuming equal amounts of each polishing grade is produced. The largest average carbon footprints are produced by the distribution to W10, followed by W5 (4231 $kgCO_2eq/1000L$). The smallest footprint is produced by the distribution to W2.

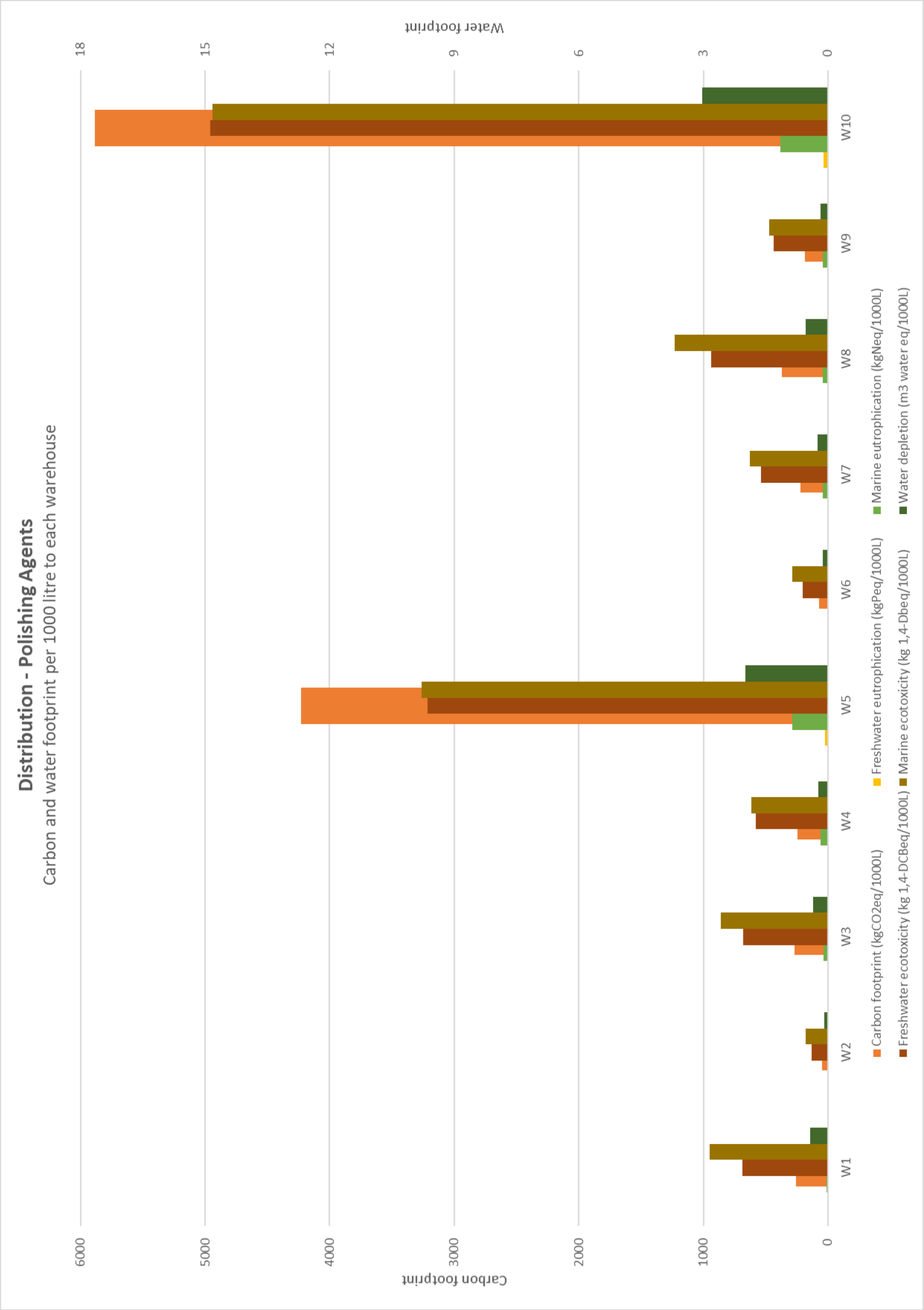

Figure 26. Summary of the carbon and water footprints for the distribution of polishing agents.

