APPLICABILITY OF ENVIRONMENTAL HANDPRINT IN PRODUCT DEVELOPMENT OF LIMESTONE-BASED PRODUCTS

Case Nordkalk

Lappeenranta–Lahti University of Technology LUT

Master’s Programme in Sustainability Science and Solutions, Master's thesis

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Examiners: Professor Risto Soukka

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ABSTRACT

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Keywords: limestone, limestone-based products, environmental handprint, handprint assessment, positive environmental impacts

The purpose of this thesis is to research the environmental handprint potential of limestone-based products. First, the manufacturing methods of limestone-based products and their uses are explained. In addition, environmental impacts of these use applications are analyzed. The positive environmental impacts to customers contributed by the use of alternative limestone-based products are evaluated. The environmental handprint framework developed by LUT University and VTT is followed, and the aim is to identify the different handprints defined in the framework for limestone-based applications. The thesis analyzes the applicability of the handprint methodology as part of the company's sustainability reporting.

In the case study a handprint assessment is carried out for one of the company's limestone-based products. The GaBi life cycle modeling software is used to implement the case study calculations. The case review focuses on the partial replacement of a traditional paint pigment with a limestone-based alternative produced by Nordkalk. Nordkalk wants to offer sustainable limestone-based solutions to customers and help them to maximize the environmental handprint of their products. The case can give direction to the product development of a limestone-based pigment which is used in paints to replace titanium dioxide. As a result of the case review, it can be stated that the limestone-based product has positive environmental impacts as an offered solution for a pigment substitution in paints.

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Ympäristökädenjäljen sovellettavuus kalkkikivipohjaisten tuotteiden tuotekehityksessä

Case Nordkalk

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Tämän diplomityön tarkoituksena on tutkia kalkkikivipohjaisten tuotteiden ympäristökädenjälkipotentiaalia. Ensin selvitetään kalkkikivipohjaisten tuotteiden valmistustavat ja niiden käyttökohteet. Lisäksi analysoidaan ympäristövaikutuksia näissä käyttökohteissa. Kalkkikivipohjaisten tuotteiden käytön positiivisia ympäristövaikutuksia asiakkaalle tunnistetaan. LUT-yliopiston ja VTT:n kehittämää viitekehystä ympäristökädenjäljestä seurataan ja pyritään tunnistamaan viitekehyksessä määriteltyjä eri kädenjälkiä kalkkikivisovelluksille. Työssä analysoidaan kädenjälki metodologian soveltuvuutta yrityksen kestävän kehityksen raportoinnin osaksi.

Case-tarkastelussa toteutetaan kädenjälkiarviointi yhdelle yhteistyöyrityksen kalkkikivipohjaiselle tuotteelle. Case-tarkastelun laskennan toteutukseen käytetään GaBi elinkaarimallinnusohjelmistoa. Case-tarkastelu keskittyy perinteisen maalipigmentin osittaiseen korvaamiseen Nordkalkin valmistamalla vaihtoehtoisella kalkkikivipohjaisella pigmentillä. Nordkalk haluaa tarjota asiakkailleen kestäviä kalkkikivipohjaisia ratkaisuja ja auttaa heitä maksimoimaan tuotteidensa ympäristökädenjälkeä. Case voi antaa suuntaa kalkkikivipohjaisen pigmentin tuotekehitykselle, jota käytetään maaleissa korvaamaan titaanidioksidia. Case-tarkastelun tuloksena voidaan todeta, että kalkkikivipohjainen tuote saa aikaan positiivisen ympäristövaikutuksen tarjottuna ratkaisuna pigmentin korvaamiseksi maaleissa.

SYMBOLS AND ABBREVIATIONS

Chemical names

$CaCO_3$	calcium carbonate	calcite
CaO	calcium oxide	quicklime/burned lime
$Ca(OH)_2$	calcium hydroxide	slaked lime/hydrated lime
CO_2	carbon dioxide	
H_2O	water	
$MgCO_3$	magnesium carbonate	magnesite
Na_2CO_3	sodium carbonate	soda ash
$NaOH$	sodium hydroxide	caustic soda
SO_2	sulphur dioxide	
TiO_2	titanium dioxide	

Abbreviations

ADP	Abiotic Depletion Potential
AP	Acidification Potential
B2C	Business to Customers
BAT	Best Available Technique
BAU	Business-as-usual
BF	Blast Furnace
BOF	Basic Oxygen Furnace
CCS	Carbon Capture and Storage
EAF	Electric Arc Furnace

EP	Eutrophication Potential
EPD	Environmental Product Declaration
EU	European Union
GHG	Greenhouse gas
GWP	Global Warming Potential
ISO	International Organization for Standardization
KPI	Key Performance Indicators
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
OPC	Ordinary Portland Cement
PCC	Precipitated Calcium Carbonate
SCM	Supplementary Cementitious Materials

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Abstract

Symbols and abbreviations

1. Introduction

“Lime is everywhere” is the first statement on the website of a limestone company called Nordkalk. Limestone-based products are told to be essential raw materials for numerous industries and important in applications such as purification of water and air. (Nordkalk, 2022a.) In addition to this Boynton (1980) stated that limestone is “one of the six essential building blocks for commerce and industry” with iron ore, salt, sulphur, petroleum, and coal. Every home has objects or products which have required a limestone-based product in some phase of its manufacture, directly or indirectly. Limestone-based solutions have been important to our society without which life would be less developed. (Boynton, 1980.) Nowadays limestone has numerous applications such as soil conditioner and agricultural use, building materials like an aggregate for the road infrastructure and a component in cement concrete, raw material to glass and many fillers, and important to steel and metal processing as well as paper and pulp industries (Ganapathi & Phukan 2020).

The extent of limestone and limestone-based applications makes it important to consider their environmental impacts. Since limestone is so widely used, the environmental impacts of limestone quarrying are already broadly researched for example. According to Ganapathi and Phukan (2020) carbonate rock resources, such as limestone, always cause environmental impacts when quarried or mined. They also found out that there are many studies already describing negative environmental impacts of mining limestone. However, the use of modern technologies reduces these impacts. (Ganapathi & Phukan, 2020.) Limestone and products made of it are researched broadly also in the building and construction context, where they are used extensively in a wide range of structures thanks to suitable characteristics like durability, versatility, and relatively easy availability around the globe (Smith, Gomez-Heras & Viles, 2010).

Sustainability and environmental impacts of limestone-based products in their use stage at customer’s process are in the core of this study. This is an aspect which is not so broadly researched and therefore, the focus on this study is the environmental handprint of limestone-based products, which is the interest of Nordkalk company also. It is not widely studied how limestone-based products possibly contribute to bigger environmental handprints or sustainability in different industries and what kind of opportunities the product development around limestone can have. Nordkalk also wants to identify the good characteristics of limestone-based products and identify what benefits they may have compared to other solutions or competing products in the markets. It is not known can limestone-based products be considered as sustainable solutions and what kind of handprints they can create in different applications. There is not an indicator to demonstrate the environmental handprint of Nordkalk yet assessed in their sustainability report or strategy, that’s why an evaluation of the situation is needed to get started in the handprint assessment. In product development context, Nordkalk wants to develop solutions based on limestone and use virgin raw materials as efficient as possible targeting to 100 % material efficiency in their whole production. Improvements in material efficiency, side streams utilization and circular solutions prevents waste and energy consumption according to Nordkalk (2023). The desire to communicate positive environmental effects of the company can be seen and the growing environmental handprint of limestone-based product is in the core of interest. This kind of environmentally beneficial applications based on limestone can be for example low carbon products, circular economy products and solutions substituting harmful chemicals. (Nordkalk, 2023.) There is also a need to communicate and present the environmental benefits and handprint potential of limestone-based products to customers in order to gain a competitive advantage.

1.1. Objectives and research questions of the study

The objective of this study is to research what kind of positive environmental impacts limestone-based products possibly have in end use and secondly to assess what kind of handprints they can possibly generate in the use of Nordkalk’s customers. This study is also aimed to be helpful for further use of Nordkalk in their sustainability reporting and identifying the opportunities related to handprint methodology. Therefore, investigating the current situation and studying the possibilities of handprint thinking and handprint assessment is in the core of this study. A handprint assessment aims to solve the issue how the offered products of a company help to maximise environmental handprint and where limestone-based products may have the biggest potential to cause positive environmental impacts contributing to a bigger environmental handprint to customers. Research questions in this study are the following ones.

1. What kind of environmental handprints Nordkalk's products possibly have?
2. How to increase the handprint potential of a product with the help of product development by demonstrating the handprint potential with one specific product?
3. Where is the biggest potential of product development to result in positive environmental impacts and a competitive advantage in limestone-based business?
4. What are the factors or mechanisms of limestone-based products contributing bigger environmental handprints to Nordkalk customers compared to the use of other alternative products in the same application?

1.2. Background context

Findings from previous studies revealed that environmental handprint in limestone context is not studied very comprehensively. However, Nordkalk company has identified the environmental handprint as a part of sustainable solutions in their Sustainability Programme. There is not a suitable indicator or a measuring instrument indicating the handprint effect defined yet for Nordkalk limestone-based products and therefore this study is aiming to assist in this matter. However, the objective of the company is to grow the positive environmental impact of their solutions and increase the share of sustainable solutions. Also, fossil-free production and operations, and 100 % material efficiency are included in core targets. According to Nordkalk's Sustainability Report (2022b), their Sustainability Programme is monitored, and key performance indicators' (KPI) progress are followed at least on a yearly basis. Nordkalk's sustainability work is guided based on the company strategy and stakeholder expectations. The sustainability programme of Nordkalk includes focus areas and KPI targets from environmental, social and governance sustainability perspectives. The goal of Nordkalk concerning environmental handprint is to get enabled a “model for more detailed assessment of environmental handprint of Nordkalk products and services” and in the long term “increase the share of sustainable solutions”. (Nordkalk, 2022b.) Nordkalk also wants to communicate about the opportunities of limestone-based product use transparently and reliably to the stakeholders and customers avoiding green washing and empty promises.

1.3. Methodology and structure of the thesis

The structure of this study consists of a theory and an empiric part. Firstly, the theory part presents the basics related to limestone quarrying, lime manufacture and limestone-based products in the chapter 2. Besides, the applications utilizing limestone-based products are shortly described. Based on the findings from previous research, many environmental impacts related to limestone-based products in different applications are covered also in the chapter 2. Secondly, the environmental handprint concept is presented in the chapter 3 including a view of the recently published handprint frameworks from a couple of authors. Chapter 4 starts the empiric part and introduces the hypothesis for potential handprints created in limestone-based applications based on the theory part. A case example of handprint evaluation is included in the chapter 5 and the results and analysis of the handprint assessment case is processed in the chapter 6. Finally, the chapter 7 concludes this study and make suggestions for the future research.

Case examples focus on Nordkalk’s Enrich product group, because it is an innovative product series consisting of three versatile high-end products suitable for many applications. There is also an available data of the environmental impacts of Enrich products because the Environmental Product Declaration (EPD) made in Nordkalk. Besides, a lot of research has been made concerning Enrich product series and it may have many innovative opportunities in novel solutions.

2. Environmental impacts and applications of limestone

This chapter focuses on the diversity of limestone-based products and how these products are produced after limestone quarrying. Firstly, this study deals with the main features of quarrying operations and then deepens the understanding of lime manufacturing and different limestone-based products on the market. It is also important to clarify the definitions of lime-related terms and names. From a chemical point of view lime is not found straight from nature but produced from limestone which is quarried widely around the globe. In industrial applications limestone-based products have different definitions depending on the chemical composition, purpose of usage, and hydraulic or non-hydraulic character. (Bustillo Revuelta, 2021.) Boynton (1980) clarifies well that "limestone is general term embracing carbonate rocks composed primarily of calcium carbonate or combinations of calcium and magnesium carbonate with varying amount of impurities" and states also that lime is always manufactured from limestone by calcination or burning.

2.1. Limestone quarrying

According to the National Lime Association (2022a) a naturally occurring limestone is an abundant sedimentary rock, which consist of high levels of carbonate minerals. Limestone is categorized as a sedimentary rock due to the limestone deposits have formed through biochemical sedimentation of calcium-magnesium carbonates on the sea floor over the ages. Sedimentation of rock means the process of deposition and consolidation of loose materials, gradually accumulating by layer on layer under aquatic conditions. Sedimentary rocks of limestone are usually of organic origin, consisting of shells and skeletons of plants and animals. (Boynton, 1980; Haldar, 2018.) Another way for formation of sedimentary limestone is with inorganic mechanism through carbonate precipitation from sea and inland water (Ganapathi & Phukan, 2020).

High demand for limestone-based products exists thanks to a growing number of industries using these products. Widespread limestone exploration and excavations exist around the world in very large quantities and usually limestone is quarried from open quarries on the earth's surface. However, limestone can be also mined from underground mines in some places of the world. (Ganapathi & Phukan, 2020.) As stated earlier, limestone deposits can be formed from variety of carbonate minerals like calcite ($CaCO_3$), magnesite ($MgCO_3$) and dolomite ($CaMg(CO_3)_2$). The following Table 1 summarizes the list of common carbonate ore forming minerals and content of them.

Table 1. List of limestone minerals (adapted from Haldar, 2018).

Principal ore mineral	**Mineral formula**	**% Content**
Calcite	$CaCO_3$	56 CaO 44 CO_2
Magnesite	$MgCO_3$	47.6 MgO 52.4 CO_2
Dolomite	$CaMg(CO_3)_2$	21.7 Ca 13.2 Mg
Limestone	$CaCO_3$	+50 $CaCO_3$ / $CaMg(CO_3)_2$
Marble	$CaCO_3$	<56 CaO
Wollastonite	$CaSiO_3$	48.3 CaO 51.7 SiO_2

Table 1 illustrates differences between the most common minerals of which limestones consist of and the different designation for them. Wollastonite is listed here also, because it is one rare mineral which Nordkalk is quarrying in Finland. As Table 1 presents, limestones are constituted basically by calcium carbonate (calcite), magnesite is another type of limestone and when increasing the magnesite content, the mineral is called dolomite. (Haldar, 2018.)

2.1.1. Exploration and extraction of limestone

Raw material exploration is the first phase of starting a mine regardless of the metal or mineral intended to be extracted. Prospecting a deposit is important because the concentration of minerals in deposits varies widely and the location of the deposit affects the accessibility and feasibility of the mine. Mining technique is also dependent on the location of orebody and the deposits existing close to the surface are much cheaper to utilize than underground deposits. Haldar (2018) says that “A mineral deposit becomes economic when it has a profitable commercial value attached to it”, which is why decisions related to mine exploration and starting extraction requires systematic evaluation and identification of key aspects. (Haldar, 2018.)

Exploration and evaluation phases are followed by extraction phase in a mine cycle. Limestone can be extracted from underground and surface quarries, or combination of these methods, depending on the location of the deposit. Mining methods can be divided roughly into surface and underground methods as stated earlier, but about 85 % of all the tonnages mined globally are produced in mines open to the surface. Therefore, this section discusses surface methods. Surface mining operation aims to extract minerals lying near the Earth’s surface. “In surface mining, soil and rocks overlying the mineral deposit are removed prior to extract the mineralization” says Bustillo Revuelta (2018) and this process is called stripping which means overburden removal from the intended surface quarry at the first point. After stripping, an objective is to break the mineral rock. Drilling and blasting phases cause a great impact and the rock can be fractured and extracted from the ground. Drilling is a preparation operation for blasting. According to Bustillo Revuelta (2018) “blasting is usually a part of the mining cycle” aiming to fragmentation of rock masses. Blasting is conducted with explosives which are loaded into the drill holes, after drilling process. After limestone extraction, materials need to be loaded to haul trucks and stored or further processed. Summarized, the surface quarry production as well as underground mining commonly consists of previously discussed operations; drilling, blasting, loading, and hauling. (Bustillo Revuelta, 2018.)

2.1.2. Limestone processing

Mineral processing or in this context limestone processing continues after the quarrying unless the rock is sold as a quarry stone after extraction. However, most of the quarried limestone is processed somehow in order to make a commercial product. According to Bustillo Revuelta (2021) limestone processing into different products is tightly controlled to ensure the quality. Limestone processing can happen at a quarry, next to quarry or in some other location. The first phase of processing limestone is a size reduction including crushing and grinding with the purpose of liberating valuable limestone from side stones and to facilitate the processing of limestone between unit operations. (Bustillo Revuelta, 2021.) The blasted, loaded, and transported limestone rocks are fed to primary crusher in order to obtain smaller pieces of rock. Crushed limestone is then transported by conveyors to screening and classification unit where vibrating screens separate bigger pieces of stones and small enough stones are passing to next phase of processing. The main purpose of screening and classification processes is a size separation to size fractions, which can be implemented several times as well as crushing and grinding process depending on the desired size range of limestone. Limestone can be also washed if needed to decrease the level of impurities. (Bustillo Revuelta, 2018.)

The following Figure 1 illustrates the limestone processing phases starting from the limestone extraction and quarry operations which are already discussed in this text. The previous section Limestone processing is also summarized in the Figure 1 as an example and the principles of the following section Lime manufacturing can be seen from the Figure 1 on the next page.

