Laura Lakanen

DEVELOPING HANDPRINTS TO ENHANCE THE ENVIRONMENTAL PERFORMANCE OF OTHER ACTORS

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Abstract

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Major environmental challenges, such as water scarcity and quality issues, excess use of virgin nutrients, air pollution and global climate change, have given rise to an urgent need to reduce the environmental impacts of production and consumption and to develop and implement actions towards environmental sustainability. Life cycle assessment-based methods are traditionally used to measure the lifetime environmental impacts of products and services and to detect life cycle stages with the highest emission reduction potential. In addition to measuring the adverse impacts of offerings, there is a need to evaluate and compare solutions to determine which among them are the most beneficial to the environment. With regard to greenhouse gases, the carbon handprint approach can be used to evaluate the positive climate impacts of products and services when used by customers. However, the methods focusing on positive contributions in terms of other environmental impacts and in application scopes other than products and services are still scarce.

The main aim of the present study was to develop a handprint method for quantifying and communicating the environmental benefits of products and services in terms of air quality, nutrient use and water use and quality. To this end, the specific requirements of different impact categories were identified. Another objective was to widen the application scope of carbon handprint assessment from the product level to regional consideration as cities and regions have a focal role in climate work. The method was developed based on the principles of life cycle assessment, footprinting and the carbon handprint approach. Additionally, four case studies concerning different environmental and application scopes were conducted.

The results obtained from the present study show that different environmental impact categories have specific requirements when applied to the handprint context. As central issues, the need to recognise suitable and relevant indicators regarding different environmental scopes, acknowledging the origin of emissions in the context of locality and globality of impacts and selecting between the inventory and impact assessment levels should be considered. According to the case studies, handprints are feasible indicators of positive environmental impacts. Thus, this dissertation presents a coherent environmental handprint framework across different environmental scopes and stepwise calculation guidelines.

The environmental handprint approach provides a necessary addition to the existing life cycle methods as it offers a scientific-based means of quantifying and communicating the positive contributions of products, services and regions to the environment. Most importantly, handprints can provide reliable information in different decision-making situations, such as in the business and political contexts, but they can also be used for communication and marketing purposes. In particular, environmental handprints can be used to promote circular economy targets and green transition to sustainable production and consumption patterns. From a regional perspective, handprints can be important drivers of novel sustainable solutions and regional viability and attractiveness.

Keywords: handprint, environmental handprint, regional handprint, footprint, life cycle assessment, environmental sustainability

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Abstract

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Publications

List of publications

This dissertation is based on the following papers. The publishers gave permission to include the papers in the dissertation.

I. Lakanen, L., Grönman, K., Väisänen, S., Kasurinen, H., Soininen, A., and Soukka, R. (2021). Applying the handprint approach to assess the air pollutant reduction potential of paraffinic renewable diesel fuel in the car fleet of the city of Helsinki. *Journal of Cleaner Production*, 290, 125786, doi: 10.1016/j.jclepro.2021.125786.
II. Lakanen, L., Kasurinen, H., Grönman, K., Behm, K., Vatanen, S., Pajula, T., and Soukka, R. (2022). Developing the nitrogen handprint approach to quantify the positive impacts of industrial symbiosis on nitrogen cycles. *Cleaner Environmental Systems*, 6, 100090, doi: 10.1016/j.cesys.2022.100090.
III. Lakanen, L., Grönman, K., Kasurinen, H., Vatanen, S., Pajula, T., Behm, K., and Soukka, R. (2022). Approach for assessing environmental handprints. Conference article. In: Albrecht, S., Fischer, M., Scagnetti, C., Barkmeyer, M., and Braune, A., ed., *E3S Web of Conferences*, 349, 12001, doi: 10.1051/e3sconf/202234912001.
IV. Lakanen, L., Kumpulainen, H., Helppi, O., Grönman, K., and Soukka, R. (2022). Carbon handprint approach for cities and regions: a framework to reveal and assess the potential of cities in climate change mitigation. *Sustainability*, 14, 6534, doi: 10.3390/su14116534.

Authors' contributions

Laura Lakanen is the principal author and investigator in Publications I–IV. Heli Kasurinen had a crucial role in developing the conceptual framework of the case study presented in Publication II. Heli Kasurinen and Katri Behm performed the calculations in the case study presented in Publication III. Laura Lakanen was responsible for writing the Publication II and III manuscripts.

Nomenclature

Symbols

%	Percent

Abbreviations

AEF	Avoided Emissions Framework
aLCA	Attributional life cycle assessment
BAU	Business as usual
cLCA	Consequential life cycle assessment
EC-JRC	European Commission Joint Research Centre
eq	Equivalent
EP	Eutrophication potential
EV	Electric vehicle
GHG	Greenhouse gas
GWP	Global warming potential
HVO	Hydrotreated vegetable oil
ISO	International Organization for Standardization
IU	Intended user
kWh	Kilowatt hour
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LUT	Lappeenranta-Lahti University of Technology
PB	Planetary boundary
RQ	Research question
SDG	Sustainable development goal
SHINE	Sustainability and Health Initiative for NetPositive Enterprise
t	Tonne
UAS	Unintendedly affected subject
UN	United Nations
VTT	Technical Research Centre of Finland
WWT	Wastewater treatment
WWTP	Wastewater treatment plant

Chemical compounds

CO	Carbon monoxide
$Fe_2(SO_4)_3$	Ferric sulphate
N	Nitrogen
NaOH	Sodium hydroxide
NH_3	Ammonia
NMVOCs	Non-methane volatile organic compounds

NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides
O_3	Ozone
P	Phosphorus
Pb	Lead
PO_4^{3-}	Phosphate
PM	Particulate matter
SO_2	Sulphur dioxide

1 Introduction

The world is faced with major environmental challenges, such as climate change, scarcity and depletion of natural resources, air pollution and disturbances in biosphere integrity and biochemical flows, which severely threaten the living conditions on Earth (United Nations [UN] Environment, 2019). The major challenges resulting from human activities have already transgressed the planetary boundaries (PBs), which describe the environmental thresholds within which humanity can safely operate so that the functioning of our planet and its various cycles will not be unduly endangered (Rockström et al., 2009). To date, it has been shown that human-driven activities have exceeded the PBs related to climate change, biodiversity loss, nutrient cycles (N and P), land use and novel entities (Persson et al., 2022; Rockström et al., 2009; Steffen et al., 2015). The current trends of steady population growth, urbanisation and overconsumption will increase the pressure on the Earth system (United Nations, 2018).

Alongside the PBs, the UN (2015a) Sustainable Development Goals (SDGs) set an overall global normative framework for capturing contributions to sustainable development. In addition to aiming at avoiding unsustainable actions in the social, economic and environmental dimensions, SDGs encourage positive contributions to sustainable development. According to the hegemonic definition of sustainable development, it refers to 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (World Commission on Environment and Development, 1987). In addition, sustainability goals are increasingly embedded in companies' operations.

Operating within the PBs requires developing more sustainable ways of producing and consuming (Sala et al., 2016; UN, 2015b). This, in turn, requires a systemic-level assessment of the environmental performance of products, systems and services (Whiteman et al., 2013). Environmental impacts have commonly been assessed using life cycle assessment (LCA)-based methods, which aim to model and estimate the environmental burden and potential harmful impacts on the environment along supply chains (International Organization for Standardization [ISO] 14040, 2006). The identification of life cycle stages with high environmental impacts may help both public and private actors implement interventions focused on key areas to reduce environmental impacts (Bjorn et al., 2020). Among the most used methods, LCA and the LCA-deduced footprint family provide standardised guidelines for evaluating environmental impacts throughout the life cycle (ISO 14040, 2006; ISO 14067, 2018). Combining life cycle thinking with sustainable solutions, such as technological innovations and more eco-efficient production and consumption, can curb the rapid progress of environmental challenges. However, the approaches to and methods for capturing and measuring the positive environmental performance of technologies, systems, products and services are still scarce as the commonly used LCA and footprint methods evaluate only cumulative negative emissions and their potential environmental impacts. Thus, sustainability assessment practices have focused more on being less unsustainable than on actively progressing towards sustainable development through positive actions (Dijkstra-Silva et al., 2022).

In recent years, research has emphasised the need to assess the positive sustainability performance measures of products, services and processes (Biemer et al., 2013; Grönman et al., 2019; Kühnen et al., 2019; Norris, 2015; Norris et al., 2021). Assessing and communicating positive environmental impacts have been shown to be effective in marketing and promoting sustainable consumption and in achieving actual reductions in emissions and negative environmental impacts. Mere reduction of the negative environmental impacts of companies and their offerings does not necessarily lead to a sufficient sustainability outcome, and complementary practices increasing the positive environmental impacts are needed (Kühnen et al., 2022). Moreover, in decision-making, the focus has mainly been on negative impacts and risk evaluation based on average data, which may give misleading results in varying operating environments and conditions. Thus, there is an increasing demand for transparent, specific and reliable information and communication tools about sustainability aspects to support decision-making at different levels.

Despite the recognised demand for assessing and communicating beneficial environmental impacts, the current methods, practices and terms used are inconsistent. However, the concept of handprint thinking has recently been introduced in the scientific literature. The Technical Research Centre of Finland (VTT) and Lappeenranta-Lahti University of Technology LUT's carbon handprint approach, introduced by Grönman et al. (2019) and Pajula et al. (2018), defines handprints as 'beneficial environmental impacts that organisations can achieve and communicate by providing products that reduce the footprints of customers'. Norris et al. (2021) introduced the Sustainability and Health Initiative for NetPositive Enterprise (SHINE) handprint framework, which aims to quantify actor-driven positive changes related to the environmental, economic and social dimensions. The positivity of changes is evaluated by comparing it to a baseline scenario. The environmental handprint developed by Biemer et al. (Biemer et al., 2013; Biemer, 2021) is founded on the concept of the environmental footprint and can be generally defined as 'the good we do for the environment'. Kühnen et al. (2019) embarked on a handprint project with the objective of developing an approach to assessing positive contributions to sustainable development.