The average water footprints for the distribution of polishing agents vary between 0.004 and 0.107 kgPeq/1000L for freshwater eutrophication, 0.005 and 1.139 kgNeq/1000L for marine eutrophication, 0.388 and 14.879 kg 1,4-DCBeq/1000L for freshwater ecotoxicity, 0.545 and 14.820 kg 1,4-DBeq/1000L for marine ecotoxicity, and between 0.081 and 3.024 m^3 water eq/1000L for water depletion (Figure 26), assuming equal amounts of each polishing grade is produced. For the distribution of polishing agents are the largest average water footprints (in all categories) produced by distribution to W10. The second largest average water footprints (in all categories) is produced by distribution to W5. Distribution to W6 has the second smallest average water footprints (in all categories), with distribution to W2 having the smallest associated footprints.

5 End-of-life

The end-of-life for coated abrasives and polishing agents might vary significantly depending on the geographical location of the end-of-life stage. Dumping or open burning (uncontrolled waste disposal) was common worldwide until the 1960s and is still prevalent in developing countries, but the development trend is towards improved collection worldwide (Wilson, 2015). However, waste collection coverage varies significantly, with high-income countries having waste collection coverage close to 100 % in urban areas while the collection coverage in low-income countries only reaches 36 % in urban areas (Wilson, 2015). Due to this variance in waste management and the difficulty of modelling the end-of-life stage with the database used, this chapter will cover the end-of-life from a theoretical perspective. The effect on the environmental impact by three different waste treatment options – landfilling, waste incineration and recycling – will be covered.

Landfilling can have very varying environmental impacts. They need to be managed and controlled even after closure in order to make sure they don’t have negative effects on human health or the environment (Laner et al., 2012). Mismanaged landfills can cause groundwater and air pollution, potential health hazards, and have an impact on climate through methane emissions (Aljaradin & Persson, 2012). However, an older study found that the contribution from landfilling to the environmental impact of a product’s LC is very small if only low amounts are landfilled and the landfill is equipped with a gas collection system (Ongmongkolku, Nielsen & Nazhad, 2002). The convenience landfills offer (everything thrown in a hole in the ground) is somewhat offset by the risks they pose if mismanaged, but in cases where the waste is not suitable for reuse, recycling or incineration, they might be the best waste treatment option.

Waste incineration has been around since the late 19th century and the waste-to-energy (WtE) market[3] is expected to continue to grow (Makarichi, Jutidamrongphan & Techato, 2018; Statistica, 2020). Compared to landfill gas recovery does waste incineration offer both better energy recovery as well as lower GHG emissions (Ting Tan et al. 2014), which makes incineration one option for offsetting emissions. The energy recovery possibility from waste incineration can also offset GHG emissions, since energy production using fossil fuels tend to have higher emissions than energy production through waste incineration (Cucchiella, D'Adamo & Gastaldi, 2014; Zhao et al. 2016). In addition to lower emissions and energy recovery possibilities, does waste incineration represent an environmentally friendly solution for unsorted waste (Cucchiella, D'Adamo & Gastaldi, 2014), which makes it a suitable solution for coated abrasives where it is difficult, expensive, or impossible to recycle the materials.

Possibility for recycling depends on the potential of separation, both of material components within a product and from other waste streams (Wilson, 2015). In Mirka's case, this mainly concerns packaging materials, such as bottles, boxes and pallets. Plastic has a high energy recovery rate (Chen, 2018), which makes it suitable for WtE treatment methods, but a majority of LCA studies have found that choosing plastic recycling over other waste treatment method tends to significantly reduce the environmental impacts of the plastic's end-of-life stage (Milios, Davani & Yu, 2018). GHG emissions in the plastic recycling industry in China are specifically discussed by Liu et al. (2018), who showcases an emission reduction of 7.67 MT in 2007 to 14.6 MT in 2016 thanks to rapid development of the industry. However, in the case of low-quality recycling, incineration might be preferred. If the recycled material cannot substitute virgin material, the emission savings might not be actualised and incineration would be the preferred option (Milios, Davani & Yu, 2018). In other words, recycling plastic should be the preferred

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[3] The waste-to-energy market includes thermal and biological waste treatment methods. Waste incineration falls under thermal methods and e.g. biogas production falls under biological methods. (Grand View Research, 2020.)

option, but if this is not possible or the recycled plastic does not get used due to quality issues, incineration is another valuable option.