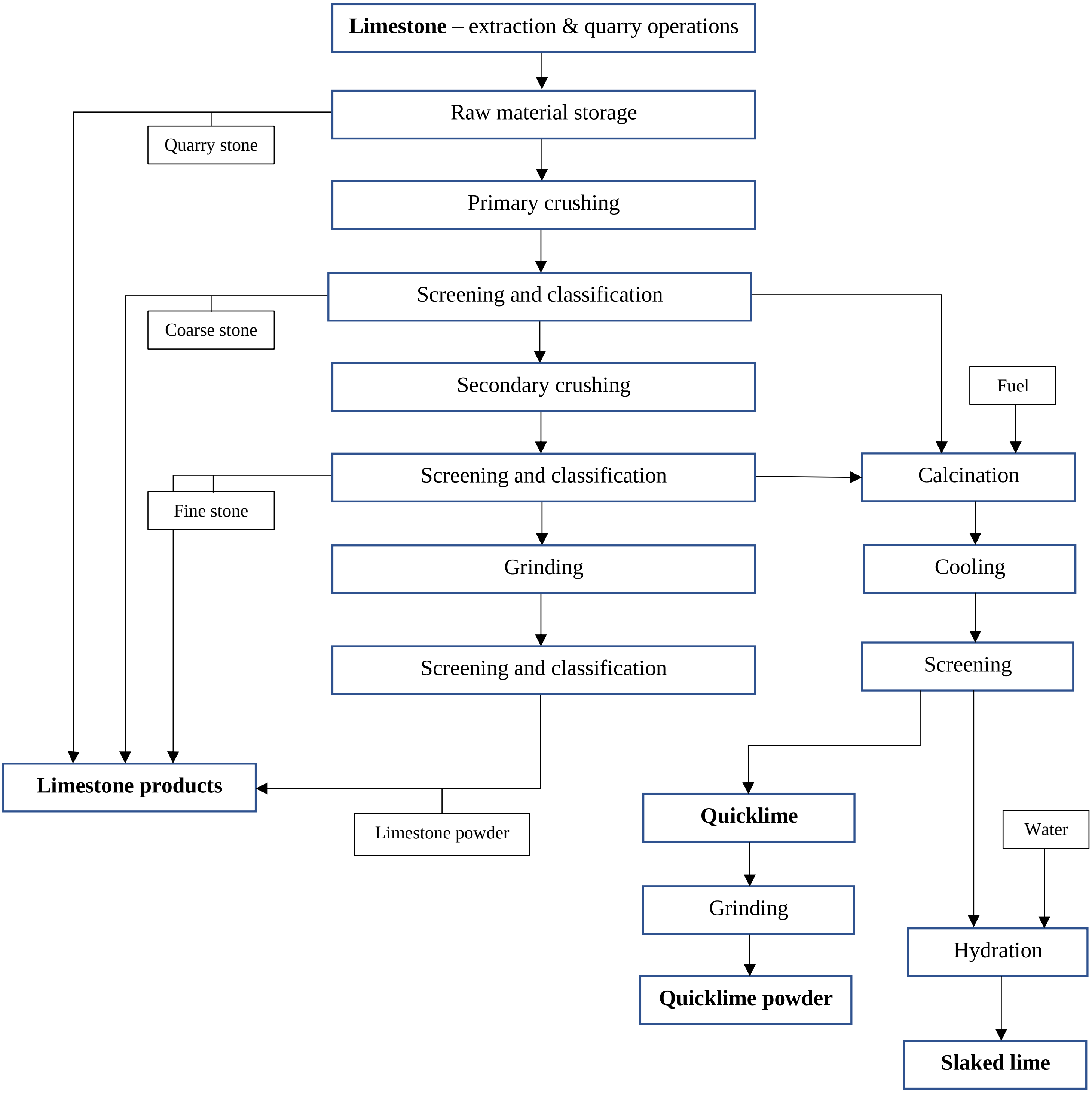


Figure 1. Basic steps of limestone processing and lime manufacturing (adapted from Environmental Protection Agency, 1998).

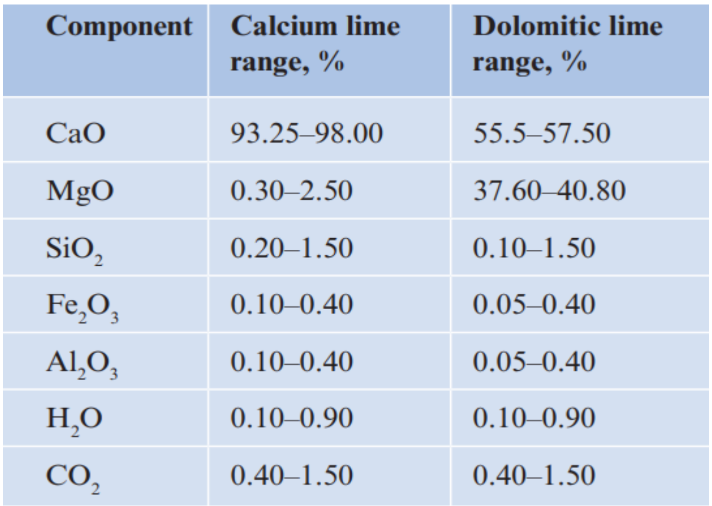
An example of a process flow chart in Figure 1 shows the most typical unit processes in limestone processing and lime manufacturing and presents how limestone can be processed more or less depending on the desired end product. Crushed or grinded stone can be sold as a limestone product or that stone can be processed further into special limestone-based products. These limestone-based products, of which quicklime and slaked lime are the main, are discussed later in this study. However, according to Nordkalk (2022) the biggest sales volume on a mass basis come from limestone products, such as limestone powders and fractioned stones.

2.2. Manufacturing of limestone-based products

Benvenuto (2015) says that limestone-based products and materials have been used for centuries and the long history of limestone is stated also by Bustillo Revuelta (2021) who mentions that the earliest evidence for limestone-based product utilization can be found from 10 000 years ago. Nowadays limestone is still one of the most commonly used alkali in the world and it has been important to our societies' growth. Even the Egyptians used limestone to build pyramids and the technology of lime burning in kilns are known from the time of the Roman Empire. (Bustillo Revuelta, 2021.) Production of lime from limestone is one of the largest chemical processes performed annually worldwide, it is quite simple process and reaction but on the other hand it is highly energy intensive, because the need of high temperature production environments (Benvenuto, 2015).

Lime can be produced also from dolostone (dolomitic limestone) in addition to limestones. Dolostone is a high magnesium limestone consisting of more than 50 % dolomite mineral besides calcite mineral, whereas limestone have high calcium content consisting mostly of calcite mineral. Dolomite is calcium magnesium carbonate - $CaMg(CO_3)_2$ as its chemical composition and calcite is calcium carbonate - $CaCO_3$. Total carbonate composition defines the suitability of raw material stones for lime production, minimum of 95 % carbonate composition is required. That's why the quality of limestone or dolomitic limestone is important and defines the end use possibilities. On the other hand, hydraulic lime for building purposes can be made of limestones containing only 65-85 % calcium and/or magnesium carbonates with more impurities such as clay. The following Table 2 presents the differences between chemical components of calcium lime from limestone and dolomitic lime from dolostone. (Bustillo Revuelta, 2021.)

Table 2. Chemical composition range of calcium and dolomitic limes (Bustillo Revuelta, 2021).



Component	**Calcium lime range, %**	**Dolomitic lime range, %**
CaO	93.25–98.00	55.5–57.50
MgO	0.30–2.50	37.60–40.80
SiO_2	0.20–1.50	0.10–1.50
Fe_2O_3	0.10–0.40	0.05–0.40
Al_2O_3	0.10–0.40	0.05–0.40
H_2O	0.10–0.90	0.10–0.90
CO_2	0.40–1.50	0.40–1.50

It can be seen from the Table 2 how the CaO content in dolomitic lime is less than in calcium lime, but magnesium oxide content is higher. Dolomitic limestones exist in many forms and are as widespread in time and space as limestones, however, dolostone is used to a lesser extent for lime production (Bustillo Revuelta, 2021).

2.2.1. Crushed limestone and limestone powder

Limestone as a raw material requires crushing and grinding to break the rock for further processing. After quarrying, limestone rocks with size of around 1 m in diameter are typically crushed to smaller pieces in primary crushers. On the other hand, crushing is also important process to extract side stones from limestone rocks. Crushed side stone is natural aggregate, extracted from quarries. Separated side stones can be utilized for aggregates to concrete production or ballasts to road construction for example. Crushed limestone is screened to separate bigger pieces of rock to secondary crushers and pieces small enough are passing through the screens to enter in kiln feed. Crushed limestone is a raw material for limestone products such as fillers and binders. Limestone can be crushed and screened in many phases to reduce its size depending on the object of use. Limestone can be also grinded to powder without other processing. Limestone powder is used in many applications such as agriculture, construction, and environmental applications. (Bustillo Revuelta, 2021; Etelä-Suomen Aluehallintovirasto, 2022.)

2.2.2. Quicklime

Quicklime is produced in kilns from crushed limestone. Quicklime is a typical type of a limestone-based product which is produced by the direct heating of limestone. High temperature causes a chemical reaction liberating the carbon dioxide (CO_2) gas from calcium and/or magnesium carbonates and consequently solid quicklime or dolomitic lime is obtained. Quicklime, sometimes also called burned lime or unslaked lime, is calcium oxide (CaO) as its chemical name. (Benvenuto, 2015.) Another feasible product, dolomitic lime is calcium and magnesium oxide ($CaMgO_2$). Bustillo Revuelta (2021) says that “The process of limestone thermal decomposition into quicklime and carbon dioxide is termed *calcination of limestone* or simply *calcination*”. This calcination reaction requires approximately 900-1200 Celsius degrees (°C) to run and a sufficient long period of time to complete the reaction. Quicklime is formed through calcination of limestone or dolostone with reactions which are presented in the following reaction formulas 1 and 2. (Bustillo Revuelta, 2021.)

$$CaCO_3\ (\text{solid}) + \text{heat} \rightarrow CaO\ (\text{solid}) + CO_2\ (\text{gas}) \qquad (1)$$

$$CaMg(CO_3)_2\ (\text{solid}) + \text{heat} \rightarrow CaMgO_2\ (\text{solid}) + CO_2\ (\text{gas}) \qquad (2)$$

To conclude, calcination reaction requires enough heat and time to finish and to avoid under-burned lime (Bustillo Revuelta, 2021). The calcination reaction can be categorized as endothermic reaction favored by higher temperatures (Stanmore & Gilot, 2005). Commonly used kiln types for lime production are rotary kilns and vertical shaft kilns both of which Nordkalk also utilizes. A shaft kiln is vertical in design and a rotary kiln is an inclined tube which is usually fired with fossil fuels as well as a shaft kiln. A major advantage of shaft kilns is lower fuel consumption, whereas a greater reactivity can be achieved in a rotary kiln. Nordkalk mostly uses coal and oil as fuels in kilns. However, utilization of waste fuels and biomass in lime kilns has gradually increased according to Bustillo Revuelta (2021) but is depended on the expected lime quality. (Bustillo Revuelta, 2021; Etelä-Suomen Aluehallintovirasto, 2022.)

2.2.3. Slaked lime

Slaked lime is the second type of a typical lime product. In order to produce slaked lime, limestone must be calcinated first in kilns as well as in quicklime production. Then slaked lime is obtained through quicklime hydration process where quicklime is mixed (or slaked) with water. Hence hydration reaction requires the addition of water to calcium oxide. The chemical reaction of hydration in slaked lime production is following formula 3.

$$CaO + H_2O \rightarrow Ca(OH)_2 + heat \qquad (3)$$

Slaked lime can be called also *hydrated lime* by the name of the production process, or *milk of lime* or *lime putty* when the water is added extensively. Slaked lime is calcium hydroxide ($Ca(OH)_2$) as its chemical name. The rate of added water to lime defines the outcome of slaked lime. Slaked lime is a dry powder when the affinity of quicklime for moisture is satisfied with a sufficient amount of added water. Excess water is then converted to steam because the hydration reaction is an exothermic reaction. If water is added more, slaked lime takes the form of a slurry and then milk of lime or lime putty terms are better descriptive names for suspension of calcium hydroxide. (Bustillo Revuelta, 2021.) Following Figure 2 illustrates the basic lime-related processes concisely and describes the limestone cycle in different lime products production.

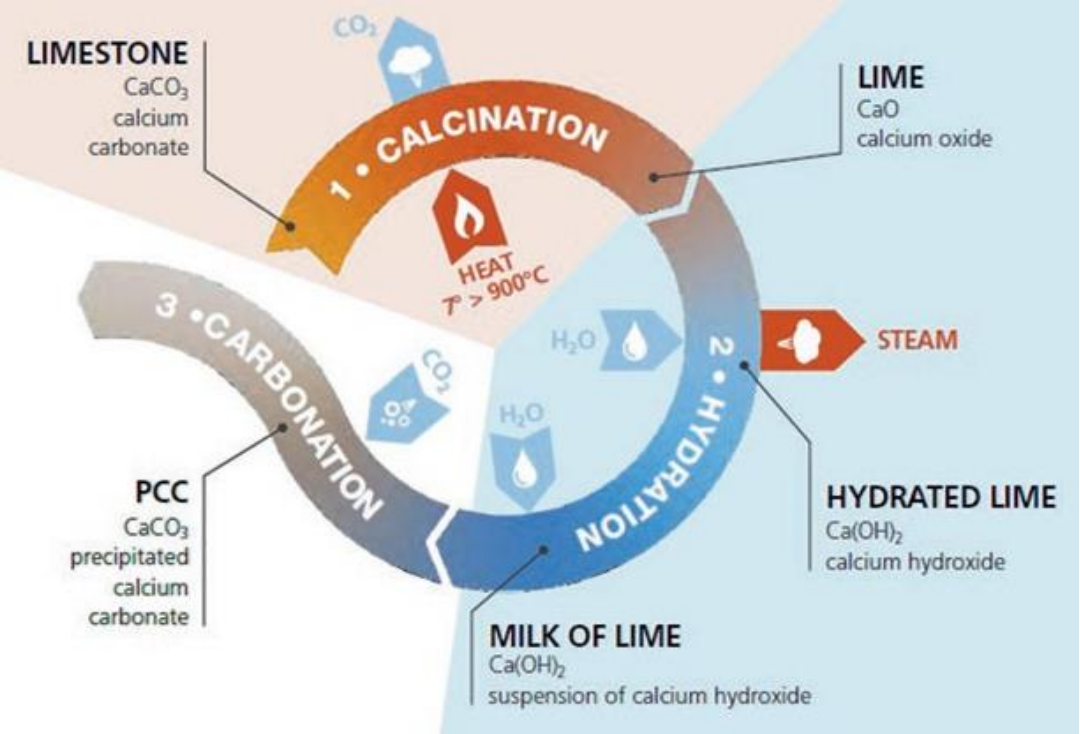


Figure 2. Limestone cycle in lime processes (Bustillo Revuelta, 2021).

Figure 2 presents how limestone can be processed in three steps, two of which have been discussed previously. Step 1 “calcination” creates quicklime from limestone with heat, then further processing with water addition in step 2 “hydration” forms hydrated lime or other words slaked lime. In addition to these two processes, Figure 2 includes the third step called “carbonation” which is described in the next section.

2.2.4. Precipitated calcium carbonate

Precipitated calcium carbonate (PCC) can be obtained through step 3 in limestone cycle, carbonation process. According to Nordkalk (2022c) “PCC is made by slaking quicklime to create hydrated lime slurry, which is then carbonated into final product”. Carbonation of calcium hydroxide (slaked lime) back to calcium carbonate can happen with the atmospheric carbon dioxide. Combining the captured carbon dioxide with the slaked lime reforms calcium carbonate and precipitates out because since it is insoluble in water. Thus, carbonation reaction returns slaked lime back to the same chemical composition as limestone rock (calcite) thanks to its ability to react with carbon dioxide. This reaction can be seen from the following formula 4.

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \qquad (4)$$

Carbonation process has a purifying effect, so PCC products can be used for paints, adhesives, plastics, and coatings even in products that encounters food for example. High quality PCC is used in both paper and cardboard coatings for example. The particle size of PCC products can be obtained much finer than just grinding the limestone rock without lime processing and carbonation. Therefore, PCC products are called an ultrafine PCC in Nordkalk, and they can be utilized in demanding applications. (Nordkalk, 2022c.)

2.3. Uses of limestone-based products in applications

Limestone-based products are important in various applications such as environmental, metallurgical, construction, chemical, and industrial uses is stated by National Lime Association (2022b). In this section, the focus is on finding and presenting applications and studies where a limestone-based product has an impact on a process or production of goods. Some alternative chemicals/minerals or processes are intended to be found for further comparison in the empiric part. The most important, positive environmental impacts from limestone utilizing applications are in the core of research. An assessment of limestone-based products as a binder, neutralizer, sorbent and fluxing agent for example are investigated. Nordkalk’s sales volumes per product segment from year 2021 are presented in the Figure 3 on the next page as percent per sales volumes based on mass fractions. The Figure 3 illustrates what types of limestone-based products have the biggest share of sales.