Other approaches resembling the handprint concept have also been introduced. For example, the World Resources Institute's (WRI) framework for estimating comparative emissions (Russell, 2019) provides guidelines for assessing both the negative and positive greenhouse gas (GHG) emission impacts of a product or service compared to the situation without the studied product or service. Likewise, Mission Innovation's Avoided Emissions Framework (AEF) enables the identification of companies, system solutions and technologies that have the potential to achieve GHG reductions (avoided emissions) in society (Mission Innovation, 2020).

In addition to robust, science-based methods, mitigating environmental challenges and creating a more sustainable future require multi-actor and multi-level actions (Sathaye et al., 2012). Co-operation between different actors and similar goals promoting sustainable development are also needed (Gupta and Nilsson, 2017), especially to scale up successful novel solutions towards sustainability targets (Lambin et al., 2020). In summary, interdisciplinary and holistic solutions combined with transformative solutions and engaged stakeholders are needed for real change (Voulvoulis and Burgman, 2019).

Among different actors, the role of companies in the mitigation of adverse environmental impacts is crucial (Aagaard et al., 2021). However, the focus of late has been on estimating and decreasing the harmful environmental impacts of production, such as by measuring the carbon footprints of products, and there is a need for novel perspectives (Dijkstra-Silva et al., 2022). In addition to lowering their own environmental burden, companies have the potential to offer products and services whose use by customers can help them make beneficial environmental contributions (Grönman et al., 2019). Consequently, the magnitude of positive environmental impacts has the potential to multiply. On the other hand, customers are increasingly becoming attentive to the environmental aspects of products and services, requiring companies to rethink and develop their strategies and business models throughout the supply chains and product life cycles (Engert et al., 2016; Saeidi et al., 2021). However, to make more sustainable choices, consumers need reliable tools for decision-making as marketing does not usually support development towards sustainability (Trudel, 2019).

In addition to companies, both national and local governments are increasingly seen as crucial actors, especially in strategic climate work. Half of the world's population are living in cities (UN, 2018), and cities account for two-thirds of the global energy consumption and over 70% of the global GHG emissions (International Energy Agency, 2021), making them focal actors in climate work. Cities have implemented various activities to reduce urban emissions and achieve carbon neutrality, mainly by utilising information gathered with city-level GHG inventories and by adopting voluntary frameworks, such as the Covenant of Mayors and C40 Cities (Mi et al., 2019). However, more widespread action is needed to achieve the global climate change mitigation targets. Concentrating only on GHG reductions towards zero emissions will make carbon offsetting inevitable as there will always be emissions at some level. Thus, novel solutions with scale-up potential and reliable verification methods are needed at the regional level.

At the company, regional or consumer levels, indicators communicating comparative beneficial environmental impacts are needed to facilitate decision-making and to promote actions towards real sustainability. In addition to climate change and water scarcity and quality, inefficient nutrient cycles and poor air quality are major challenges that need to be overcome. Sustainable resource use with decreased emissions and environmental impacts throughout the life cycles of offerings, combined with the use of up-to-date methods and novel solutions, can also preserve good living conditions for future generations. To achieve these goals, methods for evaluating positive environmental impacts must urgently be developed.

1.1 Objectives

The objective of the present study was to determine whether a handprint approach can be used to assess the environmental benefits of products or product systems within environmental scopes other than climate impacts. To this end, the environmental scope of handprint assessments was sought to be broadened to include air quality, water use and quality and nutrient use, and a coherent framework for uniformly describing the handprint assessment process across different impact categories was sought to be developed. Another aim of the present study was to broaden the application scope of the carbon handprint from the product or service level to the regional level.

Based on the objectives of the present study, the following research questions (RQs) were formulated:

RQ1. Can the handprint approach be used to quantify environmental benefits?

RQ2. How can a coherent environmental handprint framework be developed across different environmental scopes?

RQ3. How can the carbon handprint approach be applied at the regional level?

RQ1 assumes that the handprint approach can be applied to different environmental scopes to assess the environmental benefits of products. To answer RQ1, there is a need to identify specific requirements related to the impact categories of air quality and nutrient and water use and quality in the context of footprinting and handprinting. It is assumed that the identification and clarification of the carbon handprint framework modification needs will make it possible to develop a coherent framework for assessing handprints in several environmental scopes (RQ2).

RQ3 proposes that the carbon handprint will also be suitable for use in assessing environmental benefits at the regional level. To answer RQ3, there is a need to define the city- or regional-level handprint and to determine how the original carbon handprint approach should be modified to make it applicable at the regional level. Thus, there is a need to investigate the kinds of positive climate impacts that cities and regions can have.

The publications included in this dissertation aim to answer the aforementioned RQs. Table 1.1 shows the relationships between the RQs and the publications.

Table 1.1: Relationships between the research questions and publications

Publication	RQ1	RQ2	RQ3
I	X		
II	X		
III	X	X	
IV			X

1.2 Research process

This dissertation is an article-based dissertation (also referred to as a compilation dissertation) consisting of four peer-reviewed publications and a dissertation summary. Three of the publications (Publications I, II and IV) are published in scientific journals, and one (Publication III) is published in a peer-refereed conference proceedings document. The research process was initiated as part of the Business Finland-funded environmental handprint project carried out by LUT and VTT in 2018–2021. Several Finnish companies provided data and case studies for the project. The aim of the project was to develop an extensive framework for assessing environmental handprints, and the publications included in this dissertation represent only some of the results obtained from the project. However, the research conducted in the project had a considerable effect on the content of this dissertation. Publications II and III were derived directly from the research done in the environmental handprint project. Publication I is based on the research conducted in a parallel company project commissioned by a Finnish fuel company. Publication IV presents the results of the Carbon Handprint for Cities and Regions Project, which was commissioned by the Climate Leadership Coalition and funded by the Helsinki–Uusimaa regional council. The final reports of the projects related to the dissertation are available online (Grönman et al., 2021; Vatanen et al., 2021).

1.3 Research scope

The carbon handprint framework developed by Pajula et al. (2018) and Grönman et al. (2019) allows for the quantification and communication of the beneficial climate impacts of products and product systems. In the present study, the suitability of the handprint approach for air quality, nutrient use and water quality and use was investigated. In addition, the application scope was widened to include cities and regions.

In the environmental handprint project, resource use was added to the environmental scope, and organisations and projects were added to the application scope. However, these were outside the scope of the present study. Figure 1.1 illustrates the environmental and application scopes of the environmental handprint framework and related publications.

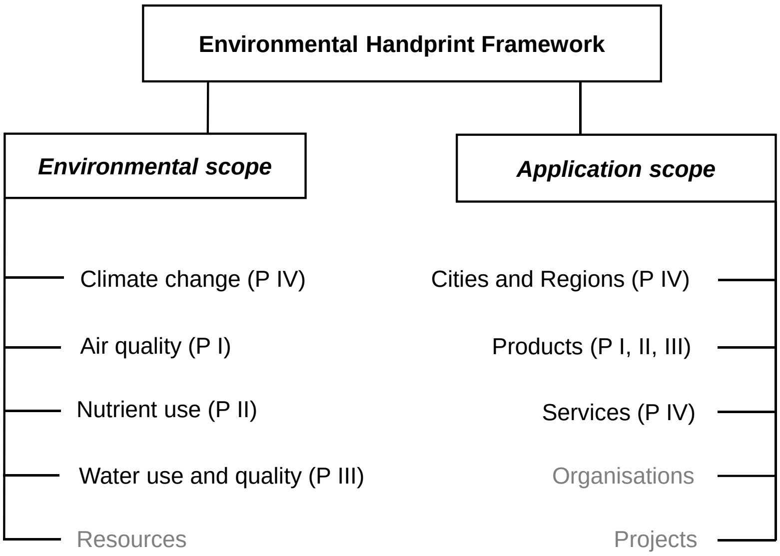

Figure 1.1: Environmental and application scopes of the environmental handprint framework and their relation to the publications included in this dissertation (P). The subareas in black were within the scope of the present study, and those in grey were excluded from the study.

Publication I focuses on the air quality handprint and provides a framework for assessing the beneficial air quality impacts of products and services. Air quality handprint assessment was demonstrated in the case study of paraffinic diesel fuel in a real operation environment. In the case study, the air quality indicators of nitrogen oxides (NO_x) and fine particulate matter ($PM_{2.5}$) were included in the calculations.

Publication II concerns the applicability of the handprint approach in the context of nutrients and introduces a framework for assessing the positive impacts enhancing N cycles (i.e. N handprint). The feasibility of N handprint assessment was tested in the case study concerning recycled nutrient products in industrial symbiosis.

Publication III presents the framework for assessing the air quality, nutrient, water and resource handprints of products, services, organisations and projects. However, in the present study, only previously described environmental and application scopes were included. Publication III also presents a case study of water handprint calculation, in which a novel water purification technology was used in a mining company’s wastewater treatment (WWT).

Publication IV concerns the specific features of regional carbon handprint assessment and provides a framework for assessing and evaluating the climate leadership actions implemented by cities and regions. The handprint assessment approach for cities and regions was applied in the case study involving the city of Espoo.

1.4 Structure of the dissertation

This dissertation consists of six chapters and is structured as discussed below.

Chapter 1 briefly provides the background of the study topic, introduces the objective and research questions, clarifies the scope of the study and describes the research process employed and the structure of the dissertation.

Chapter 2 reviews the recent scientific research relevant to the scope of the dissertation. The objective of the chapter is to present an overall view of the research associated with assessing and communicating positive environmental impacts and with handprint approaches.

Chapter 3 describes the materials and methods that were used in the present study and the case studies that were conducted.

Chapter 4 presents the research contribution of the present study by introducing the main results of the case studies presented in each publication and drawing combined conclusions.

Chapter 5 discusses the theoretical and practical implications of the present study's findings, the study limitations and further research needs.

Chapter 6 summarises the main findings and contributions of the present study.

2 State of the Art

This chapter introduces the background of the present study and the relevant scientific research related to its topic. Assessment of positive environmental impacts is first discussed at a general level, and then handprint thinking and approaches are discussed. Communication of positive environmental impacts is also reviewed.