Paperboard already has a history of recycling, with recovered paper making up 53 % of the total pulp used in the European paper industry in 2013 (Wilson, 2015) and the paper waste recycling market is expected to grow (Business Wire, 2020). An LCA study on delivery packages in China found that recycling has a lower carbon footprint and eutrophication potential than the incineration for corrugated board (Yi, Wang, Wennersten & Sun, 2017). However, according to Chen (2018) does paper waste have the highest energy recovery rate to GHG emission rate between paper, plastic and textile waste. An older study found that a one time direct reuse of a paperboard box has the potential to reduce environmental impacts by 50 % (Ongmongkolku, Nielsen & Nazhad, 2002). In summary, paperboard is part of an established recycling market which lowers its environmental impacts. One way to further lower impacts could be to explore reuse possibilities before the paperboard is sent for recycling.

Pallets are almost exclusively made out of wood (approximately 90 %) and most pallets are refurbished at some point during their LC (Carrano, Thorn & Woltag, 2014). One way the lifecycle and refurbishment are managed is by pallet pooling (Carrano, Thorn & Woltag, 2014), which lowers the environmental impact since the pallet is reused multiple times before it reaches its end of life (Deviatkin, Khan, Ernst & Horttanainen, 2019). However, non-reusable pallets make up 19 % of wood waste worldwide and provide a comparatively clean source of wood waste (Berger, Gauvin & Brouwers, 2020), which makes is suitable for recycling. One study showed how production of particleboards from wood waste can save 428 kgCO2eq per tonne wood waste (Kim & Song, 2014) while another highlighted wood waste specifically from pallets as an “excellent candidate for WWCB [wood wool cement board]” (Berger, Gauvin & Brouwers, 2020). In comparison has it been reported that wood waste is a suitable substitution (through WtE conversion) to fossil fuels, but that GHG emissions from incineration of wood waste are 55 % higher than for biogas burning for electricity production (Shahidul, Malcolm, Hashmi & Alhaji, 2020). In conclusion should pallet LCs be extended for as long as possible before they are considered a waste. When they cannot be refurbished anymore, recycling is a preferable option before incineration.

In conclusion, due to the difficulty of separating materials in the coated abrasives waste incineration is the best waste treatment method. For packaging materials recycling is often the best option, but it requires the separation of materials from other waste streams. Landfills should be chosen as a last alternative and they do not have a big environmental impact on the LC of a product if only small amounts are landfilled.

6 Comparison with Henriksson's 2012 study

The comparative cradle-to-factory gate LCA focuses on the products PRODUCT 1, PRODUCT 2 and PRODUCT 3. In order to make the comparison only the production steps that were covered in Henriksson's 2012 thesis were included.