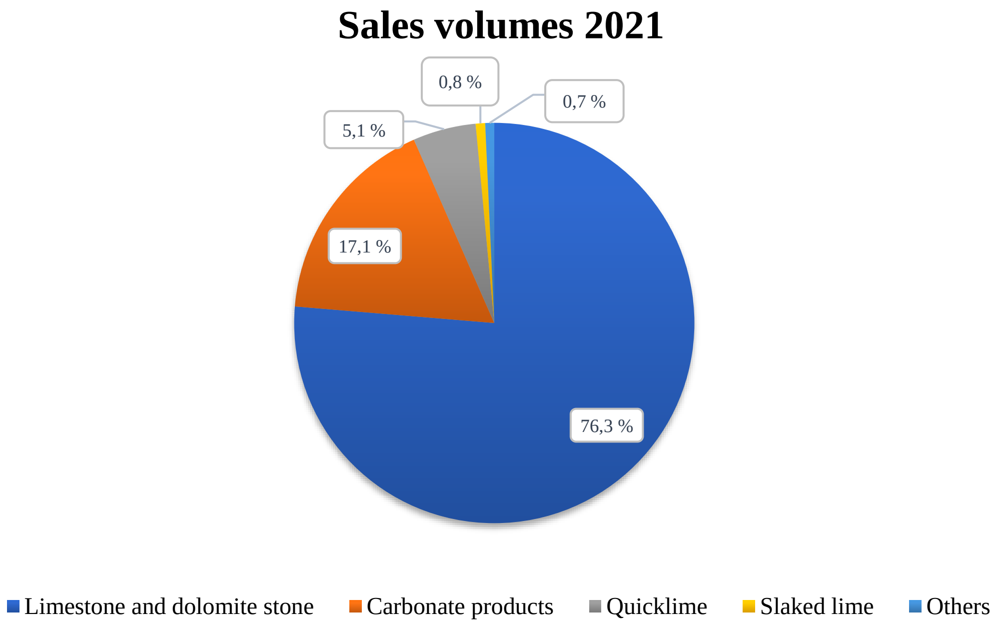


Figure 3. Nordkalk sales volumes 2021 per product segment, based on t/a as percentages.

Figure 3 clearly presents that the biggest volume of Nordkalk's sales are limestone products such as crushed stones, granulates, and limestone powders. Then again, more quicklime products are sold than slaked lime. The biggest limestone consuming industry is a building and construction. Next different limestone-based applications are studied more widely and the handprint potential in them is evaluated.

2.3.1. Agriculture & forestry

Soil acidification is a challenge affecting negatively to food production and soil degradation worldwide and therefore it is important to optimize soil fertility and manage soil acidity (Müller, Dechow and Flessa 2022). According to Müller et al. (2022) "Soil pH is one of the key factors affecting soil fertility" and their study revealed that "the carbonate content was the major factor explaining soil pH variability". That's why adding a limestone-based product or in other words liming of cultivated land is noticed to be the most common method for pH management and neutralizing soil acidity. Depending on the pH level, liming requirement varies but the lower the pH level the higher lime requirement is. Limestone-based products have a considerable potential to improve productivity of crop yields by more regular soil pH management with the help of liming. (Müller et al., 2022.) In addition to neutralization of acids, liming has also various other far-reaching impacts on soil structure and nutrient availability in agricultural applications (Leenen, et al., 2019). According to study conducted by Leenen et al. (2019) liming would have no negative consequences on growing of plants but successful level of lime requirement for agronomic needs is depended on climatic conditions and regional soil properties.

In addition to liming of cultivated lands, limestone-based products also have benefits in forest liming. According to the study conducted by Melvin et al. (2013) forest liming with calcium carbonate can increase soil pH and calcium (Ca) concentration diminishing effects of acidification. It was also noted that the lime addition occurred a quite rapid improvement in soil besides the increase of neutralizing Ca concentration remained elevated in the forest soil a long period of time. Melvin et al. (2013) researched also how Ca availability influences C and N uptake and retention in forests and noticed that C and N stock was greater in limed soils. The research suggested that "liming can have large effects on ecosystem C and N balance" and observations of increased decomposition with liming was made which "showed a trend toward lower CO_2 efflux in limed soils". (Melvin et al., 2013.) Another study of liming conducted by Long et al. (2015) revealed that Ca, Mg and pH was significantly increased in soil thanks to liming and the application of lime maintained its effect through 21 years of study period. Some reductions of potentially toxic Al and Mn concentrations were also observed due to lime treatment, occurring changes in upper soil layers and more slowly in the deeper layers of studied soils. (Long et al., 2015.)

Another study related to effects of lime treatment on metal sequestration in lakes conducted by Wällstedt et al. (2008) also found that "liming causes increased sequestration of Al, As, Cd, Co, Fe, Mn, Ni and Zn" in lake sediments, which are acidifying compounds. Acidification of lakes and ponds is influenced by pH changes and decreasing pH level affects the increase in solubility and mobility of acidifying compounds. Neutralizing effect of limestone-based products has been helpful to counteract the negative acidification of lakes. The study suggested that lake's surface water liming has a moderate long-term effect on a higher element sequestration in many metal concentrations, but no significant influence of lime treatment could be demonstrated for all elements that are less influenced by pH fluctuations. (Wällstedt et al., 2008.) According to a study conducted by Prepas et al. (2001) lime treatment can improve also eutrophic hardwater lakes by reducing P (phosphorus) concentration, phytoplankton and other biomass. Lime applications were researched both in anthropogenically and naturally eutrophic lakes and lime treatment was feasible without negative affect on pH level. Long-term control of P concentration in lakes required multiple treatments, but the use of lime can be preferable over other treatments, because it is economical and non-toxic alternative. (Prepas et al., 2001.)

2.3.2. Construction

Construction industry is under pressure of reducing carbon dioxide emissions and one example of a tangible action is substituting the use of ordinary Portland cement (OPC) as a binder material in concrete manufacturing. Cement manufacturing is amongst the largest CO_2 emitters within the mineral processing industry, but lots of research has been concentrating on potential supplementary cementitious materials (SCM) lately. (Kumar et al., 2013.) According to Kumar et al. (2013) there is interest in using limestone to reduce the clinker factors of OPC and thus OPC use in concrete. Lime-based binders are studied to have lower porosity and higher strength in SCM, and the strength may have been improved even further when having a higher ratio of calcium hydroxide. According to the article conducted by Mishra and Yu (2022) so called green cement is recently emerging as a promising alternative to OPC and it performs as well as OPC. Green cement is composition of clinker, gypsum, calcined clay and limestone powder and it is stated that it can become high-volume replacement of binder in concrete and be a circular economy-based material in construction sector and also have a great potential to decrease the carbon dioxide emissions on the field.

Lime can be used as a binder material or a filler also in manufacturing of other building materials like mortars, plasters, and bricks. Raeis Samiei et al. (2015) noted that different outcomes emerge from different studies depending on the specific composition of building materials and how the binder interacts with aggregates. For example, properties of lime mortars differ a lot depending on the composition of the mortars. The properties of lime mortars are also affected by curing conditions like relative humidity. (Pavlik & Uzakova, 2016.) According to study conducted by Raeis Samiei et al. (2015) increased amount of recycled aggregates, like concrete wastes, in lime containing mortars show an improvement in mechanical properties of lime mortars. On the contrary, recycled aggregates worsen the properties of basic cement mortars. That’s why a portion of lime in mortars benefits the sustainability of that material. Recycling of construction and demolition waste materials helps to save natural resources and crushing them into aggregates is one of the most effective ways. It was suggested that improvement in lime mortars with the recycled aggregates mix arise from a synergic effect of lime hydraulicity and the filler effect. (Raeis Samiei et al., 2015.) A study conducted by Yeo et al. (2021) researched the potential of various types of waste materials as fine aggregate replacement in concrete paving block of which one was non-biodegradable soda-lime glass.

Soda-lime glass was noted to be the most used glass in the manufacturing industry, and it contributes to the biggest portion of waste glass with low recycling rate. Incorporation of recycled soda-lime glass to aggregate performed well, and suggested replacement level of aggregate was 30-100 % to fulfil the minimum requirements of paving blocks. Despite of reduced density of the concrete paving block, a good potential for producing an eco-friendly paving block was observed with careful consideration and optimal incorporation of the waste materials. (Yeo et al., 2021.)

Performance of any pavement or highway is largely attributed to the quality of the base and subgrade layers. Limestone-based products are widely used for soil stabilization in road construction and “soil stabilization is the one of the popular techniques for the improvement of poor-quality soil for road and highway construction” as stated by Majumder & Venkatraman (2022). In the study, quicklime was used to investigate the influence on soil improvement and results show that the plasticity, the initial compressive strength, the stability and the workability increased with lime addition. According to Majumder & Venkatraman (2022) “lime suffices the required criteria of subgrade” and lime can replace also widely used cement as a stabilizer and even be a better solution to the environment due to the high toxicity and high CO_2 emissions of cement. (Majumder & Venkatraman, 2022.) A study conducted by Li H. et al. (2022) noted a huge demand for road construction materials but stated that “inorganic binder base stabilizing materials such as lime and cement have been widely used” thanks to their good characteristics, but base structures consume a lot of industrial materials. Therefore, the study researched a possibility to use solid waste soda residue as a part of lime stabilization in pavement base. Soda residue lime soil base material showed remarkable economic and technical benefits and furthered recycling of soda residue. (Li, H. et al., 2022.)

Another study conducted by Kumaran et al. (2018) investigated the strength characteristics for soil stabilization with the fines from the concrete demolished waste mixed with hydrated lime. They referred also to other studies on the field and stated that “The results confirmed that the fines from concrete wastes provide the same improvements as that from lime or cement.” However, the final analysis revealed that fines from concrete performed better than other two considered soil stabilizers, cement and lime, in the studied silty sand soil as subgrade for the pavement. (Kumaran et al., 2018.)

2.3.3. Pulp & paper

Limestone-based products play an important role in chemical recovery cycle at pulp mills. A causticizing process recover green liquor from the soda boiler with the help of quicklime back into white liquor in a slaker unit process. White liquor is an important chemical used in pulping, which is reused in the cooking process after recovery in a causticizing plant. The causticizing process produces also lime mud as a by-product, which is mostly precipitated calcium carbonate as its formula, and it is reburned in a pulp mill’s lime kiln to convert the lime mud back into quicklime for reuse in the causticizing process. That’s why the lime cycle or calcium cycle and the chemical recovery cycle of pulp mills are connected. (Hart et al., 2021; Nurmesniemi et al., 2005.) According to Hart et al. (2021) the calcium cycle is an essential part of the pulp mills, and it enables the causticizing process in addition to increase the overall resource and recycling efficiency of the mill.

A study conducted by Doelle & Bajrami (2018) investigated the possibility of using hybrid system consisting of sodium hydroxide and calcium hydroxide in the oxygen bleaching at pulp mills to make the process more environmentally friendlier. Calcium hydroxide is said to be less expensive to use than sodium hydroxide and overall oxygen bleaching reduces the environmental impact of wastewater because of a lower chemical oxygen demand compared to chlorine bleaching. A hybrid bleaching system was suggested with 4 % sodium hydroxide and 2 % calcium hydroxide content, but also other aspects influence bleaching efficiency, besides more than 2 % calcium hydroxide dosage had a negative impact on bleaching in this study. (Doelle & Bajrami, 2018.)

According to the study conducted by Santos et al. (2021) a carbon-negative system based on calcium looping for CO_2 capture can be integrated in the lime cycle. The major contributing industries to the global CO_2 emissions, so called energy-intensive industries, are pulp & paper, cement, petroleum refining and iron & steel. A decarbonisation of these industries will play a crucial role to comply with the Paris Agreement. Carbon capture and storage (CCS) technologies are thought to be one route for an industrial decarbonisation. The study conducted by Santos & Hanak (2022) reviewed the current situation of CCS technologies and emphasized the recent developments in calcium looping. They noted the importance of limestone and stated that it is the most commonly considered sorbent for calcium looping, besides it is already used in the energy-intensive industries. According to Santos & Hanak (2022) these industries can benefit their inherent decarbonatization potential by implementing calcium looping. The retrofit of calcium looping is studied to lower the cost of avoided CO_2 compared to more mature CCS technology amine scrubbing for example. (Santos & Hanak, 2022.) Lime mud from the existing lime cycle of pulp and paper mills can be successfully used as CO_2 absorbent in calcium looping and other limestone-based products have low cost and high availability in other energy-intensive industries. In addition, calcium looping with limestone has other benefits as well as a drawback of the reactivity decay of the sorbent. Therefore, a fresh sorbent is continuously fed in. Techno-economic performance and the feasibility of calcium looping is recognized according to these studies, and it is shown as promising CCS technology. (Santos et al., 2021; Santos & Hanak, 2022.)

2.3.4. Steel & iron

Previously discussed calcium looping can be applied also into steel & iron industry as stated before. The purified CaO from calciner reactor can be reused for steel & iron industry. (Santos & Hanak, 2022.) In addition to this, limestone-based products have a role in both steel and iron production. Iron ore is the fundamental raw material in these industries and blast furnaces produce iron from iron ore. After blast furnace, production of steel continues, and steel is an alloy of iron and carbon with small amounts of other components. A modern blast furnace is a most used furnace for steel & iron production nowadays. Iron ore fines are prepared for blast furnace burdens as lump, sinter or pellets. (Lu, 2015.)

According to Fedina et al. (2021) quicklime is used in blast furnace sinter production, which is important mixture of solid mass for raw material of steel & iron industry. Sinter traditionally consist of iron ore concentrate, limestone or dolomite, sinter fines, coke, water, and various other additives. Quicklime has a role of water absorbent in sinter, because of calcium oxides reduce the moisture content of the iron ore concentrate and prevents it from freezing and hardens the mixture. Quicklime addition to the wet concentrate achieves hydration reaction where the mass fraction of water is converted from free to bound form, or in other words, to slaked lime. Exothermic nature of that reaction also causes water to partly evaporate. (Fedina et al., 2021.) According to Fedina et al. (2021) “lime is commonly added to the sinter charge to keep the concentrate basicity above 1.0.” A study conducted by Kurkin et al. (2007) suggested the use of milk of lime in sintering instead of quicklime, because the greater amount of water present the faster binder effect between the components occurs. Milk of lime in sinter charge solidifies faster during mixing of components, fills up the capillary channels between the colloidal particles and forms a homogeneous sinter. (Kurkin et al., 2007.)

In addition, lime can be used “as additive as well as fluxing agent for making iron ore pellets” stated by Mandal et al. (2016). Mined ore for iron and steel making is used directly as lump or converted into sinter or pellets, both of which can contain lime additives. Use of pellets results in improvement of energy and flux efficiencies in the blast furnace for production of iron and steel. Besides, lime as an additive in pellets have a little advantage over the conventionally used additive called bentonite due to the increased basicity. Lime-fluxed iron ore pellets showed better mechanical properties such as higher crushing strength and tumbler resistance, but on the contrary, physical properties like density and porosity were slightly worse than in conventional pellets. (Mandal et al., 2016.) According to a study conducted by Cheng et al. (2019) quicklime (CaO) has a great desulfurization capability, and it is used as fluxing agent in process metallurgy. Desulfurization characteristic of quicklime is studied widely in steel processing because sulphur is a harmful impurity in the steelmaking and “the desulfurization capacity is gradually improved with CaO addition increasing” as stated by Cheng et al. (2019).

Production of steel utilizes limestone-based products as well and generally virgin steel is produced through a blast furnace-basic oxygen furnace (BF-BOF) route from iron ore. The second step basic oxygen furnace (BOF) turns iron, with some additives, into steel. A secondary steel production route called an electric arc furnace (EAF) steelmaking usually utilizes mostly recycled steel scrap. The basic oxygen furnace process is the most typical process for steel production with 60 % share of total steel produced in EU. Iron from blast furnace is converted to steel in BOF with oxygen, which burns unwanted impurities. (European Steel Association, 2020.) Dissolution of quicklime in the BOF slag neutralizes the acid slag containing metal elements (e.g., Si, Mn, Fe, P) which tend to oxidize rapidly. Quicklime addition improves the steel process productivity when a suitable slag can be formed quickly, therefore quicklime dissolution aids in slag formation by creating a lower-melting-temperature oxide mixture with metal oxides (Li, Z. et al., 2022).

2.3.5. Flue gas treatment

Limestone-based products are used as a sorbent in flue gas treatment to control SO_2 emissions in power plants. The most typical post combustion flue gas treatment is flue gas desulfurization system, which can be dry, semidry or wet scrubbing. However, the reactivity of the lime-based sorbent can be increased with addition of additives like inorganic salts, sodium hydroxide or silica for example. It is researched that significantly higher utilization of calcium can be obtained by mixing lime with additives. (Gong et al., 2008.) A study conducted by Gong et al. (2008) researched the feasibility of a sorbent prepared from hydrated lime and blast furnace slag, which is a waste generated in steel industry. They noticed that the SO_2 capture was higher with the prepared sorbent mixture than hydrated lime alone mostly due to the increased specific surface area. The sorbent mixture was seen potential and from the circular economy perspective the use of waste material was beneficial. (Gong et al., 2008.)

A study conducted by Salih et al. (2018) researched the utilization of lime sludge generated by water treatment utilities for flue gas desulfurization. Reusing of lime sludge in power plants replaced a virgin limestone-based product and promotes circular economy. The research came to a result after life cycle assessment that environmental sustainability of lime sludge reuse for flue gas treatment was better solution than a landfill disposal of lime sludge or a virgin limestone usage in flue gas treatment. (Salih et al., 2018.)

2.3.6. Water treatment

Limestone-based products are used in water treatment for pH correction in coagulation. Mostly slaked lime is used because lime is typically dosed as a slurry. Controlling and monitoring chemicals used in coagulation is critical to ensure optimal treated water quality and to minimise chemical costs and overdosage. For example, chlorine disinfection process is more effective at a neutral or acidic pH whereas an alkaline pH is better to avoid corrosion. Dosing lime to raise the pH can be used to regulate pH value. (Binnie et al., 2018.) Other alkalinity and pH adjustment chemicals can be sodium hydroxide (NaOH) or soda ash (Na_2CO_3) in addition to calcium hydroxide (Crittenden & Borchardt, 2012).