2.1 Assessment of positive environmental impacts

Environmental impacts refer to any changes in the natural environment that directly result from activities (Abdallah, 2017). Most impacts are adverse, such as GHG emissions from the use of fossil fuels driving climate change or biodiversity losses due to land use changes. Thus, managing environmental impacts over products' and services' life cycles is crucial to preserving the biosphere and human living conditions for the next generations (Pajula et al., 2017). However, according to Bjorn et al. (2020), despite the implemented ecoefficiency actions, the impacts of production and consumption activities remain too high for ensuring operation within safe environmental boundaries. This is due to the steady economic growth. Thus, solely mitigating harmful impacts is not adequate for ensuring the achievement of sustainability goals; proactive enhancement of positive contributions is needed (Bjorn et al., 2020; Di Cesare et al., 2018; Dijkstra-Silva et al., 2022; Kühnen et al., 2022).

The assessment of environmental impacts has traditionally concentrated on capturing only the harmful side and consequently on reducing the detected adverse impacts (Dijkstra-Silva et al., 2022; Sala et al., 2012). However, the urgent need to assess and promote companies', products' and services' positive contributions to sustainable development has been widely acknowledged from the environmental, social and economic perspectives (Grönman et al., 2019; Husgafvel, 2021; Kühnen et al., 2022, 2019; Norris, 2015). Nevertheless, the inclusion of a positive point of view of sustainability still has several challenges. Firstly, according to Dijkstra-Silva et al. (2022), there is no consensus on the definition of 'positive contributions to sustainability', and in many cases, they predominantly refer only to lessening the harm done. Although the reduction of adverse impacts has a significant role in companies' and organisations' sustainability work, making more widespread contributions to sustainability at the local, regional and even planetary levels requires positive actions (Hjalsted et al., 2021; Whiteman et al., 2013). Secondly, the need for robust sustainability performance measurement and assessment approaches has been recognised. Despite the existence and rapid evolution of methods assessing positive impacts, there is no consistent and standardised framework for assessing positive impacts; the existing frameworks are complex and incoherent. Table 2.1 shows examples of different approaches to assessing positive contributions to sustainability from an environmental perspective.

Table 2.1: Approaches to assessing positive environmental impacts

Handprint approaches	Authors	Scope	Applicational scope	Consistent standards
Carbon handprint LUT&VTT	Grönman et al. 2019, Pajula et al. 2018	Climate change	Products and services	ISO 14040-44, ISO 14067
SHINE	Norris et al. 2021	All LCA relevant impact categories	Actions	Partially ISO 14040-44 compliant
Kühnen et al. 2019	Kühnen et al. 2019	37 environmental, economic and social indicators	Products	ISO 14040-44
Avoided emissions frameworks				
Avoided emissions framework (AEF)	Mission Innovation 2020	Climate change	Products, system solutions, companies and cities	GHG Protocol
Comparative emissions	WRI, Russel 2019	Climate change	Products	GHG Protocol

LUT = Lappeenranta-Lahti University of Technology LUT; VTT = Technical Research Centre of Finland; SHINE = Sustainability and Health Initiative for NetPositive Enterprise; WRI = World Resources Institute; LCA = life cycle assessment; ISO = International Organization for Standardization; GHG = greenhouse gas

All the methods and frameworks listed in Table 2.1 aim to indicate beneficial impacts on the environment or on sustainability. However, their perspectives, definitions and calculation guidelines vary. In general, handprint assessments aim to estimate positive impacts in footprint-consistent units. In the present study, three handprint approaches were closely considered: the carbon handprint approach developed by LUT University and VTT (Grönman et al., 2019; Pajula et al., 2018), the handprint framework developed in the SHINE project led by Gregory Norris (Norris, 2015; Norris et al., 2021) and the handprint approach developed in The Collaborating Centre on Sustainable Consumption and Production in Wuppertal and published by Kühnen et al. (2019). These approaches were chosen as they were derived from the most recent studies on the topic and also aim to give guidelines for quantitative handprint assessment.

In handprint approaches, a baseline is needed to justify a positive change. Typically, the footprint of a solution with potential beneficial impacts is compared to that of a baseline solution (Grönman et al., 2019; Norris et al., 2021); thus, baseline selection significantly affects the handprint results. The baseline should be defined from a period representing the current state of an influenced system and that is long enough to include the variations in an operating environment. Although the handprint is calculated for a product, service or solution, the credits are given to the solution provider or to the actor implementing the actions.

Regarding the scopes of the approaches, the carbon handprint approach by LUT University and VTT concentrates on the impact category of climate change (Grönman et al., 2019), whereas the SHINE method and the handprint approach by Kühnen et al. include several indicators (Kühnen et al., 2019; Norris et al., 2021). Handprint approaches mainly follow the principles of LCA, with specific additions and minor differences, such as those concerning the functional unit and system boundary setting (Grönman et al., 2019; Norris et al., 2021). There are other important differences related to setting a baseline and allocating a handprint to the different actors involved. The features of the selected handprint approaches are discussed in greater detail in section 2.3.

The concept of avoided emissions closely resembles handprint thinking. Avoided emissions frameworks are suggested, for example, by Mission Innovation (2020) and WRI in their respective working papers (Russell, 2019). According to Mission Innovation (2020), avoided emissions describe whether a solution (product or service) enables the same function to be performed with significantly less emissions than in a business-as-usual (BAU) scenario. The main purpose of the framework is to provide a method for assessing and comparing the current and potential impacts of novel solutions to GHG emission reduction and thus promote a way to a net zero development path. The working paper for estimating and communicating comparative emissions (Russell, 2019) presents a framework for estimating the GHG emission impacts of products or services compared to situations where such products or services do not exist. The differences in GHG impacts may be negative or positive, and positive differences are referred to as avoided emissions. However, rather than giving detailed calculation guidelines, the framework seeks to address central generic issues when assessing the comparative impacts of products, especially at companies.

Both approaches concerning the assessment of avoided emissions use the guidelines given in the GHG Protocol and are suitable only for assessing climate impacts (Mission Innovation, 2020; Russell, 2019). The AEF by Mission Innovation (2020) enables assessment of avoided GHG emissions of products/solutions, system solutions and companies. The framework by WRI provides guidelines for the study of products' comparative GHG emissions (Russell, 2019).

2.2 Handprint thinking

The core idea of handprint thinking is to encourage the implementation of actions with positive impacts. The term 'handprint' was introduced in 2007 by the United Nations Educational, Scientific and Cultural Organization as a measure for Education for Sustainable Development action to decrease the human footprint (Handprint Actions towards Sustainability, n.d.). Since then, handprints have emerged from several independent quarters in response to footprint approaches (Biemer et al., 2013; Grönman et al., 2019; Kühnen et al., 2019; Norris, 2015). However, to avoid confusion in terminology, handprint thinking should be separated from handprint assessments. Whereas handprint thinking provides an uncontroversial, conceptual basis for all handprint-related work, handprint assessment frameworks vary greatly in their definitions, contents and guidelines (Guillaume et al., 2020).

Guillaume et al. (2020) proposed three main principles of handprinting. Firstly, the main aim of handprints is to encourage actions with positive impacts. This can be done in several ways, such as by providing indicators to identify improvement potential or positive impact evaluation or by providing tools to support decision-making. Secondly, handprint thinking is closely linked to consideration of footprint reductions or other negative measures, but adding value to them. Footprints and handprints often use the same impact indicators and, in some cases, have the same notions of indirect impacts. Added value due to handprints may be created, such as by using positive impact indicators, utilising relative points of view in assessments or acknowledging systemic levels to achieve widespread positive impacts. Thirdly, handprint thinking aims to point out future potential rather than measure only realised actions and results. The importance of considering alternative decisions and potential improvement actions leading to differences in analysis, consequences and results has also been highlighted by Lahtinen et al. (2017).

2.3 Classification of handprints

Due to the rapid evolution of handprints over the past years, the methods, practices and terms used are inconsistent (Guillaume et al., 2020). Consistent classification and terminology will promote the evolution, use and communication of handprints (Alvarenga et al., 2020). Alvarenga et al. (2020) suggested a framework for classifying handprints intended to be used in LCA and life cycle sustainability assessment studies. The classification, based on attributional LCA, was the first attempt to categorise handprints uniformly.

Alvarenga et al. (2020) categorised handprints into three main types: direct, indirect and relative handprints. These can be further divided into subcategories. The direct handprint refers to a product's possible (absolute) positive impacts for its intended users (IUs). Absolute positive impacts may arise due to the product's functional properties or intervention flows. The direct handprint can be communicated when the product's beneficial impacts are higher than its adverse impacts (Alvarenga et al., 2020). Previous studies on the direct handprint are presented, such as those by Saarinen et al. (2017) and Stylianou et al. (2016), related to the benefits achieved with a certain diet.

The indirect handprint refers to a product's possible (absolute) positive impacts for subjects other than its IUs (unintendedly affected subjects [UASs]), and its mechanisms are similar to those of the direct handprint (Alvarenga et al., 2020). A footprint-consistent indirect handprint approach was used, for instance, by Pini et al. (2017) to assess coating materials in buildings to generate a benefit for terrestrial acidification.

The relative handprint refers to a product's possible (relative) positive impacts for its IUs or UASs compared to a baseline product due to the product's improved functionality and/or intervention flows. Apart from the results of traditional comparative life cycle sustainability assessment studies focusing on downstream products with potential upstream benefits, the relative handprint describes benefits for downstream customers due to a final application (Alvarenga et al., 2020). The handprint assessment for renewable diesel by Grönman et al. (2019) represents a relative approach to handprinting.

2.4 Handprint approaches

In this chapter, three handprint approaches are introduced in greater detail: the carbon handprint approach by LUT University and VTT (Grönman et al., 2019; Pajula et al., 2018), the SHINE handprint framework (Norris, 2015; Norris et al., 2021) and the handprint approach by Kühnen et al. (2019). AEF is also introduced.

2.4.1 Carbon handprint approach by Lappeenranta-Lahti University of Technology LUT and Technical Research Centre of Finland

Carbon handprint is an LCA-based approach that enables the assessment of a product's or product system's beneficial climate impacts compared to the BAU scenario or baseline solution (Grönman et al., 2019; Pajula et al., 2018). According to Pajula et al. (2018), a product's carbon handprint can be quantified by comparing the carbon footprints of baseline and handprint solutions when used by customers. However, the key principle is that reducing only one's own footprint is not a handprint; instead, the carbon footprint of a defined customer should be reduced due to the studied handprint solution because, based on LCA, carbon handprint assessment is conducted throughout the whole life cycle of the studied system (i.e. from cradle to grave). Another fundamental issue is setting a reasonable baseline for comparison, which significantly affects the results. As an LCA-based metric, the handprint assessment framework comprises the typical LCA phases, with some additional steps. The stages and steps of carbon handprint assessment are considered more closely in section 3.3.