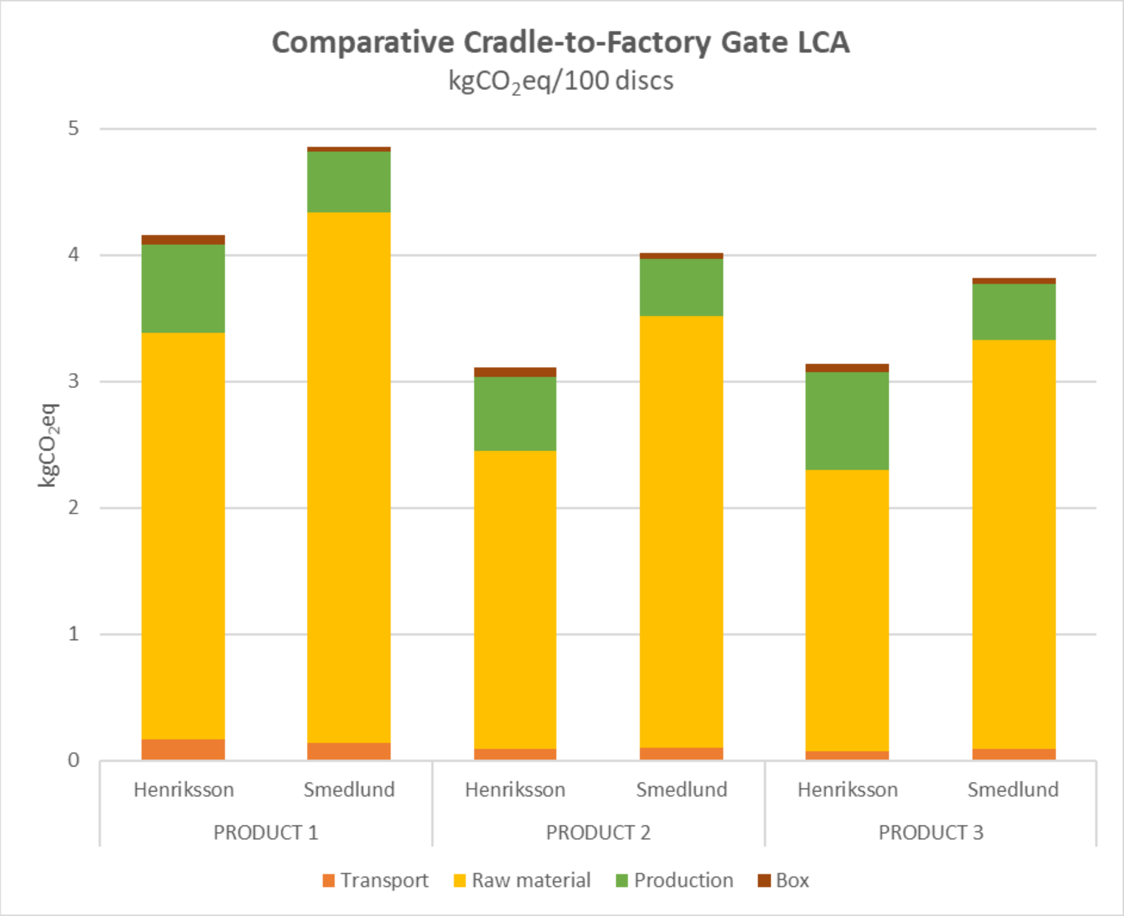

Figure 27. Results for the total carbon footprint in the comparative cradle-to-factory gate LCA study.

The carbon footprints calculated from this study are 4.86 $kgCO_2eq$/100 discs for PRODUCT 1, 4.02 $kgCO_2eq$/100 discs for PRODUCT 2 and 3.82 $kgCO_2eq$/100 discs for PRODUCT 3. In Henriksson's thesis the carbon footprints were 4.15 $kgCO_2eq$/100 discs for PRODUCT 1, 3.11 $kgCO_2eq$/100 discs for PRODUCT 2 and 3.14 $kgCO_2eq$/100 discs for PRODUCT 3. Comparing the results show that the new ones are noticeably higher, but in order to study the results, the carbon footprint was divided into four categories (Figure 27). *Transport* includes both raw material transport and internal transport between Mirka's facilities. *Raw material* is based on background data for raw material production. *Production* includes the energy needed for production at all stages of the production process, from the first use of the raw materials to the final cutting of round and putting into boxes. *Box* includes the production of the box used for 100 discs. The same categories were used in Henriksson's thesis.