Another application for a limestone-based product in drinking water purification is to control water hardness. Water carbonate hardness results from dissolution of Ca^{2+} and Mg^{2+} cations in water. Lime softening can be used to remove hardness of water due to chemical precipitation. Lime softening by chemical precipitation relies on the insolubilities of calcium carbonate and magnesium hydroxide. The softening required can be accomplished by pH adjustment alone with lime addition, but also soda ash can be used as a precipitating chemical if needed, also together with lime. (Crittenden & Borchardt, 2012.) According to Crittenden & Borchardt (2012) “lime softening has many potential health benefits as well” because it can remove heavy metals, iron and manganese and some organic compounds effectively.

A study conducted by Kuster et al. (2022) researched the possibility to purify urban stormwater with spent lime drinking water treatment residual, which is a by-product of lime softening. Stormwater influents and effluents were collected and analysed over a 5-year study period. Stormwater treatment with lime drinking water treatment residual showed significant reductions in phosphorus (P) concentrations, heavy metals and total suspended solids in stormwater discharging. Consequently, a recycled limestone-based product has a value and an ability to decrease the external nutrient loading runoffs from urban areas to receiving water bodies and affecting eutrophication. There are also other P removal structures based on filtration and a sorbent such as steel slag, acid mine drainage residue, quicklime and limestone. However, spent lime drinking water treatment residual is rich in calcium and therefore a feasible choice as a filter material for a phosphorus removal structure as stated by Kuster et al. (2022). As a recycled by-product it is also cost-effective and promotes circularity, besides achieved phosphorus and other pollutants removal efficiency was high (Kuster et al., 2022).

2.3.7. Miscellaneous applications

In addition to many industrial applications of limestone, limestone-based products play a role on chemistry, fodder, and food and sugar refining. A limestone-based additive can be found from plastics, rubber, ceramics, paint or coating. Limestone-based products reduce costs of paints and coatings by replacing pigments or substituting binders or fillers without compromising properties or performance of the end-product. High purity limestone-based products can increase stability and brightness in these demanding applications. (Nordkalk, 2022d.)

In glass manufacture slaked lime provides great transparency to the glass, increase solution rates and reduce heat requirements compared to limestone. In plastics and rubber manufacturing processes quicklime is often used as a water absorbent due to its rapid hydration reaction with any free water. Water removal from plastics and rubbers is important to avoid any bubbles in the finished product. (British Lime Association, 2022.)

Limestone-based derivatives are a part of many inorganic salts which are additives in food and drink like calcium citrate. Besides, the production of sugar requires quicklime or slaked lime depended on the sugar containing plant. In sugar processing limestone-based product raises the pH of heated sugar solution and most importantly precipitates acids, suspended and colloidal matters which can be then removed easily by filtration. Lime addition works for sugar purification. In addition to human food, limestone-based products include in animal fodder also, for example in chicken feed supplements improving the strength of eggshells. (British Lime Association, 2022.)

3. Environmental handprint

There is an increasing interest in accounting of beneficial impacts in environmental management and sustainability strategies according to the research conducted by Guillaume et al. (2020). Also, the interest of assessing the positive environmental consequences of actions or offerings is noted by Lakanen et al. (2022) who also mentioned that the guidelines for evaluating positive environmental impacts have been lacking. Concept of environmental handprint was developed for this need and alongside to the footprint approach. Guillaume et al. (2020) noticed that environmental footprint is already well-known and widely applied, but the handprint approach has not consolidated its position equally yet. The handprint approach is thought to encourage actions with positive impacts to sustainability, add value to footprint reductions and address the actions that should be taken. The environmental handprint approach with measuring and accounting of beneficial impacts can work as an incentive to action, as value adding communication tool and as a constructive approach focused on opportunities rather than problems. (Guillaume et al., 2020.) According to Lakanen et al. (2022) approach to measure positive impacts of actions have recently been introduced by many researchers and therefore the definitions of handprint concept vary. “Based on the most up-to-date definition a handprint refers to the beneficial environmental impacts that organizations can achieve and communicate by offering products and services that reduce the footprint of others” (Lakanen et al., 2022). Pajula et al. (2021) also presents that the handprint approach is an additional key to solving present environmental challenges and systemic transition from producers to reducers of emission and resources is emerging.

3.1. Different environmental handprint approaches

The environmental handprint approach presented by Lakanen et al. (2022) follows the guidelines of Life Cycle Assessment (LCA) based on standards made by International Organization for Standardization (ISO). Another approach to measure positive environmental impacts is recently presented by Norris et al. (2021) in their project called The Sustainability and Health Initiative for NetPositive Enterprise (SHINE). The SHINE handprint framework is also LCA-based quantitative methodology according to Norris et al. (2021). In the SHINE handprint framework, the business-as-usual (BAU) is used to describe the current situation in a comparison. The BAU footprint is calculated and “then compared with actual footprint calculated with changes to assess the handprint”. Environmental, social, and economic positive changes are called handprints in the SHINE and organizations can create handprints through reductions in their own footprint or in the footprints of others. (Norris et al., 2021.) The environmental handprint framework presented by Lakanen et al. (2022) use the baseline footprint in comparison to the offered solution’s footprint. Lakanen et al. (2022) states that handprint “is a comparative indicator, which describes about the emissions or consumption that can be reduced or avoided using a certain product instead of a baseline product”. In this framework, handprints can be created by using the offered solution with lower environmental burden or using the offered solution which actualizes the environmental impact reductions in applications (Lakanen et al., 2022). According to Pajula et al. (2021) baseline is described to be “a product, a service or a product chain which delivers the same function(s) to the user as the offered solution and is used for the same purpose(s)”.

These environmental handprint approaches aim to cover multiple environmental impacts, not only a single impact category. On the contrary, the carbon handprint approach focusses on a single impact category, which is the climate change mitigation potential describing the greenhouse gas emission reduction. (Pajula et al., 2021.) Many mechanisms can generate a handprint and they are called as handprint contributors. A handprint can be contributed by less greenhouse gas (GHG) intensive material or energy use, reduced waste or increased carbon capture for example. In addition to the carbon handprint, also other positive changes referring handprints can be created like water and air quality handprint or resource use handprint. Therefore, the environmental handprint can be described as an umbrella concept which includes many handprints and considers various positive impacts as stated by Pajula et al. (2021). According to methodology presented by Pajula et al. (2021) handprints can be created if the environmental impacts or emissions taken into account are lower compared to baseline emissions or handprint can be also created if it will have a positive effect on customer’s use or process compared to customer’s baseline solution. That’s why the baseline definition plays a crucial role in handprint assessment and the baseline solution must be transparently presented so that the positive impact can be assessed against the baseline. Rules for baseline definition also exist, because the baseline must deliver the same function and be used for the same purpose than the offered solution. Besides, the baseline must be available on the market in the same time period in the same geographical region. Both the baseline and the offered solution must be also assessed with consistent manner regarding data quality, system boundaries and assumptions. There’s no limit for the amount of good we can do for the environment, that’s why handprint assessment focuses on maximizing the handprints with a new way of quantification the benefits.

The following steps define the handprint assessment process based on LCA and the environmental handprint framework presented by Lakanen et al. (2022). Steps number 1 to 5 are specific for handprint assessment and steps 6 to 13 share the same principles as in footprint assessment. The following Table 3 summarizes the handprint assessment phases.

Table 3. Handprint assessment framework presented by Lakanen et al. (2022).

Stage 1 – Handprint requirements	
Step 1. Scope of the offered solution	defining a product, an organization or a project potentially creating handprints
Step 2. Potential handprint contributors	description, how the offered solution may achieve footprint reductions hypothetical benefits the product/product portfolio may create and contribute to reducing customers’ footprint compared to baseline solution
Step 3. Environmental impacts and their indicators	possible impacts to climate change, eutrophication, land use, air quality, resource depletion, acidification, ozone depletion, ecotoxicity, water, human toxicity, nutrients and their impact category indicators

Step 4. The users and beneficiaries of the solution	potential or actual customers or other parties who can benefit from the offered solution
Step 5. Baseline definition	a baseline as a point of comparison for reduced environmental impacts a reference product which delivers the same functions in the same geographical area
Stage 2 – LCA requirements	
Step 6. Functional unit definition	the measure of the offered solution and a baseline
Step 7. System boundaries	similar life cycle stages of the offered and the baseline solution
Step 8. Data needs and sources	representative and accessible data with the similar geographical and time-related coverage
Stage 3 – Quantification	
Step 9. Calculate the footprints	the chosen footprint calculations based on relevant ISO-standards where applicable
Step 10. Calculate the handprints	difference of the footprints calculated
Stage 4 – Communication	
Step 11. Relevant indicators to be Communicated	confirmation of the accurate indicators presenting the results needs to be identified
Step 12. Critical review of the handprint	recommended in business to customer (B2C) communications and mandatory if the results are intended for comparative assertions to the public
Step 13. Communicate the results	respecting appropriateness, clarity, credibility and transparency

Table 3 delivers guidelines for handprint assessment based on a comparison of footprints between the offered solution and the baseline solution. The assessed handprint results work as indicators describing the improvement, change or development in environmental impact categories chosen to cover compared to previous product or solution.

3.2. Potential benefits of handprint thinking for business activities

Handprint thinking is referred to a common foundation for a diversity of different handprint assessment methods regarding to Guillaume et al. (2020). Overall, the term handprint means actions that have positive impacts, so environmental handprint encourages actions with positive environmental impacts. Handprint thinking and an implementation of potentially quantitative handprint assessment have an important role in moving towards sustainability. Business activities and companies can benefit from evaluating positive impacts of their actions in order to achieve sustainability, because of knowing them would help to improve the situation and encourage doing good. Handprint assessment or handprint thinking will add value for business activities and can be connected to analyses of footprint reductions possibly made. (Guillaume et al., 2020.) Also according to Husgafvel (2021) the handprint concept can be very useful for modern organizations and the handprint approach can promote innovation and collaboration considering global challenges. Besides, handprint assessments can help to promote a systemic thinking and circularity instead of a linear thinking perspective. Husgafvel (2021) also mentions that handprints can be social, environmental and economic so they can promote the overall sustainability and therefore contribute to global sustainable development targets.

Organizations, companies or individuals can create handprints through actions that result in positive impacts, but what are the motivating factors to do such actions. Actions can be voluntary, for example initiatives or behavioral changes, but on the other hand regulations and targets may push actors to react. Handprint actions such as process or product innovations or investments can be driven by emission reduction targets, strategy goals of a company or stakeholders’ influence for example. Handprint assessment can be useful in managing the life cycle of a product or service to reduce environmental impacts. With the help of handprint assessment, the producer of offered solution can create a handprint and focus on communicating the advantages of the offered solution, which then again help customers to choose improved product and decrease their own footprints. (Grönman et al., 2019.) So can be said that also marketing and communication can benefit from handprint assessments results and it can be a motivating tool to utilize when environmental aspects are considered as a competitive advantage. Companies who wish to communicate the environmental benefits of their actions or wish to prove their sustainability efforts can be motivated to use handprint assessment. Recognized calculation method based on LCA is a trustworthy tool to use in companies’ sustainability and responsibility reporting and strategies to avoid greenwashing. Nowadays, customers have more and more environmental awareness, so sustainability aspects become increasingly important.

4. Evaluation of environmental handprint potential of limestone-based products

The environmental handprint potential of Nordkalk's product portfolio is analysed and evaluated based on the theory part in this chapter. Evaluation of potential environmental handprints is presented in the following Table 4. The Table lists applications of limestone-based products identified in the theory part and gathers information of benefits and qualities of limestone-based products use in these applications. Secondly, hypothesis of handprint potentials forming in these applications through limestone-based product utilization are listed. Thirdly, Table 4 includes a short explanation of mechanisms which may contribute positive environmental impacts, hence create the potential handprint defined. These mechanisms can also be called handprint contributors. Lastly, suggestions for a baseline definition for handprint assessment is evaluated and presented in the Table 4. The baseline definition is important to determine in handprint assessment framework because the chosen baseline will clearly have a remarkable influence on the handprint results. Sometimes the reference baseline cannot be defined because the baseline needs to deliver the same functions in the same purpose as the offered solution. (Pajula et al., 2021.) For example, in steel and pulp industries, limestone-based products have a fundamental role in some processes, and they are used by default. Lime utilizing processes may also be licensed according to the environmental legislation and a requisition for an environmental permit is that best available techniques (BAT) are used in processes to reduce environmental impacts (Finnish Environment Institute, 2013). A baseline definition for some of the applications is can be hard to conduct or not appropriate, because some of the applications utilizing limestone-based products can be described as business-as-usual (BAU) practices or processes.

Table 4. Evaluation of potential environmental handprints of limestone-based products.

Application	Benefits and qualities of limestone-based product's use in application	Handprint potentials	Mechanisms contributing handprints (handprint contributors) or other positive impacts	Baseline definitions
Agriculture				
Liming of fields, lakes and forests	Manage acidification, enable pH adjustment, reduce potentially toxic (e.g., Al, Mn) leaching and increase beneficial nutrients (e.g., Ca, Mg) availability by better soil structure. Improve soil fertility and better productivity of crops. Increasing of pH and reducing the acidity of lake water.	Nutrient handprint Carbon handprint Water handprint	A neutralizing contributor helping the efficient use of nutrients, an effect to solubility and retention of elements - nutrient balance. Contributing carbon sinks can decrease GHG emissions. Fewer discharges entering to waterbodies due to improved soil structure. Improves the water environment for certain species.	No liming pH adjustment with ash or slag
Fodder lime	Ensure an adequate intake of calcium to animals and livestock.	No handprint, because of business-as-usual manner	A high calcium carbonate content, an important supplement.	Solution already a BAU practice
Construction				
Soil stabilization	Improve the strength and the stability of poor-quality soils both in pillar stabilization and surface stabilization. Increase the workability of soil.	Carbon handprint Nutrient handprint Resource handprint	Less CO_2 intensive solutions decrease GHG emissions. Nutrient cycles and ecosystems can be negatively affected by high toxic cement, that's why lime products are preferred. Lime is considered as abundant material, affecting less abiotic depletion potential.	The use of cement products.

Application	Benefits and qualities of limestone-based product’s use in application	Handprint potentials	Mechanisms contributing handprints (handprint contributors) or other positive impacts	Baseline definitions
Construction				
Road construction and asphalt filler	Improve the quality and the durability of the asphalt. A possibility to use solid waste soda residue or concrete demolished waste with lime in pavement base and promote circularity.	Carbon handprint Resource handprint	The use of limestone-based fillers in asphalt mixture increases the performance and a lifetime of asphalt reducing a carbon footprint. Suitable properties to mix with recycled and waste materials and make a more resource efficient products.	The use of other filler materials in asphalt.
Building material manufacture and aggregates	Enable the use of recycled aggregates in some building materials (e.g., mortars) with limestone-based binder, reduce the need of virgin raw material by utilizing by-product aggregates.	Resource handprint	A binder material, which helps saving natural resources and can reduce the abiotic depletion potential contributing to a resource handprint. May also has an effect on decreased energy demand and reduced waste when utilizing by-products.	Using aggregates which are not a by-product and other binder materials such as cement.
Cement and concrete industry	Decrease CO_2 emissions from cement manufacture by using supplementary limestone as a raw material in concretes.	Carbon handprint	Replacement of CO_2 intensive cement binder in concrete can reduce GHG emissions.	The use of ordinary Portland cement.

Application	Benefits and qualities of limestone-based product’s use in application	Handprint potentials	Mechanisms contributing handprints (handprint contributors) or other positive impacts	Baseline definitions
Pulp & paper				
Causticizing process	Increase the overall resource efficiency and recycling of the mill by enabling the chemical recovery cycle and reuse of white liquor in the cooking process thanks to lime products.	No handprint, lime has a fundamental role in causticizing.	Quicklime is an integral part of chemical recovery and can be reused in the process. A possibility to use causticizing by-product lime mud as a CO_2 absorbent in emerging calcium looping technology in the future.	Solution already a BAU process
Bleaching and pigments	Hybrid bleaching with calcium hydroxide and NaOH reduces organic content levels in wastewater compared to chlorine bleaching.	Water handprint	Non-toxic and more environmentally friendly bleaching solution affecting fewer water pollution.	Other bleaching systems
Steel & iron				
Sintering process	Control the iron ore concentrate basicity and a prerequisite for a binder effect in forming homogeneous sinter.	No handprint, a fundamental component of iron ore sinter in blast furnace.	A basic filler and binder causing a hydration reaction to solidify the sinter mass. Water absorbent capability promotes the process.	No baseline, solution already a BAU process
Steel making	Improve the energy efficiency by enabling a-lower-melting-temperature metal oxide.	No handprint, a fundamental part of steel process.	Limestone-based products form a suitable slag quickly and removes impurities which enhance the steel productivity.	No baseline, solution already a BAU process

Application	Benefits and qualities of limestone-based product’s use in application	Handprint potentials	Mechanisms contributing handprints (handprint contributors) or other positive impacts	Baseline definitions
Flue gas treatment				
Desulfurization systems (dry, semidry, wet)	Capture and control SO_2 emissions in power plants diminishing acid deposition.	Air quality handprint	A purifying alkaline sorbent reducing air pollution contributes an air quality handprint if performs better than NaOH. In the future the possibility to utilize limestone-based CCS technology with calcium looping.	The use of caustic soda (NaOH)
Water treatment				
Drinking water purification	Control water hardness to avoid corrosion in piping, potential health benefits. Water pH correction to desired level.	Water handprint	Lime softening by pH adjustment precipitates out excess carbonate hardness and some detrimental compounds contributing water quality. limestone-based alternatives are more economical, easy and more secure to handle than caustic soda.	The use of caustic soda
Wastewater treatment plants	Management of pH with a lime product improves coagulation and flocculation processes by accelerating particles reacting more easily.	Water handprint	A neutralizing coagulant aid chemical may contribute both water scarcity and quality handprints if enabling water circulation in processes and reduction of impurities from wastewater streams.	The use of NaOH in pH adjustment

Application	Benefits and qualities of limestone-based product's use in application	Handprint potentials	Mechanisms contributing handprints (handprint contributors) or other positive impacts	Baseline definitions
Miscellaneous				
Plastics & rubbers Adhesives & fillers	High purity limestone-based additives can replace other materials providing brightness and stability without compromising properties.	Resource handprint	A substituting functional filler, reducing non-renewables or fossil-based materials and therefore contributes to a resource handprint. An ability to absorb water and low costs can also be beneficial.	Totally fossil-based products.
Paints & coatings	Decrease the use of a titanium dioxide (TiO_2) pigment by replacing it with limestone-based extender providing same properties.	Carbon handprint Water quality handprint Resource use handprint	Replacing a potentially carcinogenic white pigment TiO_2 with limestone-based solution, which also reduce GHG emissions of paints.	An ordinary product without lime solution.