Carbon handprints can be created in different life cycle stages of handprint products or services, as shown in Figure 2.1 (Pajula et al., 2018). The handprint solution may have lower emissions in cradle-to-gate processes, such as through reduced material consumption in manufacturing (Figure 2.1, handprint solution A), or it may achieve GHG emission reductions in gate-to-grave processes, such as through energy efficiency (Figure 2.1, handprint solution B). There can also be two different ways to achieve a handprint in the same handprint solution. Increases in carbon footprints in either the cradle-to-gate or gate-to-grave processes are allowed as long as the total carbon footprint of a handprint solution is lower than that of the baseline (Grönman et al., 2019).

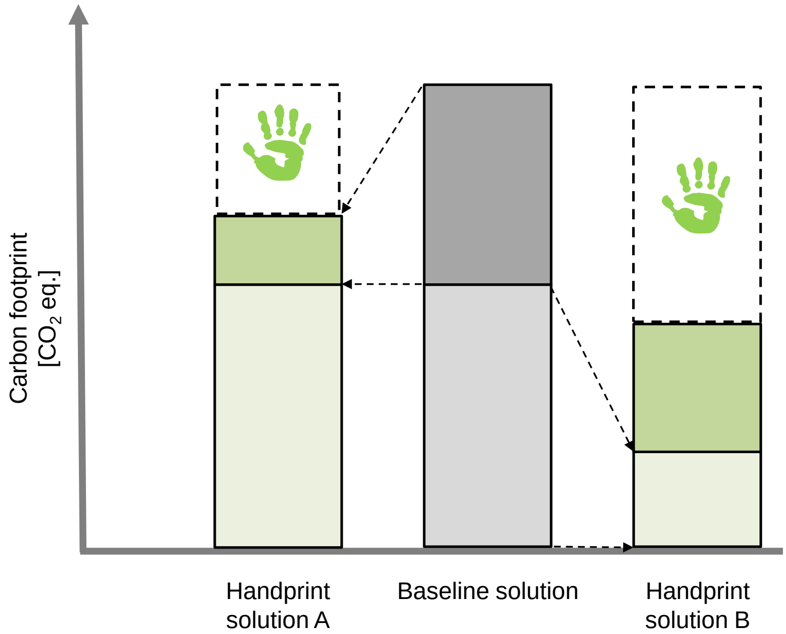

Figure 2.1: The two main mechanisms for handprint creation. The upper parts of the pillars with solid lines show the carbon footprints of cradle-to-gate processes, and the lower parts show the carbon footprints of gate-to-grave processes (reproduced from Pajula et al., 2018).

Carbon handprints provide information about positive climate impacts by communicating a customer's carbon footprint reduction compared to the baseline situation. This information can be used for marketing and communication purposes, especially for potential customers of a handprint solution. In addition to marketing and communication purposes, a carbon handprint is a useful tool for identifying the improvement potential across the life cycles of products and services from a climate perspective. Companies should simultaneously aim to reduce their products' carbon footprints and maximise handprints. However, it is important to note that a footprint can never be subtracted from a handprint. The carbon handprint can also be utilised for decision-making as it provides reliable information for comparisons. The typical target groups for communications are consumers and companies, but there are other potential audiences, such as other organisations, industries, political decision-makers and communities.

2.4.2 Sustainability and Health Initiative for NetPositive Enterprise handprint

SHINE provides a framework for assessing positive environmental, social and economic changes called handprints (Norris, 2015; Norris et al., 2021). Its core idea is to quantify the positive actions and changes caused by an actor and to compare them to those in the BAU scenario in footprint-related metrics. As stated by Norris et al. (2021), the SHINE handprint is dynamic, which means that an action's possible impacts are measured in comparison to a scenario without the specified action (i.e. the BAU scenario). Handprints can be created within and outside the scope of the actor's footprint by achieving footprint reductions for the actor itself (internal handprint) or by achieving reductions in some other actors' footprints when compared to BAU (external handprint). The total handprint of an actor can be calculated as the sum of the internal and external handprints. In addition to handprints, SHINE proposes the concept of net positivity, which can be achieved by doing more good than harm (Norris et al., 2021).

SHINE utilises dynamic LCA-based modelling and includes the four main phases of LCA: goal and scope definition, inventory analysis, impact assessment and interpretation of results (Norris et al., 2021). The first phase has the most differences from the ISO LCA method, such as in terms of scoping, system boundary setting and functional unit. In terms of scope, that of SHINE includes actors (e.g. companies, institutions, organisations, individuals) instead of products. In terms of system boundaries, unlike in the typical product-focused LCA, in the SHINE approach, the system boundaries are expanded beyond the scope of the actor's footprint because the aim is to acknowledge the wider influences of actions, including the ripple effects. The most noticeable difference concerns the functional unit; in the SHINE footprint and handprint assessment, no functional unit is needed as the comparison is performed between two different scenarios: with and without a specified positive action. (Norris et al., 2021.)

In the inventory analysis phase, data regarding all input and output flows related to a BAU scenario and a positive change are gathered. In the impact assessment phase, handprints are quantified by evaluating the environmental, social and economic impacts in the same units as footprints with the existing life cycle inventory (LCI) databases. In the last phase, the results are interpreted, but the net positivity of an actor may also be assessed. This can be done by comparing the magnitude of an actor's footprint with that of the actor's handprint for each studied impact category with similar temporal boundaries. Consequently, an actor may become net positive when its handprint is higher than its footprint in the studied time frame. (Norris et al., 2021.) Thus, the SHINE handprint approach allows for subtracting the footprint, for example, of an organisation, from its handprint to achieve net positivity.

The main purposes of the SHINE method are to provide a framework for assessing and quantifying positive changes and to encourage actors to implement actions with positive impacts. This may further help reduce adverse environmental and social impacts. (Norris et al., 2021.)

2.4.3 The handprint approach by Kühnen et al.

Kühnen et al. (2019) introduced a handprint approach for assessing businesses' positive contributions to the attainment of the SDGs. The aim of the framework is to widen the perspective from concentrating only on the reduction of negative and unsustainable business practices to covering actions striving to promote beneficial contributions to sustainable development. The approach is based on environmental LCA and is in line with ISO 14040 (2006) and 14044 (2006), hence following the typical steps of LCA, but with the SDGs integrated into it. Additionally, the handprint framework utilises fuzzy set theory to consider the verbal fuzziness of the SDGs for companies and their products in the evaluation (Kühnen et al., 2019). The framework suggests prioritised handprint indicators allocated for the social, environmental, economic, governance and institutional areas and relates them to relevant SDGs. The approach is aimed at companies and is applicable to different sectors, from local to global operations (Kühnen et al., 2019).

Similar to LCA, handprint calculation includes goal and scope definition, data inventory, evaluation and interpretation phases (Kühnen et al., 2019). In the first phase, the objective of the assessment and the studied product are described, and the functional unit and system boundaries are defined. Handprint indicators are also selected from the suggested indicator pool and prioritised, and suitable UN SDGs are selected to set the reference point from a normative perspective. The main purpose of the indicators is to reflect contributions to different SDGs at the fuzzy level, in accordance with fuzzy set theory, rather than acting as precise indicators. In the second phase, data from all the life cycle stages of the studied product are gathered, in line with the principles of LCA. In the third phase, the potential positive contribution of the studied product to sustainable development is evaluated, and the fuzziness of the SDGs at the organisational and product levels is addressed by applying a fuzzy set approach. In the fourth and final phase, the handprint results are interpreted. The required sensitivity analyses and critical review are also conducted, and recommendations for further actions to increase the positive contribution to the SDGs are given. However, as the method is still under further development and the authors are calling for more case studies, some method specifications are needed. (Kühnen et al., 2019.)

2.4.4 Avoided Emissions Framework

AEF provides guidelines for measuring, assessing and comparing the impacts of innovations that lead to GHG emission reduction, hence contributing to a net zero development path (Mission Innovation, 2020). In general, the avoided emissions concept aims to communicate whether a product or service enables the same function to be performed with less GHG emissions. As the assessment is based on comparison, the lifetime GHG emissions of the enabling solution are compared to those of a baseline scenario (i.e. a scenario without the enabling solution) or the BAU scenario. The method is applicable to products and solutions, system solutions and companies and is closely linked to the GHG Protocol. The main purpose of the framework is to provide a method for assessing and comparing both the current and potential impacts of novel solutions to help reduce GHG emissions and thus promote a way to a net zero development path. However, in communications, avoided emissions should be clearly reported separately as they are not allowed to be subtracted from the company’s own emissions. (Mission Innovation, 2020.)

The AEF framework provides guidelines for calculating or quantifying avoided emissions (i.e. carbon abatement), which are caused by the ‘enabling effect’ of a technology or solution (Mission Innovation, 2020). To assess system-level GHG emission reduction, the emissions from four different categories need to be calculated: those from the BAU scenario (without the enabling solution), the avoided emissions due to the use of the enabling solution, the direct life cycle emissions of the enabling solution and the rebound effect, which refers to the increase in BAU emissions as a result of the enabling solution implementation (Figure 2.2). After the calculation of the different categories, the net avoided emissions can be derived by deducting the direct solution emissions and rebound emissions from the enabling avoided emissions. Alternatively, net avoided emissions can be defined in relation to the BAU scenario, by deducting the emissions of the solution-enabled scenario from those of the BAU baseline scenario (Mission Innovation, 2020).