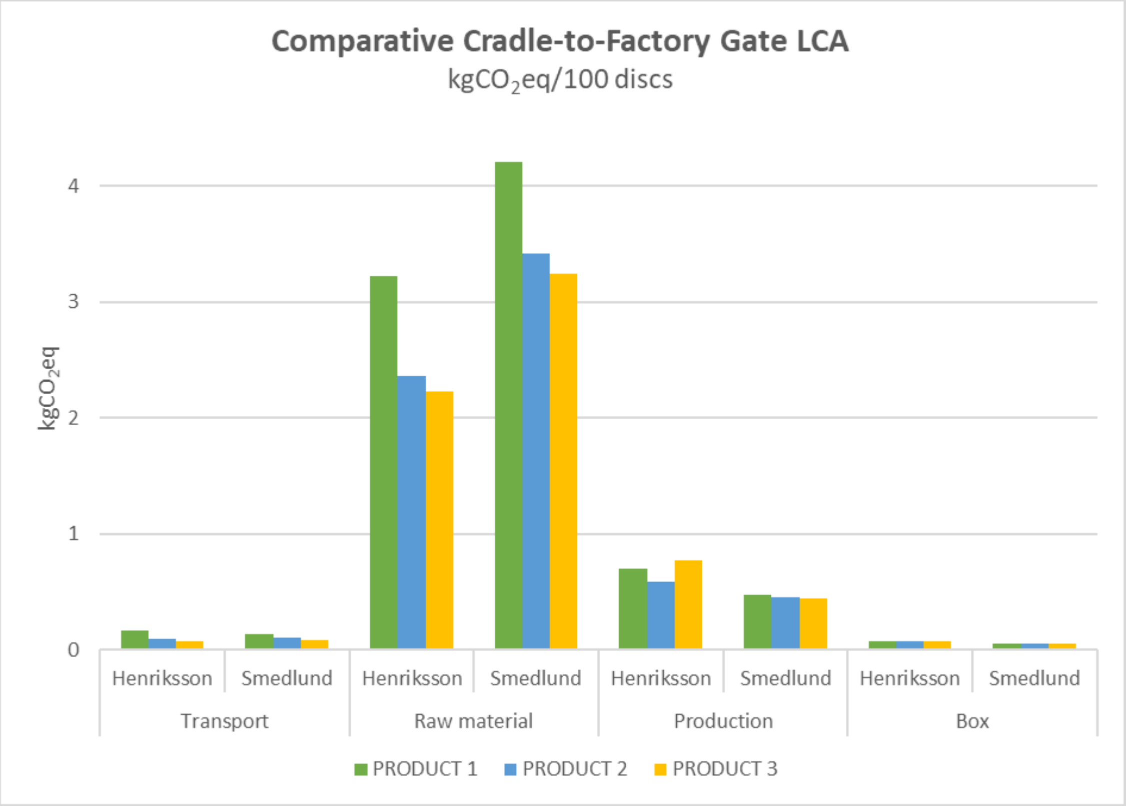

Figure 28. Results for the carbon footprint per category in the comparative cradle-to-factory gate LCA study.

The footprint related to transport has not changed much. Comparing the new results to Henriksson's thesis, the footprint for PRODUCT 1 has decreased by 0.025 $kgCO_2eq$ whilst it has increased for PRODUCT 2 and PRODUCT 3 by 0.010 and 0.016 $kgCO_2eq$ respectively (Figure 28). The increase is due to raw material transport, since the footprint for the internal transport makes up less than 10 % of the transport footprint and has decreased for all the products.

In Table 7 are the distances the raw materials travel summed up and when comparing them to the footprint results, it becomes evident that despite the transport distance increase, the mode of transport has lowered the impact. However, the transport distances in this study are calculated from raw material production site (if the information was available from the supplier) but Henriksson does not specify if her distances are from production sites or warehouses.

Table 7. Total raw material transport distances, comparative LCA.

Product		*Lorry (km)*	*Container ship (km)*	*Ferry (km)*	***TOTAL (km)***
1	*Henriksson*	10 994	9 583	-	**20 577**
	Smedlund	10 502	32 635	456	**43 593**
2	*Henriksson*	7 288	5 970	-	**13 258**
	Smedlund	9 411	44 230	424	**54 065**
3	*Henriksson*	7 288	5 970	-	**13 258**
	Smedlund	9 411	44 230	424	**54 065**

It should be noted that the footprint is not only tied to the distance, but also on the weight transported and type of transportation. Allocation of the footprint further depends on the mass-% the raw material makes up in the final product. The total transport distance does therefore not correspond directly to the footprint, as can be seen when comparing transport distances and total km transported between the products, e.g. PRODUCT 1 has the highest transport footprint, but the shortest total transport distance.

Raw material production makes up the largest part of the carbon footprint. In Henriksson's thesis it accounted for between 68 and 75 % of the total footprint, while it in this study makes up between 84 and 86 % of the total footprint. The footprint due to raw material production has increased by around 1 kgCO_2eq/1000L for each of the products and is the largest increase in the carbon footprint across the categories.

The large increase in the raw material production emissions could depend on a few factors. Firstly, the background data used in Henriksson's thesis locates all the raw material production in Europe opposed to this study where some of the raw material production is set elsewhere in the world. Secondly, both the ecoinvent database containing all the background data on material production and the calculation method used have gone through major updates (Steubing, 2016; Wernet et al., 2016) since Henriksson's study. Thirdly, due to the updated background data, the names of the data sets have changed and, in some cases, split to indicate different regions or production methods. In other words, the raw material production carbon footprint depends largely, but not completely, on factors outside of Mirka's control.