Possible positive environmental impacts and a potential handprint effect is analysed in the Table 4 for limestone-based products of Nordkalk in all applications used nowadays. The research conducted by Pajula et al. (2021) has defined the environmental impacts which can be assessed with their handprint framework. Environmental impacts related to climate change, resource depletion, water, nutrients and air quality can be assessed with the handprint framework currently. The handprint potentials in these previous impacts categories are described as carbon handprint, resource handprint, water handprint, nutrient handprint and air quality handprint. However, a comprehensive life cycle assessment can result also many other negative impacts to human, environment and resources, but there is not a handprint definition yet for all environmental impacts researched. In the future, the biggest handprint potential which can be reached by limestone-based product utilization can be found from the construction field due to the huge interest towards greener and more sustainable construction materials and the volume of them needed. Moreover, the use of limestone-based products in construction is already typical and from the product development point of view limestone may have suitable characteristics in many applications so the future potential can even increase. Besides, an increase in handprint potential can be seen in miscellaneous products and other chemical industry uses where fossil-based materials are desired to be replaced with more sustainable solutions.

5. Case example

This chapter focuses on a case example of environmental handprint assessment applying the handprint framework presented in Carbon handprint guide V. 2.0, applicable for environmental handprint researched by Pajula et al. (2021). This handprint approach is closely linked with the LCA methodology which is standardized in ISO 14040 and ISO 14044 and there are many similarities and same features in handprint and life cycle assessment. Therefore Stage 2 in the handprint framework presented earlier includes LCA requirements, and the footprints of studied systems must be calculated first in handprint assessment for a comparison of the chosen handprints against the baseline defined. So, quantification in Stage 3 in handprint framework includes footprint calculations of chosen impact categories and that must comply with the LCA methodology. (Pajula et al., 2021.) Applying an LCA method is a prerequisite to assess variety of emissions. Therefore, an LCA software is utilized in this study to calculate emissions concerning the selected impact categories in interest and then indicate the potential handprints under the environmental handprint concept.

The case example concerns the Enrich product group of Nordkalk, which includes three products of precipitated calcium carbonate. These products are manufactured in Parainen and they are typical additives in papers, paints, varnish, plastics and many other chemical industry uses. Environmental product declaration is made for Enrich products based on standard EN 15804, which provides core rules for EPD assessment of construction products. (SFS-EN 15804:2012.) The Enrich EPD made in accordance with standard EN 15804 results a carbon footprint of Enrich product according to a cradle-to-gate system boundary. Since only a carbon footprint is assessed in the Enrich EPD, more research is needed in order to analyse other than global warming potential and a carbon handprint. Nordkalk desires to investigate more comprehensive environmental handprint of the Enrich products and that’s why this topic is researched in this case. The idea of handprint assessment is to calculate the amount of good which can be created by offering a solution with a lower footprint than the baseline’s footprint. The offered solution, an Enrich product in chemical applications can hypothetically substitute other conventionally used products with higher impacts on the environment.

5.1. Limestone-based innovation substituting titanium dioxide pigment in paints

Nordkalk is interested in applying the environmental handprint concept in their sustainability strategy, but the research during this thesis has shown that the conventional applications utilizing limestone-based products are not necessarily suitable for a handprint assessment. Baseline definition can also be challenging, if there are no comparable products used in the same application providing the same functions. Limestone-based products in traditional and standardized processes like steel making and pulping do not create handprints if they are already widely used, there are not a better alternative existing and when they are in accordance with best available techniques. In that case, limestone-based products do not provide any new positive impacts for the application or process, even though they possibly have a very important role. For that reason, the case example was selected based on the potential to deliver a sustainable solution in the future. The Enrich product group is a result of innovative product development process and the product development is continuing. Assessing the environmental impacts of a product under continuous development can bring meaningful information and even boost an interest around the product. With the help of product development, even increase in handprint potential can be achieved if the product development has succeeded, and environmental aspects are considered. Therefore, a handprint assessment can provide useful information for a product development's needs.

Nordkalk has been developing a limestone-based innovation where the Enrich product can replace the use of titanium dioxide (TiO_2) pigment in paints. This innovation has researched and tested many times during the development process. The offered paint solution is told to have a positive impact on environmental, social and economic sustainability. This case evaluates the positive environmental impacts of the paint innovation and it's potential to create environmental handprints. According to Nordkalk (2021) raw material costs are also lower with paint innovation. Besides, it is told that powder form of TiO_2 is recently labelled as a possible carcinogenic substance in chemical classification when containing nanosized particles and inhaled (Turvallisuus- ja kemikaalivirasto (Tukes), 2020). This also motivates to continue the product development of a replacing product. Therefore, a social sustainability of the paint innovation can also be enhanced with the replacement of carcinogenic component even though this is not the core in this case.

The following Table 5 presents the step-by-step guidelines for a handprint assessment process and the potential handprints of Enrich product is assessed within the guidelines. The hypothetical assumption is that the limestone-based pigment has a potential to reduce environmental impacts in the customer’s use in their paint production over a baseline option. A pigment, either Enrich or TiO_2, can be used as a component in paint. Typically, water-borne paint recipes include 10-20 % of titanium dioxide of the total mass according to Lammela (2023). Nowadays most paints are water-borne, but previously they were mostly solvent based (Tikkurila, 2023). A water-borne paint includes typically 50 % water of its mass so dry paint film consists of 20 – 40 % titanium dioxide of which 10 – 25 % can be replaced by Enrich product. Also, the binders in paint composition can be replaced with Enrich product probably in the future and dry paint film consists of 20 – 40 % binder, which is typically some kind of fossil-based polymer. So, Enrich product may have potential also as a binder replacement, but this aspect is not studied in this context.

Table 5. Handprint assessment for Enrich product.

Stage 1 – Handprint requirements	
Scope of the offered solution	Nordkalk’s limestone-based product has a potential to partly substitute potentially carcinogenic TiO_2 pigment in paints. A limestone-based Enrich product delivers the same properties as a pigment in paints than TiO_2 with a currently possible 10-25 % replacement rate. In this calculation, 20 % replacement rate of TiO_2 is assumed. Potential environmental benefits (environmental handprint) with the offered solution compared to the baseline solution.

Potential handprint contributors	The offered solution decreases the use of TiO_2 and possibly also a polymer component in the future in paints, which may decrease environmental burden. Emission reductions may be achieved by changing to more sustainable product component which may have a positive impact on water quality and abiotic resource depletion for example. A hypothesis is that the production process of offered solution is less GHG intensive, utilizes less fossil fuels, water and chemicals which may contribute water, carbon and resource handprint for example. Overall, the handprint contributor is simply a more sustainable production process of required pigment component.
Potential environmental impacts and their indicators	Climate change impact – GHG emission reduction, global warming potential indicator Toxicity impact – non-toxic stone material with no need of strong chemicals in production– human health and ecotoxicity indicator Water scarcity and quality impact – production in a country with low water scarcity and few discharges to water, good wastewater management – eutrophication and acidification potential indicator
The users and beneficiaries of the Solution	Paint manufacturers who purchase paint components and want to evaluate the alternatives.
Baseline definition	The baseline solution is a titanium dioxide pigment manufactured with a sulphate process in Germany according to average data from BAT reference document.
Stage 2 – LCA requirements	
Functional unit definition	1000 kg of dry weight paint
System boundaries	Cradle-to-gate: production stage including raw material extraction, transport to manufacture and manufacturing processes with some exceptions, which are documented in the study.

Data needs and sources	All available data related to the sulphate process and the Enrich production process, production recipes, raw material extraction. Enrich data source is Nordkalk and their materials. Titanium dioxide data source is BAT. Paint composition and the substituting percentage of offered solution is an assumption.
Stage 3 – Quantification	
Calculate the footprints	Life cycle inventory results assigned to impact categories based on CML2001 method are calculated with the GaBi LCA software.
Calculate the handprints	Handprints are calculated and presented in the result chapter.
Stage 4 – Communication	
Relevant indicators to be Communicated	Confirmation of the accurate indicators presenting the results is identified in the result and analysis chapter.
Critical review of the handprint	Critical review is not conducted, however it would be recommended if the handprint results are communicated externally.
Communicate the results	Communication of the results do not include in this thesis.

Table 5 includes the assessment phases of handprint framework for this case study focusing on the replacement of titanium dioxide pigment in paints. Titanium dioxide has been a critical inorganic additive already a hundred of year in paint, paper and plastics applications due to it has the highest refractive index. 95 % of titanium mineral ores are consumed for titanium dioxide pigment manufacture globally. (Middlemas et al., 2015.) The potential environmental benefits of limestone-based products substituting TiO_2 can be high due to the significant quantity of TiO_2 production worldwide. There may be a huge potential for limestone-based pigment especially in the paint manufacture, because titanium dioxide is the major pigment in the field. Titanium dioxide is processed from heavy mineral sands, most commonly from minerals called ilmenite and rutile. According to research conducted by Farjana et al. (2018) the major environmental concerns of extraction titanium oxide minerals are pollution of ground-water resources affecting eutrophication, land use change and climate-change effect. Besides, mining heavy mineral sand for a raw material has generally high water use requirements and global demand for paint is increasing according to Perks et al. (2022).

Research conducted by Middlemas et al. (2015) compared the traditional and emerging commercial TiO_2 manufacturing processes using an LCA method with a cradle-to-gate system boundary. With the growing global concern over environmental impacts, a new TiO_2 production process has emerged aiming to reduce carbon footprint of the titanium dioxide production. The new ARTS process emits 10-15 % less CO_2 emissions than traditional processes, chlorine and sulfate. (Middlemas et al., 2015.) On the other hand, research conducted by European Chemical Industry Council (2013) calculated the cradle-to-gate carbon footprint of the average manufacturing processes for titanium dioxide pigment. The carbon footprint in this research for the industry average TiO_2 production is told to be 5.3 t CO_2 eq./ t TiO_2 product based on data year 2012, but the functional unit was 1 kg of product containing 80 % TiO_2. For a comparison, an assumption of 1 kg of product containing 100 % TiO_2 is solved and listed in the following Table 6. The LCA results from literature shows that TiO_2 production has a greater carbon footprint than Enrich production process presented with global warming potential (GWP) impact category, which can be seen from the Table 6.

Table 6. Comparison of GWP of studied products, based on literature.

Product	GWP/functional unit	Source
Enrich product group (EPD)	0.48 kg CO_2 eq./1 kg of Enrich product	Nordkalk (2022)
The industry average TiO_2 production	6.63 kg CO_2 eq./ 1 kg of 100 % TiO_2 product	European Chemical Industry Council (2013)

Inorganic titanium dioxide pigment can be made by a couple of different chemical processes, the most typical of which are the chloride process and the sulphate process. As the name of the processes indicate, titanium ore leads to TiO_2 products by reacting with either chlorine gas or sulphuric acid. Both process types are quite common and based on statistics from year 1995 world TiO_2 production capacities were split to 47 % for the sulphate process and 53 % for the chloride process. Overall consumption of titanium dioxide was 3.4 million tons in 1996 of which even 59 % went into paints. It is also stated that titanium dioxide is the most important pigment in terms of quantity and because of its properties and a wide of range of applications. However, the sulphate process route is more common among European producers and more investments have been put into sulphate process in Europe. Besides, it is noted that environmentally there is only a little difference between these two processes, nevertheless the two processes are different in most aspects. (European Commission, 2007a.) The sulphate process is chosen for the titanium dioxide production process in this case and this process is modelled with GaBi software.

5.2. Applying life cycle assessment method in handprint assessment

Emissions occurring from the production of the baseline solution and the offered solution systems is needed to calculate handprints of the Enrich product. A possibly occurring reduction in emission is calculated against the defined baseline solution in accordance with the following equation.

$$\text{Handprint}_{\text{product}} = \text{Footprint}_{\text{baseline}} - \text{Footprint}_{\text{offered solution}}$$

Environmental impact calculation is based on life cycle assessment, which evaluates the potential environmental impacts of a defined system throughout its life cycle. LCA includes four phases, which are goal and scope definition, inventory analysis, impact assessment and interpretation phase. A footprint usually refers the negative environmental impacts what are generated by our actions and left behind in contrast to a handprint which is referred to the good we can generate by our actions and prevent or minimize environmental impacts. The handprint framework’s Stage 2 includes already the goal and scope definition phase where the product system is described, and functional unit and system boundaries are identified. The studied product system includes a set of unit processes which are within the defined system boundary and unit processes are linked together by flows. There is no intention to conduct a full life cycle assessment, but LCA rules clarified in ISO 14040 & 14044 standards are applied and needed also in handprint assessment method. As stated in SFS-EN ISO 14040 (2006) the depth of a particular LCA study can differ notably depending on the objective and there is a flexibility in implementing LCA. It is also noted that the LCA methodology can be applied in cradle-to-gate studies with most requirements, nevertheless it is not a comprehensive LCA study. Product sustainability LCA software called GaBi made by Sphera, is used for life cycle assessment. GaBi software is an effective tool to assess environmental impacts and to model the studied system.

5.2.1. Goal and scope definition

Following the guidelines and requirements of ISO 14040 and 14044 standards, the first step is goal and scope definition. The goal of this case study is to compare two pigment alternatives to solve that can positive environmental impacts be created with the use of a limestone-based pigment in paints. The intended application here is a paint manufacturing and the focus is on a pigment production for paints. Only environmental impacts of a pigment manufacturing are considered, because of lack of data in other paint components such as polymers. However, the results are considered also in a paint context, which is more familiar product to consumers than pigments. This was also a wish from the cooperating company. The reasons for carrying out this study is to demonstrate the potential of a limestone-based product series called Enrich utilization in paints as a substitute for traditional titanium dioxide pigment. The typical percentage of pigment in paints is considered and a comparative study is conducted where a traditional paint containing titanium dioxide pigment is compared against a paint innovation containing a portion of Enrich limestone-based product. Intended audience is the limestone-based solutions manufacturing company Nordkalk and possibly their customers and stakeholders are also interested in the results. The results of the case may be used in communication purpose, however a critical review of this case in not conducted. The chosen life cycle impact assessment methodology is CML 2001 midpoint approach in this study. It reviews potential environmental impacts summed up to impact categories to define impacts to environment, human health, and resources. Types of midpoints impacts which are in the greatest interest in this case are global warming potential, eutrophication and resource depletion. Covered impact categories are then climate change, eutrophication, and resource depletion potential (fossils and elements). Category related emissions are presented quantitatively with characterization factor, for example global warming potential kg CO_2-eq./kg product. These impact categories could have an influence on endpoint areas of protection, but they are not analyzed deeply in this study, but these category indicator results are the foundation of handprint assessment. Finally, the environmental handprint potential is evaluated with the help of following handprint potentials; carbon handprint, water quality handprint and resource use handprint.

The scope of the case study includes functional unit and system boundary descriptions, data and data quality requirements, assumptions and limitations. The functional unit in comparison between two pigment manufacturing systems need to be consistent and deliver the same functions. The functional unit is defined to be 1000 kg dry weight of paint. That amount of dry weight paint delivers same functions in the comparison of two chosen paint solution with the assumption that both pigments have similar properties as a paint component. The function of pigment in paint solution is to provide the desired optical property, brightness and opacity. There are many types of paints mixed with different solvents and many types of paints with varying ingredients ratio for multiple uses in the field, so one simple paint composition is made. The basic paint composition is assumed to be 50 % solvent, 30 % polymer binder and 20 % pigment and when dealing with dry weight of paint only, solvent is excluded and then 1000 kg dry weight of paint consists of 60 % polymer binder and 40 % pigment. In other words, a functional unit of 1000 kg dry weight of paint is used with the assumption that it consists of 60 % polymer binder and 40 % pigment. 20 % of pigment is assumed to be replaced with Enrich so the offered paint solution includes 8 % of Enrich. The whole portion of TiO_2 pigment cannot be replaced yet with Enrich in commercial paints. The equivalent use of TiO_2 and Enrich pigment in paint can be assumed when 10 – 25 % of TiO_2 is replaced with Enrich according to Nordkalk. (Lammela, 2023.)

According to European Commission (2007b) BAT reference document, polyvinyl acetate and polyacrylates for paints are typical products made by emulsion polymerization. Emulsion polymerization process comprises monomer, initiator, surfactant and solvent (usually water) to produce polymer. There are also many other production processes for the reaction of monomers to polymers, and a wide range of commercial polymers can be made from petrochemical feedstock. Polymers can also be a composition of one or two type of monomer. The composition of paints varies a lot, and in this context assumptions are required so the following Figure 4 presents the assumed dry weight composition of paint.