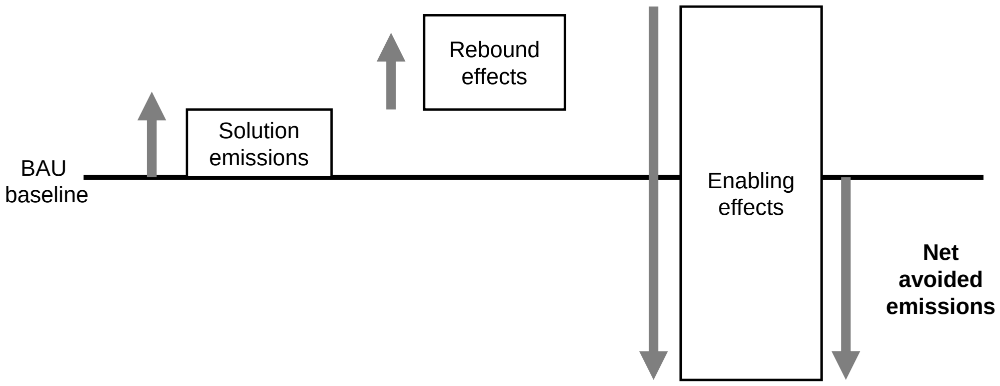

Figure 2.2: Calculation of net avoided emissions (Mission Innovation, 2020).

The net avoided emissions of each individual enabling solution are calculated by determining the carbon abatement factor, which describes the net avoided emissions per unit of the solution implemented (Mission Innovation, 2020). In calculations defining the system boundaries, the functional unit and life cycle perspectives are used in line with LCA studies.

2.5 Communication of positive environmental impacts

The public awareness of environmental challenges has increased the pressure on companies to better communicate their environmental performance and provide more sustainable offerings (Dangelico and Vocalelli, 2017; Gelderman et al., 2021; Zhang et al., 2018). Reliable and understandable information is also needed to support environmentally friendly consumer decisions because, aside from the reduction of their impacts, consumers’ choices put pressure on businesses and governments to follow the same path (Testa et al., 2020). On the other hand, marketing environmentally sustainable products is necessary to enable their spread in the market (Dangelico and Vocalelli, 2017; Rex and Baumann, 2007). However, the integration of environmental sustainability into marketing, also referred to as green marketing, has some challenges (Dangelico and Vocalelli, 2017; de Freitas Netto et al., 2020) and may lead to greenwashing, in which companies mislead consumers about their environmental performance or the environmental benefits of their offerings (Delmas and Burbano, 2011). This is often seen as a challenge, especially for marketing focused on positive environmental impacts (Russell, 2019). In businesses and industries, positive aspects are preferred as they can be used effectively in marketing; thus, maximising positive results can be more important than reducing the impacts of negative aspects (Croes and Vermeulen, 2021; Di Cesare et al., 2018).

Communicating environmental benefits and avoiding greenwashing in consumer communication require the use of robust, harmonised and science-based indicators by companies. Transparency, external verification and inclusion of the whole life cycles and supply chains of products and services may further help prevent both intentionally and unintentionally misleading marketing (Szabo and Webster, 2021). The carbon handprint approach aims to provide such a communication tool for both marketing and decision-making purposes (Grönman et al., 2019). However, harmonised and generally accepted methods for assessing and communicating positive impacts with wider applications are needed.

3 Materials, Methods and Case Descriptions

This chapter describes the research process and methods used in the development of the environmental handprint framework. As LCA provided an important basis for the work in the present study, the LCA method and LCA-derived carbon, nutrient and water footprint approaches are presented in detail herein, along with the carbon handprint framework. Towards the end of this chapter, the method aspects, assumptions and data of each publication are presented.

To develop a comprehensive and practically feasible framework for assessing positive impacts at different levels, a multi-method approach (Morse, 2003; Spratt et al., 2004) was used. In such an approach, different methods are combined in the same study of a single, specified research paradigm, and various quantitative and qualitative approaches to data collection, analysis and interpretation can be used together (Spratt et al., 2004). Consequently, a multi-method approach enables wider consideration than a single approach. Additionally, more comprehensive results can be achieved as the strengths of different approaches can be utilised and the weaknesses can be outlined (Spratt et al., 2004). The stages of multi-method research are shown in Figure 3.1.

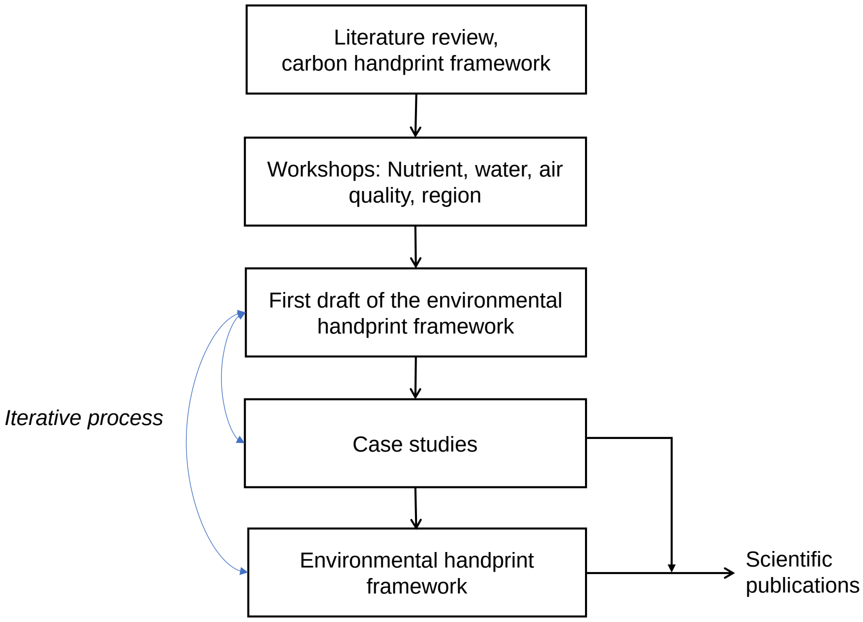

Figure 3.1: Research process.

The research process started with a review of the scientific literature concerning the assessment of positive environmental impacts, footprinting, handprinting and specific characteristics of relevant environmental impacts. Existing standards and frameworks were also scrutinised. The reviewed literature is described in this dissertation and in

Publications I–IV. Another significant starting point for the research was the carbon handprint approach introduced by Pajula et al. (2018) and Grönman et al. (2019), which is closely linked to LCA and carbon footprinting. The literature review was followed by discussions with company representatives from various industrial fields to map companies' needs for and practices regarding the assessment and communication of beneficial environmental impacts. Four workshops were organised, each focusing on a different environmental or application scope of the present study. The first two steps of the method enabled the first draft of the environmental handprint framework to be outlined. To test and further develop the framework, several case studies representing the environmental and application scopes of the present study were conducted. Bilateral discussions of the data derived from the company stakeholders were held to paint a comprehensive picture of the cases. The case studies provided important information on the framework's deficiencies and development needs; thus, their results were used iteratively to modify the framework. As the outcome, scientific publications creating bases for this dissertation were published.

3.1 Life cycle assessment

LCA is a method that can be used to evaluate the potential environmental impacts of product systems throughout their life cycles (ISO 14040, 2006). It is widely used when seeking opportunities to improve products' environmental performance and identifying environmentally critical life cycle points. In companies, governments and other organisations, LCA can be utilised for decision-making and marketing, and the results may facilitate the identification of relevant indicators that can be used for assessing products' environmental performance. LCA has been standardised by ISO in ISO 14040 (2006), which defines the principles and framework of LCA, and ISO 14044 (2006), which defines the requirements and guidelines. According to ISO 14040, LCA consists of four main phases: goal and scope definition, inventory analysis, impact assessment and interpretation of results (ISO 14040, 2006), as presented in Figure 3.2 with LCA application examples.

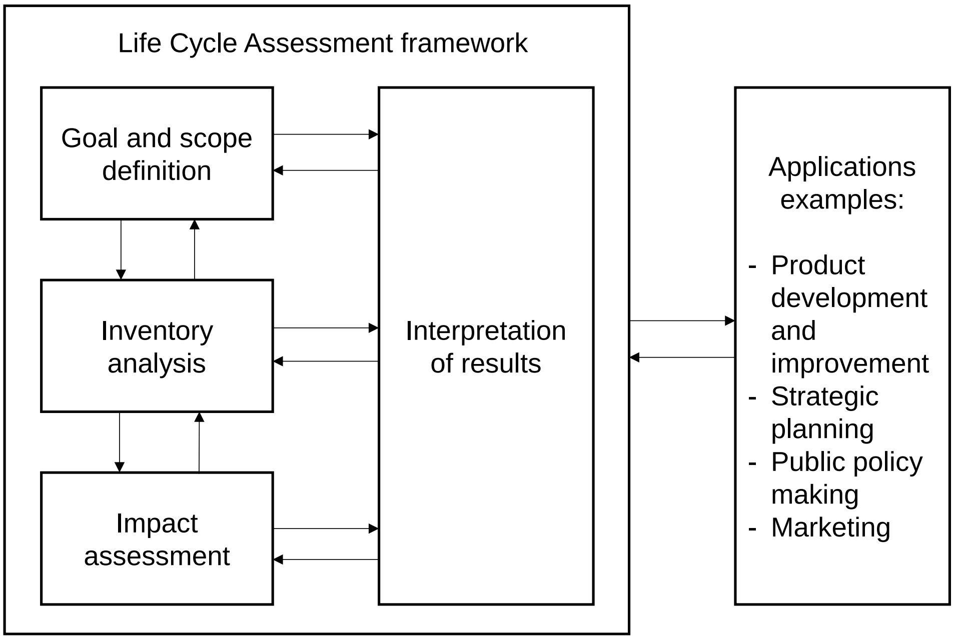

Figure 3.2: Main phases and direct applications of life cycle assessment (ISO 14040, 2006).

In the first phase of LCA, the goal and scope of the assessment are defined. The aim is to identify the purpose of the assessment and the details needed to carry out the calculation for the studied product or product system. According to ISO 14040 (2006), goal definition should describe why the assessment is to be conducted, what the intended application is, which target groups the results are aimed at and whether the results are intended to be used in public comparative assertions. Defining a scope determines the details needed for the assessment, including a description of all relevant issues to enable an accurate assessment. With regard to a studied product or product system, the function, system boundaries, potential allocation procedures, assumptions, limitations and requirements related to data gathering and quality are described. The relevant environmental impact categories are identified, and the method to be used for impact assessment are described. To ensure reliability, the type of critical review to be used and how to report the results are considered. Accurate and sufficient goal and scope definition creates the basis for reliable LCA. However, due to the iterative nature of LCA, the defined aspects of the scope can be specified later to meet the described goal (ISO 14040, 2006).