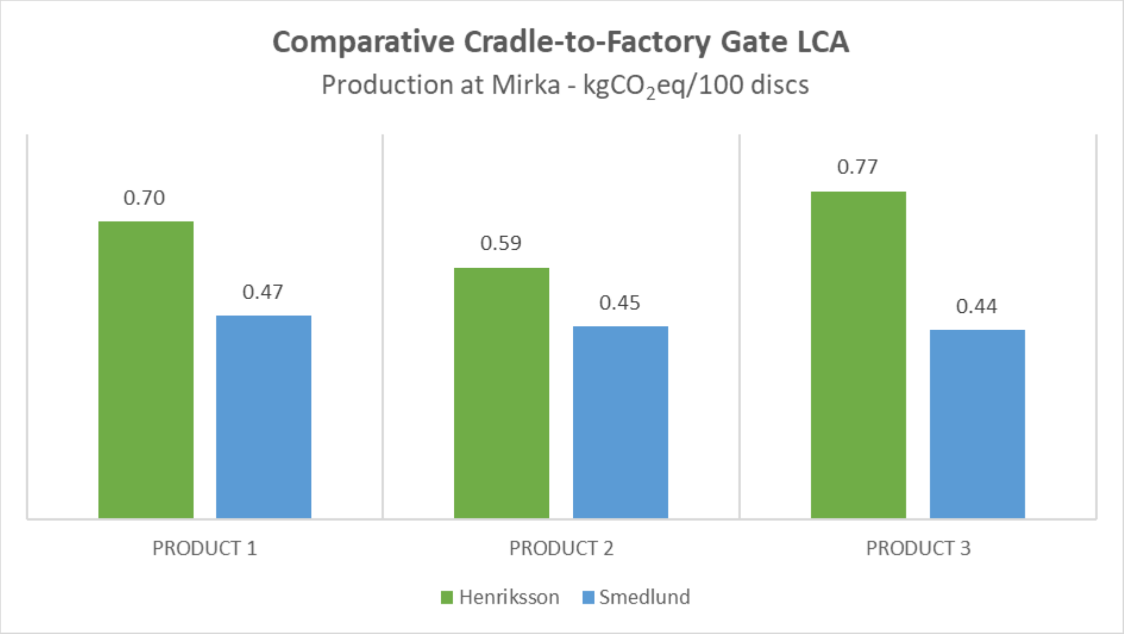

Figure 29. Results for the carbon footprint for production only in the comparative cradle-to-factory gate LCA study.

Production of the coated abrasives accounts for between 9 and 12 % of the carbon footprint. For PRODUCT 1 the footprint has decreased by 0.22 kgCO_2eq, for PRODUCT 2 by 0.14 kgCO_2eq, and for PRODUCT 3 by 0.32 kgCO_2eq (Figure 29). The background data has changed the footprint allocation from 0.0848 kgCO2eq/MJ (Henriksson, 2012) to 0.0676 kgCO2eq/MJ, but since the reduction in the footprint is bigger than the change in background data, it can be assumed that the change from using heavy oil to waste incineration for heating in some process steps has had a positive impact on the carbon footprint reduction.

The changes in the carbon footprint for the fourth category depends on background data, since it only includes the production of the box and the box's weight (which is the same as in Henriksson's thesis). For both box types used has the footprint lessened, by 0.029 and 0.017 kgCO$_2$eq respectively (Figure 28). One can thus assume that the footprint related to production of corrugated board boxes overall has lessened. Box transport is excluded both in this study and Henriksson's thesis since the box production is located at the same industrial site as where the packing of the products takes place.

In conclusion do the raw materials make up the largest part of the carbon footprint, around 85 % in the new results and around 75 % in Henriksson's results. The production is the second largest contributor to the footprint, standing for around 10 % of the footprint in this study and around 20 % in Henriksson's. Transport only contributes just over 2 %, around 3 % in Henriksson's thesis, to the carbon footprint. Lastly, the box makes up around 1 % of the footprint in this study while it made up around 2 % in Henriksson's thesis.