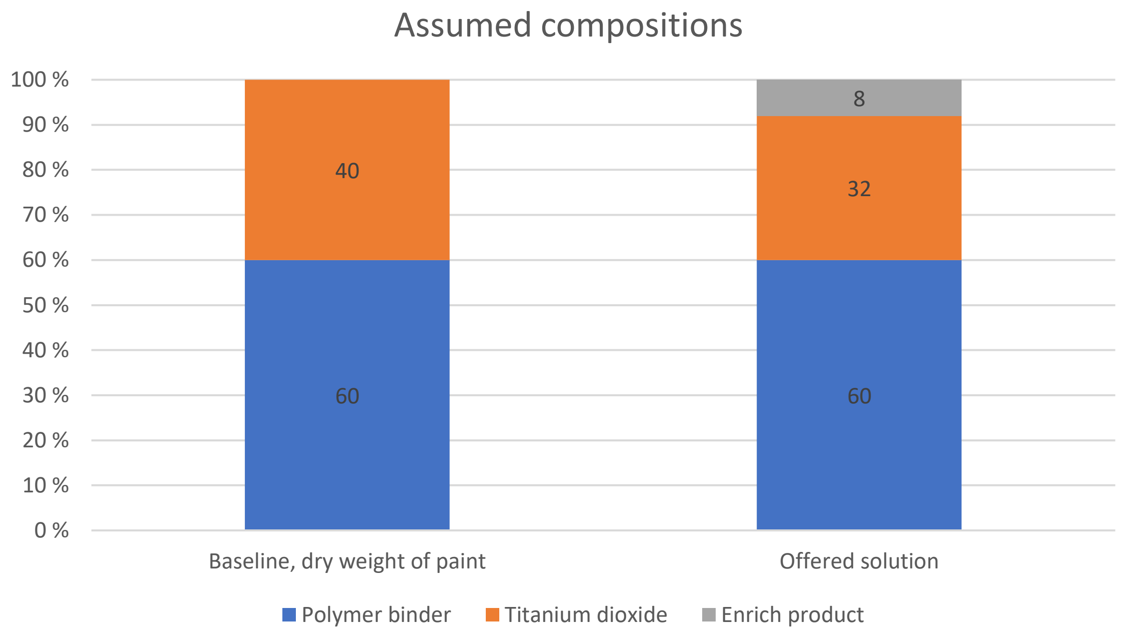


Figure 4. Assumed paint compositions of the baseline and the offered solution (dry weight).

The product systems to be studied are titanium dioxide manufacturing through a sulphate process and precipitated calcium carbonate (Enrich product) manufacturing from limestone. Both product systems produce mineral powder whose function is to act as a pigment, for example in paints. The system boundaries of two manufacturing routes for pigment need to be determined. System boundaries visualize which unit processes shall be included in LCA and presents the chosen defining of input and outputs flows. Establishing the system boundaries in this case is based on cradle-to-gate model. A cradle-to-gate LCA model includes only the first two stages of a product life cycle, which are raw material extraction and manufacturing. According to Nickel (2023) this life cycle model “assesses a products’ environmental footprint up to the point where it leaves the factory gate” and therefore use phase, transportation and waste disposal phase stay out of the boundary. This cradle-to-gate model is often used if the compared products have identical post-factory-processes, and therefore the major difference in environmental impacts occur in manufacturing phase. This explains the choice of a system boundary. However, a cradle-to-gate defining includes usually transports of the raw materials to the manufacturing phase in a factory if raw materials are extracted or acquired from elsewhere, but here it is excluded. (Nickel, 2023.) There’s no available data on titanium dioxide manufacturers which could be used as an example where the raw materials are transported to a factory and these raw materials transports are depended on many aspects, such as geographical locations. The main life cycle stages of a cradle-to-gate approach and inputs and outputs are described in the following Figure 5, which also presents the system boundary for this case study.

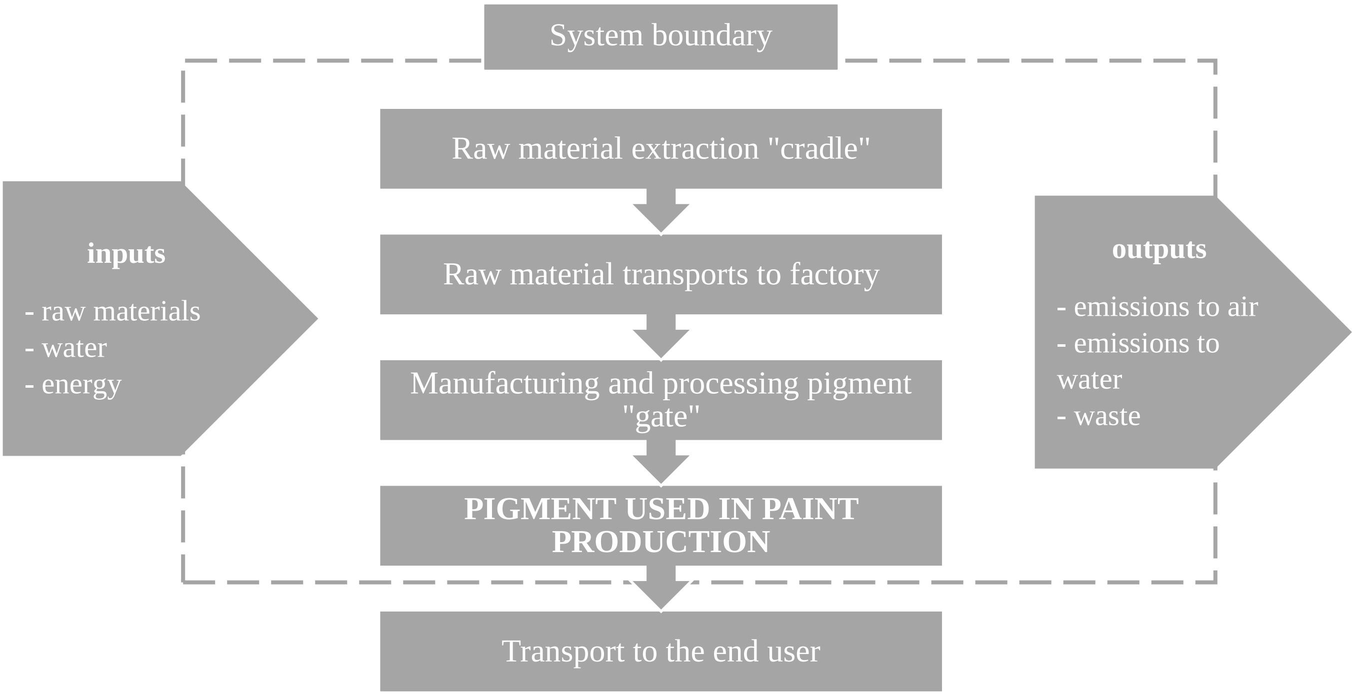


Figure 5. System boundary and cradle-to-gate life cycle stages.

These main life cycle stages presented in the Figure 5 includes all the unit processes needed to manufacture the product and extract the raw materials. The related unit processes of the product systems studied can be seen from the following two figures. The detailed process steps of sulphate process of TiO_2 or calcination and hydration of Enrich are not visualized here, because the total input and outputs assessment is more relevant in an LCA study. However, the unit processes contributing to a manufacture of TiO_2 and Enrich are included in the following Figures 6 and 7. Figures also draw the main flows between unit processes.

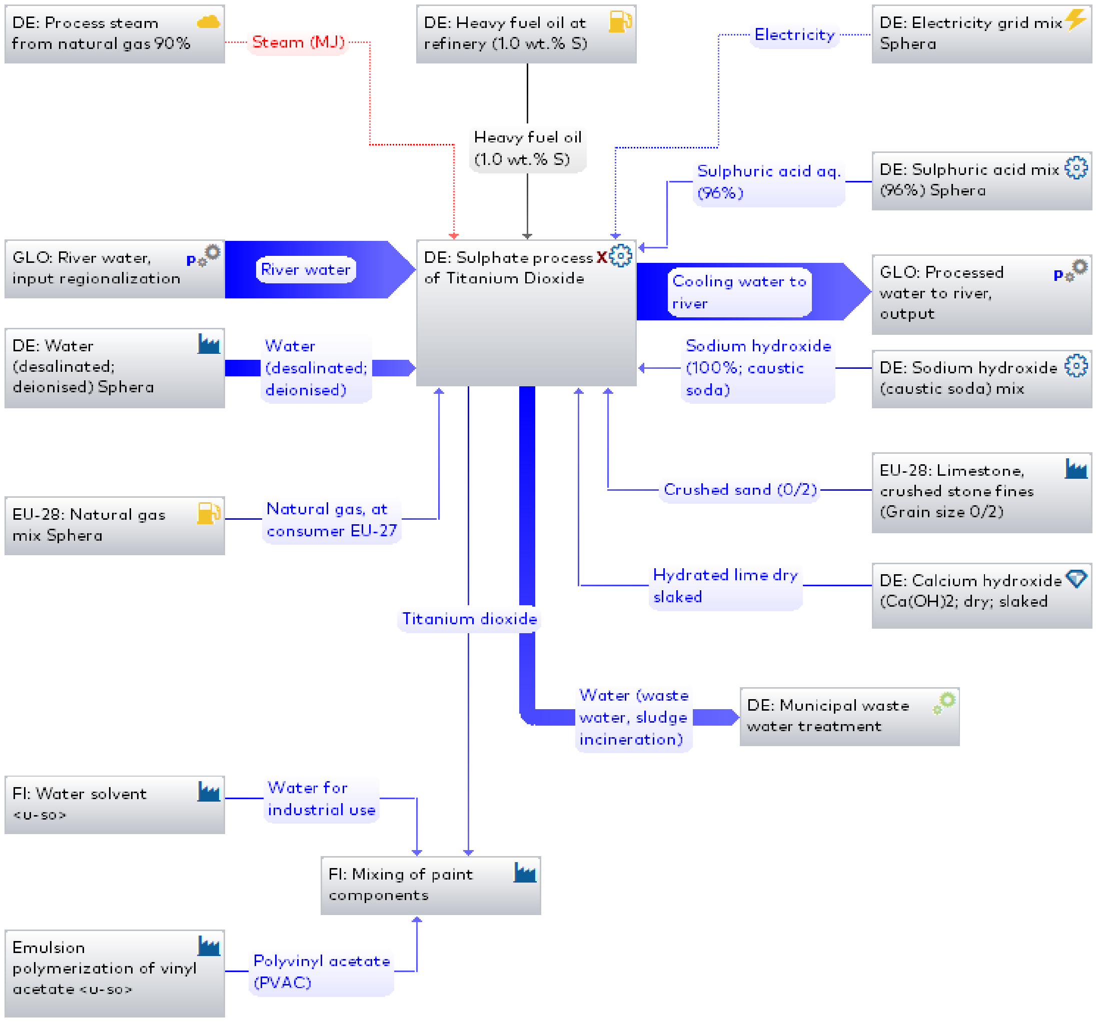


Figure 6. GaBi model of titanium dioxide manufacture.

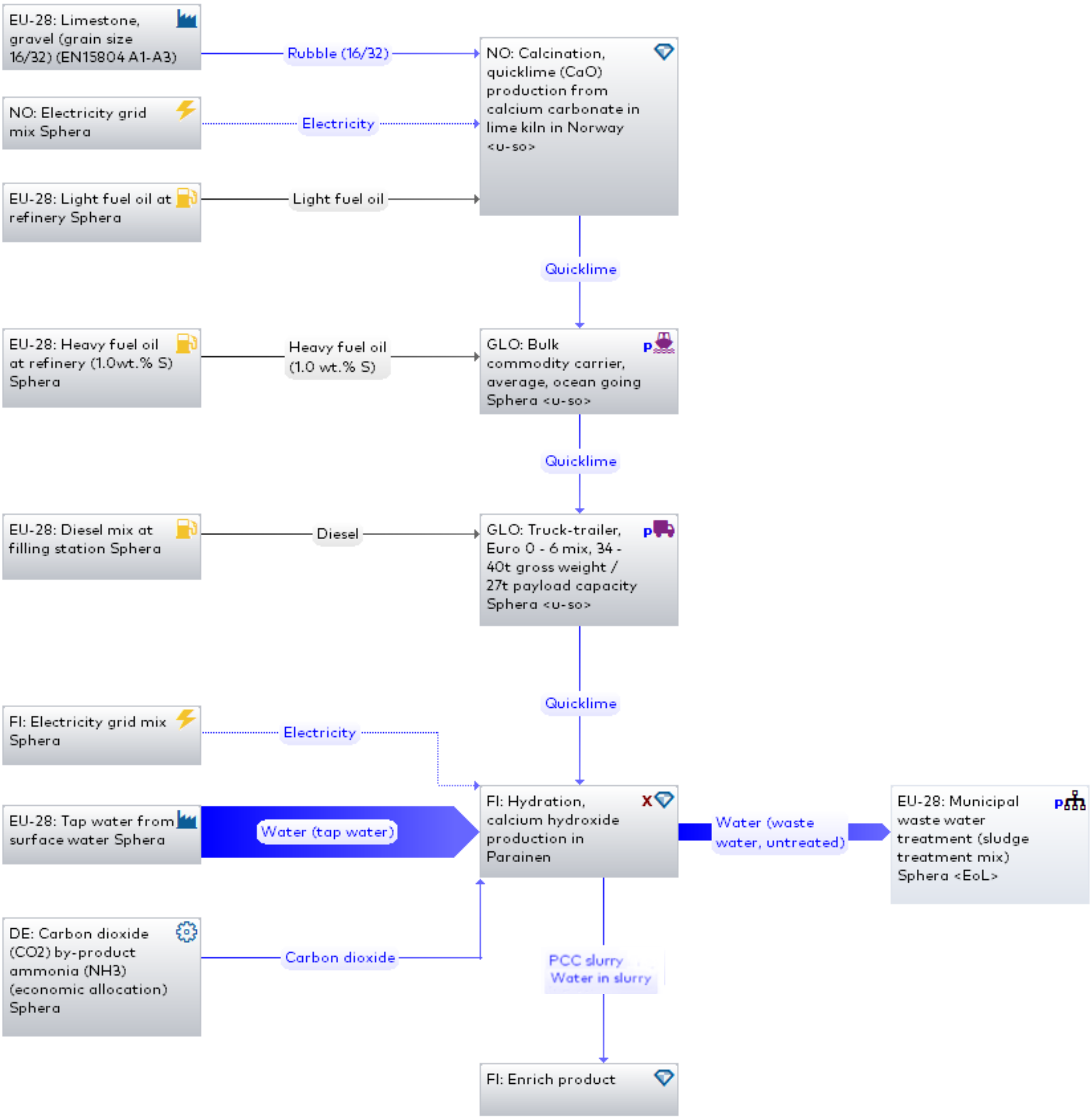


Figure 7. GaBi model of Enrich product manufacture.

Data requirements are raw materials, water and energy inputs and unit processes included in the product system. Data about titanium dioxide manufacture is retrieved from Best Available Data reference document called Large Volume Inorganic Chemicals – Solids and Other Industry. This BAT document includes data from European TiO_2 manufacture sites in the year 1999. That year there were 19 sites in Europe of which 15 utilized the sulphate process and 4 sites were using the chloride process. The sulphate process is a chosen technology for the comparison in this case, because of its popularity in Europe. Required data of TiO_2 production is an average data from these 19 sites, because no site-specific data available. (European Commission, 2007b.) Data from Enrich production comes from Nordkalk and it's the same data which was used to make an EPD of Enrich series. That data includes the raw material and energy inputs, and waste and wastewater outputs on a yearly basis of Enrich product system. Besides, the transportation distances and frequencies are covered. Under the circumstances, data quality of these two product systems differs, Enrich data is more up to date and its primary data from the specific site. Data of titanium dioxide is secondary data, but that is the best available data for this study and therefore the accuracy of results will not be precise. However, the results requirements are not very high, so the lack of accuracy is acceptable. The results are desired to show the handprint potential of limestone-based product and inspire product developments to innovate.

5.2.2. Inventory analysis

The second phase of LCA is an inventory of input and output data regarding the system studied and the system boundary defined in the first phase. Life cycle inventory (LCI) data is collected and documented and entered to the GaBi software, which provides the quantitative LCI results of relations between unit processes and flows referenced to the functional unit. GaBi software automatically calculates and assigns the specific emissions emitted within the defined system to correct impact categories, so it makes LCI and life cycle impact assessment (LCIA) phases a little bit easier. Data collection decisions shall be based on the data significance, and a sensitivity analysis can be utilized to evaluate what can be left outside of the study considering the goal of the assessment. The quality and validity of data can be evaluated and documented, and data collection difficulties can exist. (SFS-EN ISO 14040, 2006.) In this case study, data from many sources is collected. Regarding to titanium dioxide production, production recipe and raw material flows needed to produce titanium dioxide pigment are from BAT reference document. Data relating to unit processes of raw material procurement, energy and water is from GaBi software's own databases. Listing of all relevant flows entering and leaving the titanium dioxide production is included in the following Table 7. All data of flows in the Table are referenced from Best Available Techniques reference document conducted by (European Commission, 2007a). Unit processes behind the flows with red font are not included in the calculation due to lack of data of them.

Table 7. The inputs and outputs of sulphate process of titanium dioxide (European Commission, 2007a).