In LCA studies, the potential environmental impacts are studied in relation to the functional unit of a product system. The functional unit describes the ‘quantified performance of a product system for use as a reference’ (ISO 14044, 2006) and allows the comparison of two different systems by providing a measurable and accurate quantity based on the performance of the studied solution at the use phase. The system boundaries define the unit processes that must be included in the LCA and are often presented using process flow diagrams (ISO 14044, 2006). According to the main principle of LCA, all the life cycle stages of the studied product shall be included (cradle-to-grave approach). Sometimes, it may be reasonable to evaluate limited system boundaries, such as cradle-to-gate or gate-to-gate studies, through LCA, but these studies cannot be considered real LCA or LCI studies (ISO 14040, 2006).

LCI analysis is the second phase of LCA (ISO 14040, 2006). It involves data collection and inventory building of the relevant inputs and outputs of the product system being studied according to the defined goal and scope. Data can be collected from various sources and may comprise primary and secondary data from manufacturers, literature sources or calculations or estimates (ISO 14044, 2006). Data are collected for a defined system from each unit process in every life cycle phase, and they can be categorised as energy inputs, raw material inputs, ancillary inputs or other physical inputs, products, co-products, wastes and emissions to air, water, soil and other environmental aspects (ISO 14044, 2006). As the data collection progresses, new data needs may arise, and limitations may appear, requiring changes in the data-gathering procedure. Sometimes, revisions to the previously defined goal and scope may also need to be considered.

The third phase, referred to as life cycle impact assessment (LCIA), relates the LCI results to the potential environmental impacts in relation to the functional unit of the assessment (ISO 14040, 2006). Inventory data are generally associated with specific environmental impact categories and category indicators to provide information for the interpretation phase of LCA. To comprehensively conduct LCIA, three mandatory elements should be included: (1) selection of relevant impact categories, category indicators and characterisation models; (2) classification of the LCI results into selected impact categories and (3) calculation (characterisation) of the category indicator results (ISO 14040, 2006). In addition, optional elements, such as normalisation, grouping, weighting of results and analysis of data quality, can be included (ISO 14044, 2006).

In the LCIA phase, environmental impacts are characterised at the midpoint or endpoint level (ISO 14040, 2006). Midpoint impact categories focus on certain environmental problems, such as climate change and acidification, whereas endpoint indicators describe the final impacts of environmental problems on the three areas of protection: human health, natural environment and natural resources (EC-JRC, 2010). In LCA studies, the selected category indicators should comprise all the environmental issues that are relevant to the studied product system or the study's defined goals. The International Reference Life Cycle Data System handbook for LCA studies (EC-JRC, 2010) recommends that at least the following midpoint impact categories be included in LCA studies: climate change, stratospheric ozone depletion, human toxicity, respiratory inorganics, ionising radiation, ground-level photochemical ozone formation, acidification (land and water), eutrophication (land and water), ecotoxicity, land use and resource depletion (minerals, fossil and renewable energy resources, water). The midpoint and endpoint impact categories and their relationships are shown in Figure 3.3.

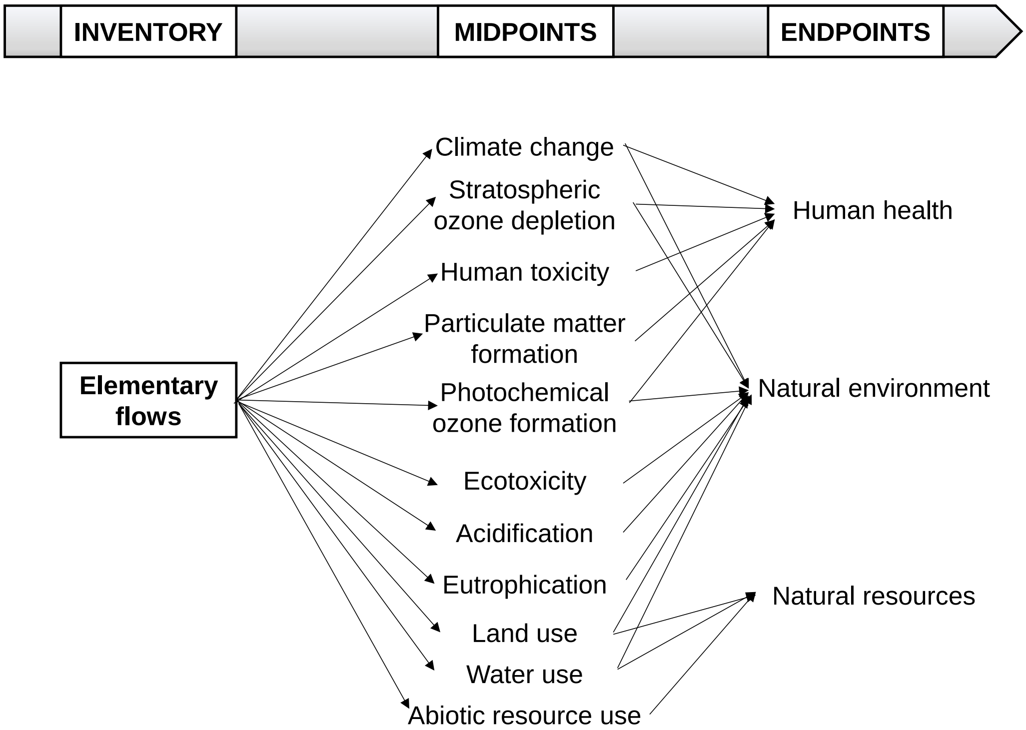

Figure 3.3: The midpoint and endpoint impact categories and their relationships, modified from EC-JRC (2010).

The final phase of LCA is interpretation, which presents the results of the inventory analysis and impact assessment phases in terms of the goal and scope of the study (ISO 14040, 2006). Moreover, the completeness, sensitivity and consistency should be evaluated, and the conclusions, limitations and recommendations should be included (ISO 14044, 2006).

There are two main types of LCA: attributional and consequential. Attributional LCA (aLCA) aims to describe all environmentally relevant input and output flows related to the life cycle of the studied product or product system and its subsystems. Consequential LCA (cLCA), on the other hand, aims to show the changes in environmentally relevant flows due to the possible decisions to be made (Finnveden et al., 2009). In addition to different purposes, the choice between the models affects the choice of method to use in LCA, such as in terms of input data and system boundaries (Ekvall, 2020). Setting the study's aim is also affected as the approaches answer different questions. While aLCA determines the studied object's share of the global environmental burden, cLCA determines how the studied object affects the global environmental burden. Thus, contrary to aLCA, cLCA can also include beneficial environmental impacts and indirect consequences outside the studied object's life cycle (Ekvall, 2020). As cLCA can reveal system-wide changes in emissions and impacts, it is recommended for use in decision-making contexts (Russell, 2019). However, it is unclear which of the two LCA types should be used in certain cases.

3.2 Footprinting

The term ‘footprint’ describes the lifetime environmental impacts of the studied products, systems, services, organisations or regions and is generally accepted and used by various actors to evaluate the environmental burden of different environmental aspects (Hoekstra and Wiedmann, 2014; ISO 14067, 2018). This chapter introduces the carbon, nutrient and water footprints as they create the bases for the corresponding handprint assessments.

3.2.1 Carbon footprint

Measuring and managing GHG emissions across value chains is essential in climate change mitigation. The carbon footprint can be used to quantify the lifetime GHG emissions and reductions of products and services expressed as CO_2 equivalents. Several protocols, including Publicly Available Specification 2050 (PAS 2050, 2011), GHG Protocol Product Standard (WRI/WBCSD, 2011) and ISO 14067 Carbon Footprint of Products (ISO 14067, 2018), have been developed for carbon footprint calculation. In addition, there are available guidelines for assessing the carbon footprints of organisations, projects and cities (GHG Protocol, 2022). In the present study, the ISO standards for carbon footprinting were used as bases for carbon handprint calculations.

The ISO 14040 family provides consistent guidelines for quantifying, monitoring, reporting and validating GHG emissions and removals (ISO 14067, 2018). ISO 14067 (2018) introduces more specific principles, requirements and guidelines for the quantification of products’ carbon footprints. Carbon footprint calculation strictly follows the principles of LCA but includes only one impact category in the LCIA phase: climate change. Thus, all the four main phases of LCA (goal and scope definition, LCI, LCIA and life cycle interpretation) are included in carbon footprint studies (ISO 14067, 2018).

3.2.2 Nutrient footprint

Nutrients are needed in large quantities in food production and industries (Kahiluoto et al., 2014; Sutton et al., 2013). However, due to human interaction, nutrient cycles have been disrupted, leading to various environmental impacts, such as in terrestrial and aquatic ecosystems (Galloway et al., 2014; Rockström et al., 2009; Steffen et al., 2015). Several methods have been developed to understand nutrient flows and their environmental impacts and to identify the nutrient use hotspots across the value chain (Erisman et al., 2018; Leach et al., 2012; Noll et al., 2020; Sutton et al., 2013; Uwizeye et al., 2016). However, due to the non-generalisable nature of different nutrients, the present study focused on the N nutrient and the methods suitable for assessing its flows. As the methods and indicators are numerous and serve different purposes, in the present study, the LCA-based nutrient footprint approach introduced by Grönman et al. (2016) was selected as the basis for N handprint development.

The nutrient footprint is a resource efficiency indicator that aims to invent nutrient flows and the nutrient balance of a system by taking into account both nutrient intake and nutrient use efficiency (Grönman et al., 2016). This method is suitable for assessing the N or P balances of food chains and other bio-based production chains. The approach includes the entire life cycle of the studied production chain, but unlike traditional LCA, the assessment is limited to the inventory level (Grönman et al., 2016). However, in addition to the amounts of nutrients, the nutrient footprint also acknowledges the quality of nutrient flows.