7 Discussion and conclusion

The aim of this study was to establish the environmental impacts of coated abrasives and polishing agents at Mirka, with a focus on carbon and water footprints. The carbon footprint for coated abrasives varies between 46 and 119 kgCO2eq/1000d and between 2502 and 3003 kgCO2eq/1000L for polishing agents. The water footprint is divided into five categories. For coated abrasives varies the water footprint between 0.009 and 0.020 kgPeq/1000d for freshwater eutrophication, between 0.017 and 0.065 kgNeq/1000d for marine eutrophication, 0.837 and 1.701 kg 1,4-DCBeq/1000d for freshwater ecotoxicity, 0.762 and 1.385 kg 1,4-Dbeq/1000d for marine ecotoxicity, and between 0.799 and 1.769 m3 water eq/1000d for water depletion. For polishing agents varies the water footprint between 1.248 and 1.372 kgPeq/1000L for freshwater eutrophication, between 0.698 and 1.946 kgNeq/1000L for marine eutrophication, 63 and 78 kg 1,4-DCBeq/1000L for freshwater ecotoxicity, 57 and 72 kg 1,4-Dbeq/1000L for marine ecotoxicity, and between 23 and 26 m3 water eq/1000L for water depletion.

A major contributor to both the carbon and water footprints is raw material production. Especially backing for coated abrasives and grits for polishing agents play huge parts in the footprint for their respective product type. This is illustrated by how the coated abrasive TEXTILE, due to its backing materials, has a significantly larger footprint compared to the other coated abrasives and how polishing agent 3's high grit content plays a part in its high footprints.

For coated abrasives is production the second largest contributor to the footprints. The shift done by Mirka to using energy from a WtE plant gives a zero footprint for the energy use in processes at the Jepua facility. This means that the production footprints are caused by the backing production and the production at the Oravainen facility. Due to be noted is that the energy requirements are largely based on recipes and not new measurements, which means that if the recipes have corrupt number the results do not provide a truthful picture of reality.

The second largest, and in some cases the largest, contributor to the footprints for polishing agents is related to packaging. The plastic bottles make up the majority of the packaging related footprint. Noteworthy is that the bottles are shipped over 2200 km, which produces 42.1 kgCO2eq per 1000 bottles (1L bottles). If the transport was shortened to 100 km, the carbon footprint for the transport would be reduced to 1.8 kgCO2eq per 1000 bottles (1L bottles).

Distribution showcases the footprint implications by different transportation methods clearly. When considering that W4 is the furthest away but only make up 4 % of W10's carbon footprint the difference between air freight (to W10) and container ship (W4) becomes evident. Comparing W8 to W4 highlight this even more. Distribution to W8 only has 17 % of the travel distance distribution to W4 has, but its carbon footprint is slightly higher due to the products being transported by lorry.

The best solution for end-of-life for coated abrasives is WtE. Currently it is too difficult to separate the material fraction and thus recycling is not an option for used coated abrasives. Recycling (or reuse) is, however, the best option for the packaging materials and should be promoted as well as taken into consideration when designing or choosing packaging, since it could offset the footprint of the product.

The second aim of the study was to compare the results with the 2012 study by Henriksson. Since both the background data and the assessment method have gone through major updates since the 2012 study, the results might not be completely comparable. This is showcased by the increased carbon footprint for raw materials, which should be quite similar since the recipes are unchanged. However, production has benefitted from Mirka's transition to WtE technology as the main energy source at the Jepua facility, and even better results would have been achieved if more parts of the production was located at the Jepua facility.

The next step for Mirka would be to search for solutions. Firstly, the areas with the largest impacts should be considered in order to reduce the impact of the products/processes. Secondly, by starting to ask suppliers if they know their environmental impact, Mirka could provide the incentive for them to improve their own processes, which would lower Mirka's environmental impact as well. Thirdly, new LCAs should be conducted in order to track changes and make improvements visible. To be remembered is that no single unit at the company can do this single handed. The environmental impact of a product is a collective responsibility and should be treated as such.

For future research it would be interesting to see an energy analysis of the production only, in order to figure out how much energy is used and where. A study on the life span of a disc in use (e.g. functional unit: $kgCO_2eq/m^2$ sanded) would also be a positive addition to this study. Lastly, a study or review on how to offset carbon could be an interesting follow-up to this thesis.