INPUT flow	Quantity	Unit
Raw materials		
Ilmenite ore (extraction not included)	1662	kg/t TiO_2 (average)
Sulphuric acid (100 %)	3250	kg/t TiO_2 (average)
Scrap iron (recycled, non-valuable)	150	kg/t TiO_2 (average)
Limestone, $CaCO_3$ (100 %)	1380	kg/t TiO_2 (average)
Slaked lime, Ca(OH)2 (100 %)	363	kg/t TiO_2 (average)
NaOH (100 %)	90	kg/t TiO_2 (average)
Energy and water consumption		
Electricity	4.2	GJ/t TiO_2 (average)
Steam	17.3	GJ/t TiO_2 (average)
Gas	12.5	GJ/t TiO_2 (average)
Heavy fuel oil	2.4	GJ/t TiO_2 (average)
Industrial water (imported into site)	77	m^3/t TiO_2 (average)
Cooling water from river	246	m^3/t TiO_2 (average)
OUTPUT flow	Quantity	Unit
Emissions to air		
Emissions to water		
Wastes to land		
Neutralised digester residue, silica content	307	kg/t TiO_2 (average)
Red gypsum (limestone neutralization)	3849	kg/t TiO_2 (average)
Wastewater for treatment	77	m^3/t TiO_2 (average)

Data quality of the Table 7 is moderate because all values presented are secondary data based on industry average values in EU factories in 1999. The source of data is a quite reliable, but not updated lately. The unit processes of the titanium dioxide production system are background data from GaBi database. Assumptions related to data collection and the titanium dioxide product system are that only ilmenite ore used as an ore feedstock, while another possibility is to use synthetic titanium slag or combination of these. Scrap iron is needed when only ilmenite ore is used, but as a recycled material it is a secondary product flow entering the system in small amounts, it is not included in the calculation in GaBi. Sulphuric acid is an important elementary flow and only a new acid is used as a raw material in production. It is also an assumption that the product system utilizes acid neutralization, no acid recycling. Both technologies require different installations and acid recycling is noted to increase the energy demand compared to neutralization. Acid neutralization is considered on data requirements and limestone and slaked lime inputs are used for that. Caustic soda is used in wastewater treatment and off-gas scrubbing. Energy demand of titanium dioxide production is depended on many things, but it is assumed that gas is used only for drying, steam is used for milling and drying, and a kiln utilizes heavy fuel oil. Energy inputs do not include energy used in the production of raw material. Industrial water input is used in production and cooling water consumption is assumed to be sea or river water running through the production process. Regarding the outputs of TiO_2 product system, releases to air and water are covered and major solid wastes are included. Co-products are excluded from the product system because there are many ways to reuse, dispose or utilize them depending on the market. Also some small amount of ancillary inputs are excluded, which may be used depending of the technology and there’s no data on them in GaBi databases. (European Commission, 2007a.)

Another product system studied in the comparison is an Enrich production process. Data from this system is more recent and at most parts site-specific data presented by the producer company. Unit processes of energy inputs are background data from GaBi database, but country specific technology production mix unit processes are used. Listing of all relevant flows entering and leaving the Enrich production is included in the following Table 8. Data of flows in the Table are referenced from Nordkalk and Nordkalk’s Enrich product EPD. Most relevant raw material extraction unit processes can be found from software’s database, but polycarboxylate and biocide production is excluded due to lack of data and small mass contribution. Unit processes behind the flows with red font are not included in the calculation due to lack of data of them.

Table 8. The inputs and outputs of Enrich manufacturing process.

INPUT flow	Quantity	Unit
Raw materials		
Limestone, calcium carbonate (Verdal)	1821	kg/t quicklime
Quicklime (Parainen)	280	kg/t Enrich
Dispersing agent (Parainen)	25	kg/t Enrich
Carbon dioxide (Parainen)	220	kg/t
Biocide (Parainen)	2	kg/t Enrich
Energy and water consumption		
Electricity (Verdal)	31.8	kWh/t quicklime
Electricity (Parainen)	150	kWh/t Enrich
Light fuel oil to kiln (Verdal)	91.3	kg/t quicklime
Tap water for hydration	8000	m3/t
Raw material transport		
Verdal – Inkoo, average bulk carrier ocean	2500	km (distance)
Inkoo – Parainen, average truck-trailer	134	km (distance)
OUTPUT flow	Quantity	Unit
Material outputs		
Reused mineral material	10	kg/t Enrich
Enrich product (dry matter)	500	Kg
Water in slurry	500	Kg
Wastewater	2.9	m3/t

After modelling the two production processes and entering the previous data, GaBi software calculates the results according to the chosen CML2001 method and these results from inventory analysis phase are utilized next in impact assessment phase.

5.2.3. Impact assessment

The third phase of the LCA methodology is life cycle impact assessment to assess a product system's inventory results from the previous phase. A better understanding of the system's environmental significance is the purpose in this phase and LCIA results are providing the environmental effect to midpoint or endpoint categories. An impact assessment is not an obligatory phase if only an LCI study is conducted. (SFS-EN ISO 14045, 2006.) In this case impact assessment method is chosen to be midpoint approach CML 2001. That LCIA method exists also in GaBi and it is utilized to handle the handle. Results from the inventory analysis (LCI results) are assigned to the selected impact categories and classified. Endpoint level impacts or area of protection are not covered.

5.2.4. Interpretation

The last phase of the LCA methodology in which the findings and results from either the LCI or the LCIA or both are assessed in relation to the goal of a study. However, the results of this case are presented in the following chapter 6 to make them clearer from the handprint assessment perspective. Moreover, an evaluation regarding the completeness and consistency of the conducted study is an important element in interpretation phase. Completeness check is established to enhance the reliability and transparency of the data collection and to make sure all relevant information is considered in the study to fulfil its purpose. The completeness check of modelled titanium dioxide and Enrich production processes is conducted in the following Tables 9 and 10. Energy used in the production of raw materials is not included in energy consumption of TiO_2 or Enrich production. Table 9 conducts a completeness check for titanium dioxide production model modelled with GaBi software. The Tables 9 and 10 gather information about the unit processes which are included in LCA models and which are not. For example, raw material procurement stage of TiO_2 production is not fully complete, whereas energy consumption and water use are fully complete. Raw material extraction processes concerning ilmenite ore mining, iron scrap procurement and minor materials are out of the system boundaries because of lack of data on them.

Table 9. The completeness check of titanium dioxide production model in GaBi.

Unit process	**Life cycle phases: TiO_2 production**	**Complete?**
Raw material procurement – partly completed		
Ilmenite ore mining	Ore mining and extraction excluded, no data	NO
Iron scrap	Excluded, recycled material with low contribution	NO
Sulphuric acid	Country specific technology mix (DE, 2020)	YES
Sodium hydroxide	Country specific technology mix (DE, 2020)	YES
Limestone, crushed	European specific technology mix (EU-28, 2020)	YES
Calcium hydroxide	Country specific technology mix (DE, 2020)	YES
Minor materials	Excluded, may be used in small amounts depending on the production circumstances	NO
Energy consumption – completed		
Electricity	Country specific technology mix (DE, 2017)	YES
Heavy fuel oil	Country specific production mix from crude oil (DE, 2017)	YES
Steam	Country-specific technology mix (DE, 2017)	YES
Natural gas	European specific technology mix (EU-28, 2017)	YES
Water use – completed		
Cooling water	River water assumed to be as cooling water, input and output to river, regionalized to Germany	YES
Process water	Country specific desalinated and deionized water supply mix (DE, 2020)	YES
Wastewater treatment	Country specific technology mix for municipal wastewater treatment with sludge incineration (DE, 2020)	YES
Transportation – not completed		
Internal raw material transports	Not included, no data	NO

From the Table 9 can be seen where the biggest uncertainties and weak spots are regarding TiO_2 model. A same kind of completeness check is conducted for Enrich production model in GaBi, in the following Table 10.

Table 10. The completeness check of Enrich production model in GaBi.

Unit process	**Life cycle phases: Enrich production**	**Complete?**
Raw material procurement – partly completed		
Limestone extraction, grain size	European specific technology mix (EU-28, 2020). Including gravel open pit mining, a transport between the quarry and the plant, milling, breaking, drying and all relevant energy and refinery products.	YES
Quicklime calcination	Calcination process modelled based on primary data from the company	YES
Carbon dioxide	Country specific average data (DE, 2020). Assumed by-product from ammonia synthesis, Haber-Bosch process. Economic allocation, 15 % of environmental impacts allocated to carbon dioxide.	YES
Biocides	No data on production, small mass contribution	NO
Dispersing agent	No data on production, small mass contribution	NO
Energy consumption – completed		
Electricity, Verdal (calcination)	Country specific electricity grid mix to consumer (NO, 2017)	YES
Electricity, Parainen (hydration)	Country specific electricity grid mix to consumer (FI, 2017)	YES
Fuel oil to kiln	European region-specific light fuel oil production mix (EU-28, 2017) from crude oil	YES
Heavy fuel oil at refinery	European production mix for bulk commodity cargo carrier (EU-28, 2017)	YES

Diesel mix at filling station	European consumption mix for truck trailer, from crude oil and bio components (EU-28, 2017)	YES
Water use – completed		
Tap water	European region-specific production mix from surface water (EU-28, 2020)	YES
Wastewater treatment	European region-specific average municipal waste water treatment with sludge treatment	YES
Transportation – partly completed		
Quicklime from Norway to Inkoo	Bulk commodity cargo carrier, ocean going average, heavy fuel oil driven. (GLO, 2020)	YES
Quicklime from Inkoo to Parainen	Diesel driven truck trailer, Euro 0-6 mix. (GLO, 2020)	YES
Other raw material transport	Not included	NO

It can be seen from the Table 10 that Enrich process model is more complete, but there is also a lack of data in unit processes concerning procurement of biocides and dispersing agent. Regarding transportations within the system boundaries, Enrich production process include raw material transports to the production site on the contrary of titanium dioxide production process. This probably have an influence on the results, therefore environmental impacts of titanium dioxide production may be bigger than calculated.

In addition to the completeness check, also the consistency check is recommended in the LCA standards. Data consistency check aims to evaluate whether the methods and data are consistent or not. Data consistency check evaluates and compares the quality of data source and data accuracy in addition to data age. Differences in data sources may have an impact on the results and primary data would be better for handprint assessment as it describes the reality instead of average values from literature. Moreover, the age of data should be noticed because technologies are constantly evolving, and recent technologies can be more environmentally friendly. The following Table 11 presents the consistency check regarding this case study and the modelled production processes.

Table 11. Data consistency check of modelled processes.

Check	A: TiO_2 production		B: Enrich production		Compare A&B
Data source	Literature	OK	Primary	OK	Consistent
Data accuracy	Average data	moderate	Site-specific	Good	Not consistent
Data age	24 years	old	2 years	Recent	Not consistent
Technology coverage	State-of-the-art	OK	Pilot plant	OK	Not consistent
Time-related coverage	Recent	OK	Actual	OK	Consistent
Geographical coverage	Europe	OK	Finland	OK	Consistent

These three evaluation Tables tells that the data used in this case is not the most recent nor fully primary. More accurate and consistent handprint assessment or life cycle assessment can be achieved with up-to-date primary data including all unit processes and life cycle stages. Also knowing the suppliers and supply chain features makes assessments more accurate and complete. If a comparison of products is intended based on handprint assessments, needs to secure the similar system boundaries, restrictions, assumptions and all, therefore a comparison of an alternative competitive product may be difficult because lack of data. From the product development perspective, it is easier to compare the product of an own company during its development steps for example. All in all, data and quality of data is very important in all environmental assessments, and they definitely have an influence of the results and the handprint potential.

6. Results and analysis

Life cycle interpretation phase of an LCA study is for analysis of the result. GaBi software is used for assignment of LCA results based on CML 2001 characterization model and GaBi automatically characterizes category indicator results to potential environmental impact categories, such as abiotic depletion potential (ADP) or acidification potential (AP). Impact categories included in CML 2001 characterization are presented in the following Table 12 per functional unit of manufacturing 1000 kg of pigment product, either TiO_2 or Enrich. These results are used to calculate the handprint potential.

Table 12. Category indicator results per functional unit of 1000 kg of TiO_2 and Enrich product manufactured. Characterization model CML 2001.

Impact categories	Unit	Enrich product	Titanium dioxide
Abiotic depletion, elements (ADPE)	kg Sb eq.	0.0000252	0.138
Abiotic depletion, fossils (ADPF)	MJ	2880	71600
Acidification potential (AP)	kg SO_2 eq.	0.225	17.6
Eutrophication potential (EP)	kg PO_4^{3-} eq.	0.0499	1.13
Freshwater aquatic ecotoxicity (FAETP inf.)	kg DCB eq.	0.886	20.2
Global warming potential (GWP 100)	kg CO_2 eq.	92.6	3394
Human toxicity potential (HTP inf.)	kg DCB eq.	6.81	165
Marine aquatic ecotoxicity (MAETP inf.)	kg DCB eq.	22600	176000
Ozone layer depletion (ODP)	kg R11 eq.	$7.65\text{^}10^{-13}$	$4.68\text{^}10^{-11}$
Photochemical ozone creation (POCP)	kg Ethene eq.	0.0221	1.13
Terrestic ecotoxicity (TETP inf.)	kg DCB eq.	0.517	8.77

From the category indicator results can be noted directly that the Enrich product has a smaller environmental impact in every impact category than titanium dioxide. However, there are uncertainty in these results due to the chosen assumptions, limitations and data availability and quality. Many aspects of handprint assessment have an influence on the handprint results and this handprint assessment case describes only one specific situation in limited context. For example, raw material procurement is not covered comprehensively within the system. However, the raw material procurement may affect the quantity of handprint potential. In addition, the transport distances of required raw materials are not considered. It may affect on results whether the raw material is sourced and transported for example from Africa instead of Europe because the transportation distance increases, and geographical impacts may differ. Another insecurity is the data related to unit processes of energy supply. Manufacturing of pigment products requires energy such as electricity, fuel oil and natural gas. Calculating of the environmental impacts related to energy unit processes is based on the datasets in GaBi. For example, electricity grid mix describes the country specific average electricity production values. More accurate knowledge of energy provider could make a difference to the handprint results if the electricity supplier utilizes only renewable sources to produce electricity such as wind or hydro power. In addition, the LCA results and furthermore the handprint assessment results do not consider the effect of the side stream or by-product handling, recycling, or disposal. So, the whole environmental burden is allocated to the manufacturing of pigments products, however the reality may differ. To summarize, there are many aspects which influences to the results and the handprint potential. The results in this case study describes the environmental impacts under the specific circumstances only.

Potential handprints in this case are illustrated next with the chosen handprint categories, which are water quality handprint, carbon handprint and resource handprint. They describe the potentially reduced amount of emissions to the specific impact category from the paint pigment replacement perspective. Firstly, the water quality handprint potential is demonstrated as a change in the eutrophication potential as an example achieved with the lower eutrophication potential (EP) unit of Enrich product than titanium dioxide. The assumed composition of dry weigh of paint is used here in calculations. There is lack of data in environmental impacts of other ingredients in paints such as polymer binder part of a paint. Therefore, the handprint potentials upcoming next are presented based on the assumed composition of paints with the idea that the influence of polymer binder stays the same in the baseline and the offered solution. Moreover, the portion/weight of pigment is taken into account and the potential replacement rate of Enrich product in the offered solution is calculated. In addition to pigment replacement, it is recognized that Enrich product also have potential to function as a binder to substitute polymer composition of paints. This still requires further investigation and product development, but development around Enrich series can form handprint potential also in other applications.

The following Figure 8 presents the assumed compositions again to remember the basis of this handprint assessment. At the moment, commercially feasible replacement of titanium dioxide in the offered solution is 8 percent of total paint recipe (dry weight) or in other words, 20 percent of titanium dioxide pigment. This is presented in the following Figure 8. Handprint potential of the offered solution may increase if more limestone-based product can be utilized in the future.

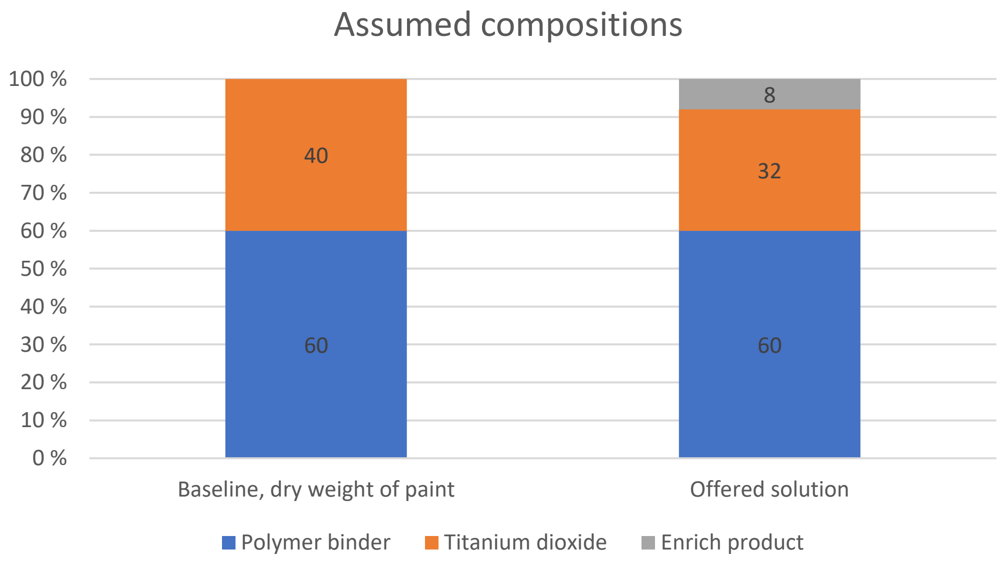


Figure 8. Reminder of the assumed compositions of the baseline and the offered solution (dry weight).