The nutrient footprint approach takes into account the virgin and recycled input nutrients and the nutrients lost from and still part of the nutrient cycle (Grönman et al., 2016). Input nutrients are separated into virgin and recycled ones because the major target in nutrient use reduction is virgin nutrients. According to Grönman et al. (2016), virgin nutrients refer to nutrients extracted from natural resources and converted to reactive forms for human use. On the other hand, recycled nutrients are already in human use. Nutrient losses to the environment may occur in several ways, such as through emissions to air or water or in a product's end-of-life phase, via incineration, landfilling or other use practices that prevent further utilisation of nutrients. The main purpose of the nutrient footprint method is to assess nutrient use across the studied value chains and to show the nutrient hotspots for further improvement steps (Grönman et al., 2016).

3.2.3 Water footprint

The growing freshwater demand, challenges in water scarcity and degradation of water quality at the local, regional, national and global levels have increased the need for a better understanding of water-related sustainability aspects. The water footprint concept was first presented by Hoekstra and Hung (2002); thereafter, water footprint methods were developed to cover different aspects and scopes of water-related issues. To date, there are two existing methods for assessing water footprints: one by the Water Footprint Network (Hoekstra et al., 2011) and the other proposed by the LCA community (Bayart et al., 2010). In the present study, the LCA-based water footprint method was utilised to ensure coherence.

Potential environmental impacts related to water can be estimated with the LCA-based water footprint assessment method described in ISO 14046 (2014) 'Environmental management—Water footprint—Principles, requirements and guidelines' and 14073 (2017) 'Environmental management—Water footprint—Illustrative examples on how to apply ISO 14046'. According to ISO 14046 (2014), a water footprint can be defined as a 'metric that quantifies the potential environmental impacts related to water' and 'identifies quantity of water use and changes in water quality'. Comprehensive water footprint assessment should consider all the relevant attributes connected to the natural environment, human health and resources, with a view to identifying potential trade-offs between attributes.

Similar to the LCA procedure described in ISO 14044 (2006), water footprint calculation includes all the life cycle stages of the studied product system, process or organisation. Water footprint assessment begins with the goal and scope definition phase, followed by the water footprint inventory analysis, impact assessment and results interpretation phases (ISO 14046, 2014). The impact assessment phase may include the assessment of one or several impact categories related to different environmental mechanism categories. When a water footprint study is limited to covering only certain impact categories, a qualifier should be used to specify the studied impacts (ISO 14046, 2014). For example, 'water scarcity footprint' should be used for water quantity, and 'water eutrophication footprint' should be used for eutrophication impact. To present a comprehensive water footprint profile of the studied system, process or organisation, all the relevant water-related impacts should be included (e.g. water use, eutrophication, acidification, freshwater toxicity), and the study can be called a water footprint study even with no specified qualifier (ISO 14046, 2014). The water footprint profile may also be aggregated into a single parameter, with weighting according to ISO 14044 (2006).

In the impact assessment phase, the results of LCIA are converted to the common unit of the category indicator with characterisation factors derived from characterisation models (ISO 14046, 2014). However, ISO 14046 does not specify the methods or characterisation factors that should be used for the assessment; thus, the selection of environmental impact categories and characterisation factors is done according to the potential environmental impacts due to the change in water scarcity level or quality caused by the studied system. As water-related environmental impacts are often local in character, site-specific conditions should be considered in characterisation (ISO 14046, 2016).

3.3 Carbon handprint framework

The main method that was used in the present study was the carbon handprint approach presented by Pajula et al. (2018) and further applied by Grönman et al. (2019). Carbon handprint calculation is guided by a step-by-step framework comprising four stages and 10 steps. The four main stages are (1) identification of the operating environment, (2) definition of the LCA requirements, (3) quantification of the carbon handprint and (4) communication. The carbon handprint framework is presented in Figure 3.4. The stages and steps are elaborated on in the following paragraphs.

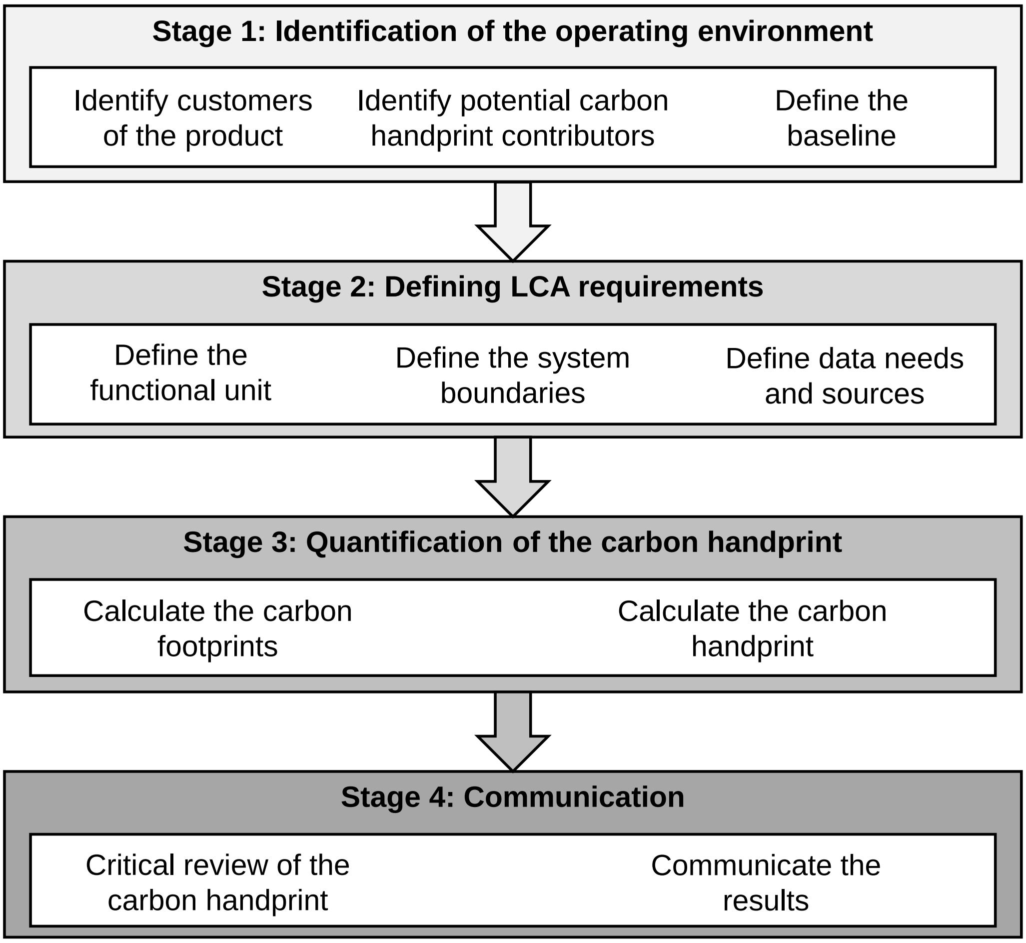

Figure 3.4: Stages and steps of the carbon handprint framework (modified from Pajula et al., 2018).

The first stage of the carbon handprint approach (identification of the operating environment) comprises three steps: identification of the product's customers, identification of the handprint contributors and definition of the baseline (Pajula et al., 2018).

In the first step, the potential users (i.e. customers) of the studied product are identified (Pajula et al., 2018). Carbon handprint is defined as the reduction of a customer's carbon footprint; thus, the recognition of the specific users is crucial. However, the studied product may have several uses, and its environmental impact may vary due to different users and geographical locations. Consequently, a number of potential customers should be identified and differentiated, although only one needs to be selected for closer examination in a handprint study (Pajula et al., 2018).

In the second step, the potential handprint contributors are identified (Pajula et al., 2018). The aim is to recognise the hypothetical climate benefits of the product and to understand how the product will reduce a customer's carbon footprint (Grönman et al., 2019). The identification of handprint contributors may be challenging, and a preliminary consideration of the potential factors contributing to carbon footprints through rough data and modelling may be required (Pajula et al., 2018). Hypothesis formulation creates a basis for the subsequent steps of setting a baseline and system boundaries and should thus be done carefully.

The third step (setting a baseline for comparison) is one of the most important steps in carbon handprint assessment as it has a major impact on the handprint results (Pajula et al., 2018). In a carbon handprint study, a carbon footprint is compared to that of a baseline solution, referring to a product that has the same function as the studied handprint solution (Pajula et al., 2018). Additionally, it should have the same use purpose for a customer as the handprint solution, and the temporal and geographical markets should be similar. With regard to the data quality, representativeness, system boundaries and assumptions, both the baseline and handprint solutions should be assessed uniformly (Pajula et al., 2018).

The second stage of the carbon handprint approach defines the LCA requirements and is built on the principles of ISO standards on LCA and carbon footprinting in accordance with ISO 14040 (2006), 14044 (2006) and 14067 (2018) (Pajula et al., 2018). At this stage, the functional unit, system boundaries and data needs and sources are described. A functional unit is needed for comparing two systems as it provides a reference point for relating the GHG emissions of the handprint solution. As a product may have several functions, a functional unit must be determined based on the defined customer (Grönman et al., 2019).

System boundaries are set according to the study's goal and defined customers, and they should be similar in both the baseline and handprint solutions (Pajula et al., 2018). The system boundaries should be well founded and, ideally, modelled so that the inputs and outputs at the boundaries would be elementary flows (i.e. illustrate the flows from the environment and released into the environment). All unit processes from cradle to grave should be included, in line with the principles of LCA. The exclusion of life cycle stages, processes, inputs or outputs within the studied system is allowed when it will not significantly affect the overall results and is transparently communicated. Likewise, in cases where the life cycles of the compared solutions include identical life cycle stages that remain unchanged, these life cycle stages can be excluded from the study. However, the use stage should always be included as it forms the basis for handprint assessments (Pajula et al., 2018).

After the definition of the functional unit and system boundaries, the data needs are identified and data are collected (Pajula et al., 2018). Primary and/or secondary data from various sources can be used. Principally, when the customer of the studied product can be specified, the most recent primary data must be used. In cases where the customer cannot be named, statistical or average data can be relied upon. It is recommended that data be collected through one calendar year, and it must be representative with regard to the geographical, temporal and technological coverage and must be precise and complete, as stated in ISO 14044 (2006).