To conclude this thesis, I want to thank my supervisor at the university, Petri Helo[4], for the help with getting started and then finalising my master's thesis. I thank my supervisors at Mirka, Charlotta Risku[5] and Maria Nystöm[6], for having helped me get the information and data needed to conduct the life cycle assessment. I want to thank Bening Mayanti[7] for the collaboration on the ecoinvent database (I still owe you a coffee). I also want to thank all the employees of Mirka who I have been in contact with for your positive attitudes, interest in my research, and your will to help. Lastly, I want to thank my family for putting up with me during the year I have worked on this. It has been a challenging and rewarding thesis topic.

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Appendices

Appendix 1. More on data collection

Background data: ecoinvent 3.6

Functional unit: 1000 discs, 1000 litres, 100 discs

Raw material

Based on recipes for the products. Materials making up less than 1 mass-% of the final product cut off.

Transport / Distribution

Data on transport distances per transport type[8] were collected for transport from the material production site (or supplier if site could not be found) to Mirka, between Mirka's facilities, and from Mirka to the main warehouses worldwide. Data based on information provided by suppliers and the distances were measured in Google Maps[9], Sea-distances.org[10] and Air Miles Calculator[11], assuming use of shortest route.

Production

Energy data partly based on recipe data and partly secondary data collected in 2018. A few production steps were measured during this study, when possible. Energy production[12] identified for the different facilities. The energy data in the recipes was transformed from €/m produced to kWh/m produced by equation 1:

$$\frac{\frac{Energy\ costs\ in\ production\ (€)}{meters\ produced\ (m)}}{\frac{Total\ electricity\ cost\ over\ 7\ months\ (€)}{Total\ electricity\ use\ over\ 7\ months\ (kWh)}} = \frac{kWh}{m} \tag{1}$$

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[8] Lorry (size and EURO level), ferry, container ship, airfreight

[9] http://maps.google.com/

[10] https://sea-distances.org/

[11] https://www.airmilescalculator.com/

[12] Electricity grid, waste incineration, wood chips

Production waste from conversion of coated abrasives was calculated based on the annual reported waste (31.8.2019-30.8.2020) and the theoretical waste due to cutting pattern. The total waste due to cutting pattern was calculated with equation 2:

$$\frac{\left(\left(\frac{m_t}{mh} - \frac{m_{wr}}{mh}\right) * W - \pi r^2 * \frac{x}{mh}\right)}{W} = m_w \tag{2}$$

where:

m_t = meters total (m)

mh = machine hour (h)

m_{wr} = meters waste, reported (m)

W = width of coated abrasive jumbo (m)

r = radius of round (m)

x = number of discs

m_w = meters waste, due to cutting pattern (m).

Packaging

Packaging includes bottles and boxes, both of which were evaluated based on their respective weight and transport distance to Mirka, as well as EURO-pallets and plastic film. For polishing agents, the 1 litre bottle assessed. For coated abrasive the boxes used for each separate product were used. Average number of boxes per pallet was estimated with the help of Mirka employees.

Since plastic bottle production was not available as background data HDPE plastic production was used instead, with the addition of the energy requirements as presented by Gleick & Cooley[13] of making a PET bottle, which is 20 MJ/kg bottle. For corrugated board was the impact of cutting the board assumed insignificant compared to the rest

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[13] Gleick, P. H., & Cooley, H. S. (2009). Energy implications of bottled water. *Environmental Research Letters, 4(1), 1–6*. http://dx.doi.org/10.1088/1748-9326/4/1/014009

of the production and thus not included in the analysis. Background data was used for the production of corrugated board and HDPE plastic.

In order to estimate the EURO-pallets' impact on the lifecycle the pallets' lifecycle was considered. According to FEFPEB[14] is the lifespan of wooden pallets 5-7 years, but in LCA studies the life expectancy of a pallet is set to 10 years[15]. Korbiel, Pawluś, & Gawroński[16] defined the lifespan as 33 handling cycles, where one cycle includes 15 handlings. For this study it was estimated that for one fully loaded pallet one handling cycle was used. A pallet's contribution to the environmental impact of one fully loaded pallet was therefore set as 1/33 of the full pallet impact.

There were two types of plastic film used for wrapping the fully loaded pallets. Background data was used for the first type whilst the carbon equivalent was provided by the supplier for the second type. Plastic sheets added as roofs on top of loaded pallets are not included, due to not finding representative background data and them not being regularly used on pallets for coated abrasives.

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