In addition to the assumed composition, cradle-to-gate LCA results from the GaBi models are needed to illustrate the handprint potential of Enrich product in this paint context. The following Figure 9 presents the emissions to water bodies from Enrich production and titanium dioxide production indicated with the phosphates equivalent units per functional unit of 1000 kg pigment manufacturing.

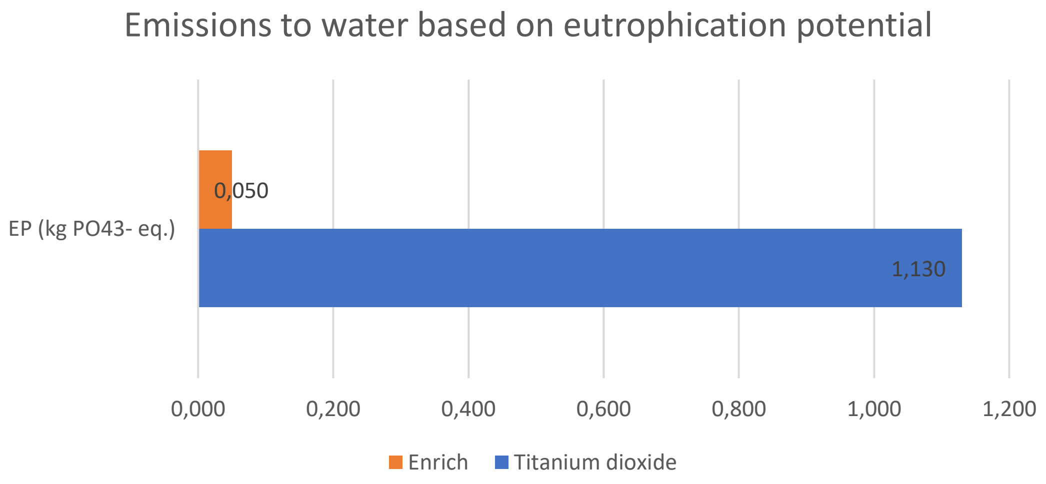


Figure 9. Category indicator results of EP for the water quality handprint assessment presented in kg PO_4^{3-} eq. / 1000 kg of pigment products.

Firstly water quality handprint for the comparable pigments is evaluated based on general eutrophication factor, phoshates equivalent. Baseline is 1.13 kg phosphates equivalent per 1000 kg titanium dioxide pigment, so 400 kg of titanium dioxide affects 0.4*1.13 = 0.45 kg phosphates eq. This is the baseline solution value here. If twenty percent of titanium dioxide is assumed replacement rate with Enrich in pigment portion of paint, it means that pigment portion in a dry weight of paint consists of 80 kg Enrich and 320 kg titanium dioxide. The proportion of polymers in paint recipe remains the same. The eutrophication impact can be then calculated as following equation, when Enrich indicator result is 0.0499 kg phosphates eq. per 1000 kg Enrich product.

=(0.08*0.0499) + (0.32*1.13) = 0.365592 kg phosphates eq. / 400kg of pigment

So the water quality handprint potential indicated by eutrophication impact category is:

0.45 kg – 0.365592 = 0.084408 kg PO_4^{3-} eq. / 400 kg of pigment in the offered solution, which can be presented as percent when calculated:

=(0.084408/0.45)*100 = 18.76 %

Meaning a 18.8 % reduction of the eutrophication potential forming a water quality handprint. Water quality handprint potential of studied solution is presented in the following Figure 10 based on the calculations presented before.

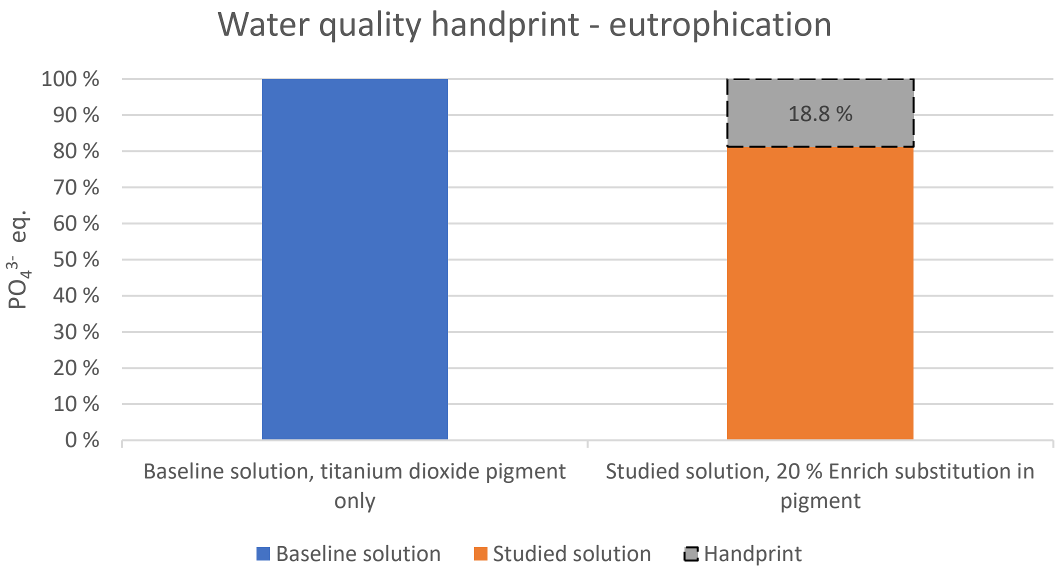


Figure 10. Water quality handprint in terms of the eutrophication potential.

Secondly, carbon handprint potential of the studied solution is determined based on the global warming potential units from the category indicator results. GWP units of Enrich and titanium dioxide are compared same way than in previous water quality handprint part for 400 kg of pigment as a part of dry weight of 1000 kg paint. Polymer portion of paint (600 kg) remains unchanged and has no effect on the results in this study. However, it is noted that Enrich products can have a potential to replace also polymers int the future. The following Figure 11 indicates the carbon handprint potential of the offered solution, which is calculated to be 19.5 %. That reduction is due to lower global warming potential of the Enrich product than titanium dioxide, in manufacturing phase. Carbon handprint potential can be increased with actions such as carbon capture and utilization, which is also also in interest of Nordkalk. Also promoting circular economy and changing to renewable fuels for kilns can have an impact on the potential increase of the carbon handprint potential.

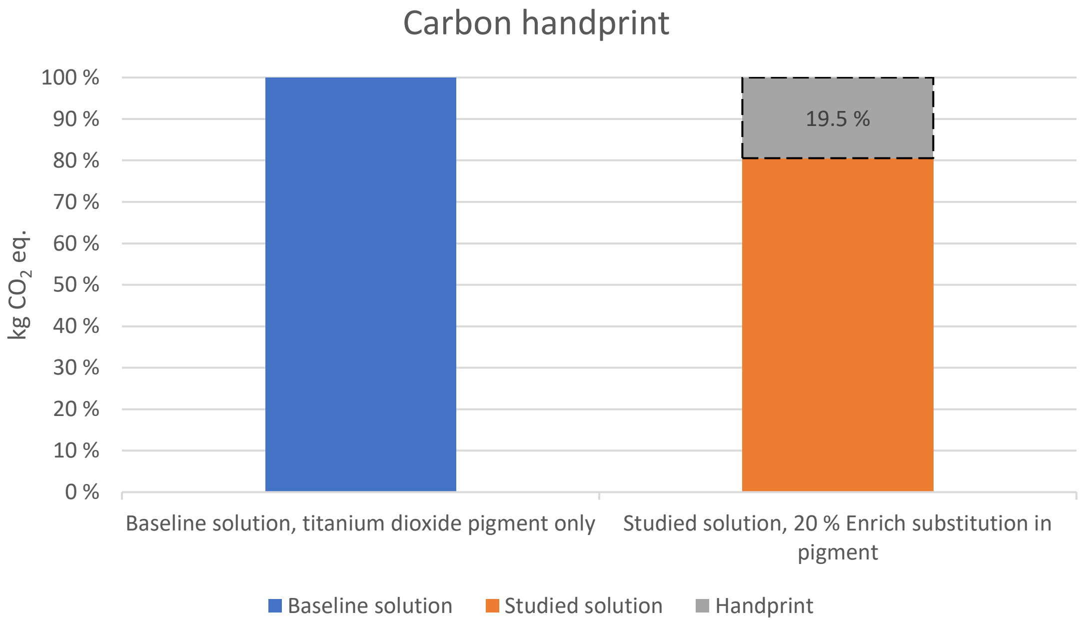


Figure 11. Carbon handprint potential of studied solution.

Lastly, resource use handprint potential is analyzed for the offered solution. Resource use handprint can be divided into two aspects, fossil fuels depletion potential and elements depletion potential. Fossil fuel depletion potential is indicated in megajoules, and resource use handprint potential of the studied solution is 5498 MJ, which means the amount of reduced fossil fuel utilization compared to the baseline solution. The resource use handprint potential, fossil fuel depletion is presented in the following Figure 12.

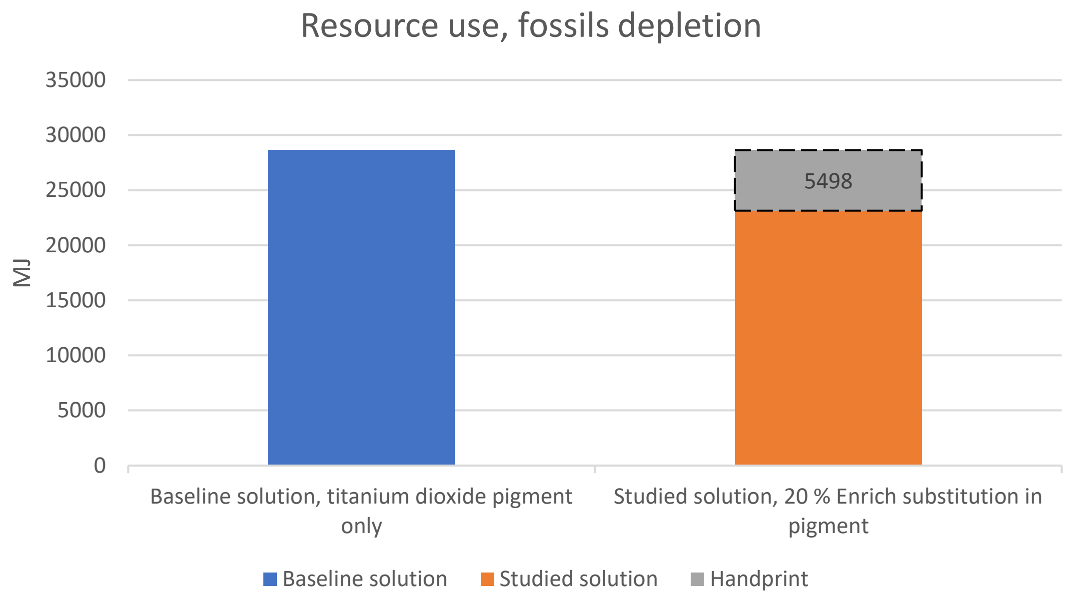


Figure 12. Resource use handprint, fossils fuels depletion.

In addition to fossils fuels depletion, also fewer elements use in product system can be indicated with the handprint assessment. Category indicator result of an abiotic elements depletion is used to indicate the another resource use handprint potential related to elements. As presented in the following Figure 13, the studied solution can achieve also resource use handprint indicated in elements depletion potential.

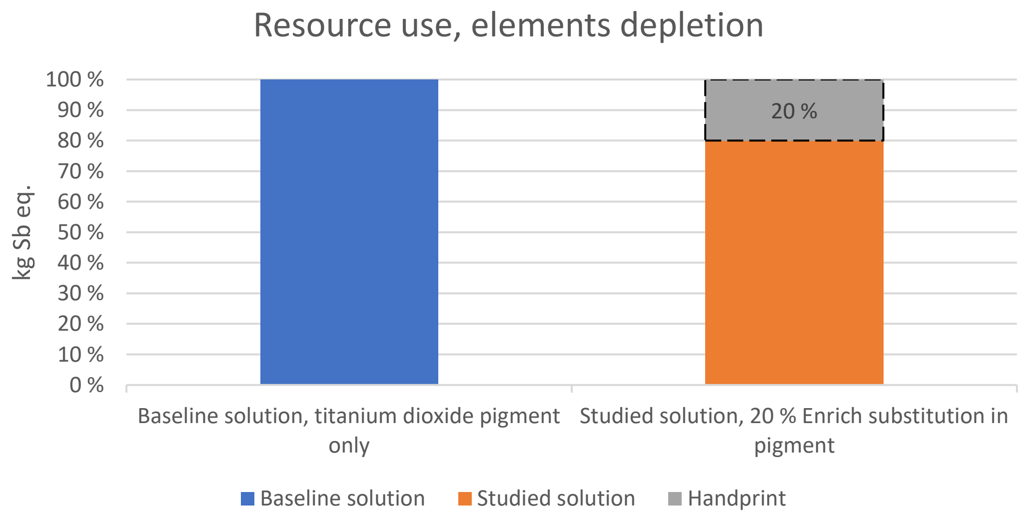


Figure 13. Resource use handprint, elements depletion.

Overall, the replacement share of titanium dioxide with Enrich in assumed paint composition is quite small, so the handprint potentials remain small. If the polymer proportion in paints can also be replaced with limestone-based product someday in the future, it may increase the handprint potential of offered paint solution. The product development plays an important role to get new sustainable limestone-based products to market. However, the manufacturing process of Enrich product is identified to have less burden on the environment than titanium dioxide manufacturing in all impact categories recognized.

7. Conclusions

Overall, the research achieved its objectives reasonably well. The research questions mentioned in the beginning of the study was dealt with and analysed. Potential environmental handprints of Nordkalk's wide range of products were assessed and evaluated versatile. The case proved that utilizing a limestone-based product can result in handprints and decrease the environmental impact of one specific solution. The customers of Nordkalk can achieve emission reductions by utilizing limestone-based solutions. Product development of Nordkalk's limestone-based products can help to increase handprint potentials even more in the future. Mechanisms and handprint contributors of limestone-based products were also discovered, and limestone-based products have many suitable characteristics for many use applications. However, more research is needed to investigate and prove the handprint potentials of other Nordkalk's products. This study researched only one product of the company. It is also good to remember that this handprint assessment conducted for Enrich product needs to be updated when background data changes so handprint assessment results are not valid forever. Usually, it is assumed that handprint's period of validity is only a year or couple of years. Therefore, the handprint assessment for Enrich product needs to be recalculated when some unit process or technology evolve, or energy grid mix values is updated for example. From the product manufacturer perspective, handprint assessment is laborious for this reason as well and requires commitment. As well as offered solutions can develop, so can baselines develop and change. Maximizing the environmental handprint becomes more and more challenging in the future when new actions are required to achieve new emission reduction targets.

Regardless of challenges in handprint assessment, the environmental handprint can be a valuable tool and indicator for companies to achieve competitive advantage and have an incentive effect. Companies utilizing handprint assessment act as an example for others to fight against the climate crisis. Although, handprint assessment is not the only indicator for sustainable actions but a great tool for direct communication to customers to increase the knowledge of company's efforts for sustainability and environment. The factors and mechanisms of limestone-based products contributing the environmental handprint as an alternative in applications were analysed and a quite big potential of limestone-based product was observed. Thanks to limestone-based products' versatility and adaptability they can be utilized in many applications. Increase in handprint potentials generally can be achieved by product development for example. The theoretical contribution of this thesis is valuable to the limestone company.

As a conclusion of this thesis, the subject was quite wide as an environmental handprint concept is. An iterative research process has deepened an understanding of the handprint assessment and its typical features. The handprint potential of a chosen limestone-based product was demonstrated in the case part of the thesis. The case achieved its objectives and the hypothesis analysed for the case part in advance was correct. Regarding the case results, can be said that the limestone-based pigment product can have a potential to form handprints at least in that specific context. However, more handprint assessment needs to be conducted if a handprint potential of some other limestone-based application is desired to analyse. Therefore, a handprint assessment is quite time-consuming for a company and requires lot of data. Comparison of the company's own products during the product development process may be easier than comparing a baseline solution of another company. However, a baseline determination and system boundaries always need careful consideration. In addition, if a company wants to apply the handprint assessment in their sustainability reporting, it requires lot of knowledge and resources, probably more than conducting footprint calculations. Therefore, the handprint assessment may not be the most convenient method for assessment of wide product portfolios. Some other way to indicate and present the good characteristics already existing in limestone-based applications needs further explanation and could be a good research topic in the future.

Handprint is maybe not the best tool or indicator to show the existing benefits of a product or solution. This current handprint methodology wasn't the best way to solve the handprint potentials of Nordkalk's product portfolio, because of many limestone-based products are so standardized part of technologies or processes that it is not easy to define a baseline for them. There is not necessarily a reasonable product or a technology that can deliver the same function than a limestone-based product. In some cases, for example in causticizing and steel processing, a limestone-based product is prerequisite which is hard to replace due to its suitable characteristics. Limestone-based products were also noted to be an integral part in many BAU processes or practices. For the future developments within the handprint concept, a baseline definition guideline could be considered more in the communications and marketing context also. However, the handprint assessment methodology is a great tool for product development needs and for communicating the positive environmental benefits that customers can achieve by choosing the offered solution.

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