Stage three of the carbon handprint approach involves the quantification of the carbon handprint (Pajula et al., 2018). To calculate the carbon handprint, the carbon footprints of the baseline and handprint solutions are quantified using equal functional units and the standardised method of calculating products' carbon footprints, ISO 14067 (2018). Consequently, the carbon handprint can be calculated as the difference between the derived footprints in $kgCO_2eq$. Generally, when the carbon footprint of a handprint solution is lower than that of a baseline solution, a carbon handprint is created (Pajula et al., 2018). It must be kept in mind that the carbon handprint is always assessed for named customers in specified circumstances and time frames and cannot be generalised for other situations (Grönman et al., 2019).

In the fourth stage of the carbon handprint approach, a critical review is conducted, and the results are communicated (Pajula et al., 2018). The aim of the critical review is to verify the handprint calculation process and its results. A critical review is recommended to be conducted in all handprint studies, but especially when the results are used in business-to-consumer communication and when a product from another organisation is used as a point of comparison (Pajula et al., 2018). These requirements are in line with ISO 14040-44 and 14026 (2017).

According to ISO 14026 (2017) and 14063 (2020), the results of handprint studies must be communicated based on the principles of appropriateness, clarity, credibility and transparency. Communications must include at least the following necessary points: the quantity and reference unit of the calculated handprint, the year the used data pertains to and descriptions of the customer, baseline scenario and major handprint contributors (Pajula et al., 2018). Information regarding how additional information will be provided to interested parties (contact information) must also be provided given. More detailed guidelines for communications are provided in the Carbon Handprint Guide (Pajula et al., 2018).

3.4 Workshops

Four workshops were organised to provide background information and to obtain the companies' viewpoints for the method development. All the relevant research and company partners of the project related to the topic of the workshop were invited to the workshops, and external experts from research organisations were also asked to join. The research partners who participated in the workshops included representatives from research institutes, Finnish companies, city and regional councils and non-profit organisations. The participant organisation types and number of participants in each workshop are summarised in Table 3.1.

Table 3.1: Participant organisations and number of participants in each workshop (WS)

Participant organisation	Number of participants in WS 1	Number of participants in WS 2	Number of participants in WS 3	Number of participants in WS 4
Research institute or consultant	2	1	1	1
Company	4	5	8	-
City and region representatives	-	-	-	13
Non-profit organisations	-	-	-	3
Organising research group	5	6	7	5
Total	**11**	**12**	**16**	**22**

Every workshop concentrated on one element in the environmental or application scope of the environmental handprint framework under development. The topics of the workshops were as follows:

Workshop 1: Air quality handprint
Workshop 2: Water handprint
Workshop 3: Nutrient handprint
Workshop 4: Regional handprint

All the workshops had similar structures consisting of introductory lectures by experts on the topics in question and an interactive workshop comprising discussions and considerations of case studies.

Workshop 1 contributed to Publication I. The aims of the workshop were to identify the indicators that must be included in air quality handprint assessment, discuss air quality handprint contributors and obtain an overall picture of the air quality handprint from companies and other stakeholders. To begin, two introductory lectures on the air quality impacts of traffic and the impact of air quality on human health were delivered by experts from external research institutes. Additionally, the carbon handprint framework was briefly reviewed to ensure that the participants would have a basic understanding of the topic. Thereafter, a workshop with discussions was held to clarify critical issues regarding the scope and goal of air quality handprint assessment. Two main questions were considered:

(1) Which indicators should be included in air quality handprint assessment? (Scope)

(2) What is a feasible point for examining air quality handprints (inventory level, midpoint or endpoint methods)? (Goal)

In the third phase of the workshop, issues regarding goal and scope definition were discussed, and other relevant aspects were applied to the four case examples to obtain further insights.

Workshop 2 contributed to Publication III. The aim of the workshop was to discuss and recognise relevant issues in the development of the water handprint approach. The carbon handprint approach and the reason for the necessity of the water handprint approach were first introduced. Then, two introductory presentations concerning water responsibility and water footprint methods were delivered. Finally, an interactive workshop was held to examine the water handprints of the case examples.

Workshop 3 contributed to Publication II and considered the aspects of nutrient handprint assessment. The aim was to find out what kinds of nutrient footprint methods should be utilised in nutrient handprint assessment and how companies prefer to communicate beneficial impacts on nutrient cycles. Handprint assessment in general was first discussed, followed by the reasons for the necessity of the nutrient handprint approach and its challenges in nutrient use. In the workshops, four major questions were considered: What are the main issues to be communicated with regard to the nutrient handprint? Which sub-areas of nutrient footprint are necessary to include in handprint assessment? What is the communication unit of nutrient handprints? What are the most important aspects related to the nutrient handprint from the point of view of companies?

Workshop 4 contributed to Publication IV. The aims of the workshop were to identify the demand for a carbon approach and to recognise handprint contributors in cities and regions. The main questions that were sought to be answered in the workshop were as follows: How can cities produce handprints? What are the main purposes of regional handprints? What sectors are the most important for GHG reduction?

3.5 Literature review

A scientific literature review was conducted to understand the state of the art in the field of assessment of positive impacts. A literature review refers to a systematic collection and synthesis of previous research on a certain topic and acts as a foundation for building and relating ongoing research on that topic (Snyder, 2019; Tranfield et al., 2003). When conducted well, a literature review can provide a basis for advancing knowledge and facilitating theory development (Webster and Watson, 2002). In addition, a literature review may inspire new ideas and directions in a particular field and pave the way for understanding research gaps and future research needs (Snyder, 2019). The results of the literature review in the present study provided an overview of the different methods that had been developed to assess positive contributions to the environment at the product, company and city levels, but also shed light on the specific features of different environmental impacts relevant to method development.

3.6 Case studies

Four case studies related to different elements in the environmental and application scopes of the environmental handprint framework were conducted to support the development of the framework. These case studies are presented in Figure 3.5.

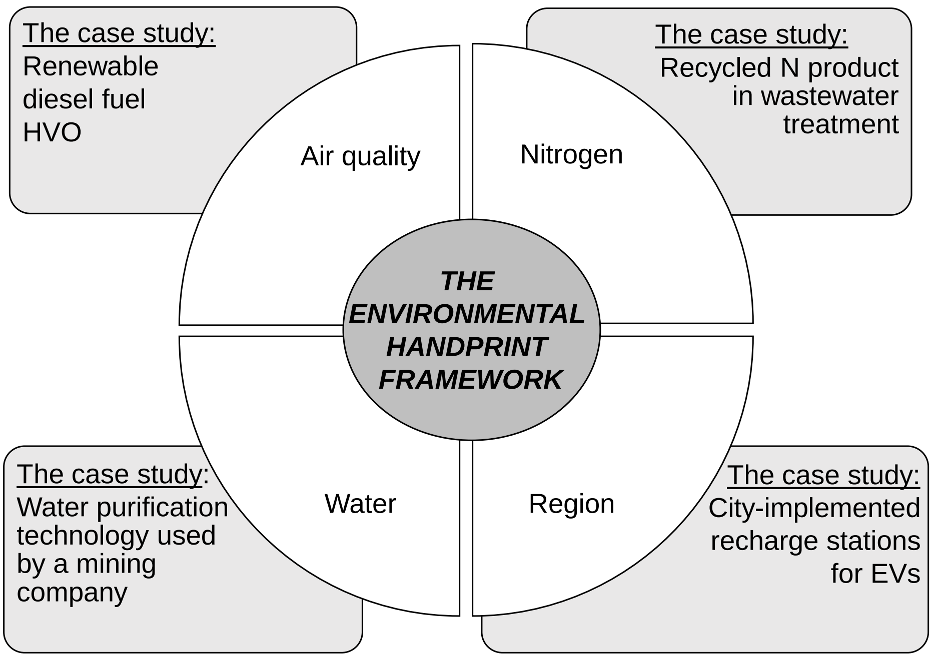

Figure 3.5: The case studies conducted in the present study and their relationships with the different elements in the environmental and application scopes of the research. HVO = hydrotreated vegetable oil; N = nitrogen; EV = electric vehicle

3.6.1 Air quality handprint

The applicability of the carbon handprint approach to air quality is the focus of Publication I. As a first step in the case study presented in the publication, the specific characteristics and requirements for the air quality impact category were identified to recognise the carbon handprint framework's modification needs according to the existing literature. Subsequently, modifications were applied to the original carbon handprint framework developed by Grönman et al. (2019). Secondly, a case study quantifying the potential air quality handprint of paraffinic renewable diesel (hydrotreated vegetable oil [HVO]) was conducted according to a previously modified handprint framework for air quality (Publication I, Figure 1). As the case study calculation provided information on the weaknesses and deficiencies of the newly developed air quality handprint framework, further improvements were made iteratively to the air quality handprint assessment guidelines.

In addition to developing the air quality handprint method, the aim of the case study was to determine whether using HVO in passenger diesel cars could reduce the NO_x and $PM_{2.5}$ exhaust gas emissions in Helsinki, and if so, by how much. The achieved reduction would then be considered a handprint for HVO manufacturers. The air quality handprint assessment was done by quantifying the lifetime NO_x and $PM_{2.5}$ emissions from HVO and the baseline diesel. According to the carbon handprint guidelines, the handprint is calculated as the difference between footprints (Grönman et al., 2019). In the case of air quality, inventory-level data were used to quantify the lifetime NO_x and $PM_{2.5}$ footprints for the baseline diesel and HVO. Subsequently, the obtained results were compared to each other when any reduction in air pollutant emissions due to HVO use resulted in an air quality handprint.

In the case study, the solution offered was HVO, a paraffinic renewable diesel fuel with zero aromatics that meets the requirements of the EN 15940 standard. Conventional diesel containing 7% biocomponents, in this case fatty acid methyl ester, was used as the baseline. In the carbon handprint approach, customer identification is focal (Grönman et al., 2019). In Publication I, the city of Helsinki, located in Finland, was used as the customer. The functional unit that was used in the study was kilometres covered by the defined diesel-powered passenger vehicle fleet in the Helsinki area in 2018. According to the principles of LCA, the examination included the entire well-to-wheel life cycle of the studied fuels. The emissions from the raw material of HVO (vegetable cooking oil) were excluded as the raw material was assumed to be waste.

The data for the case study were gathered from various sources (Table 3.2). The most recent representative data (2018 data) were used. Well-to-tank data for conventional diesel were derived from the LCA modelling software GaBi's database (Sphera, 2019), and for HVO, from the manufacturer. The tank-to-wheel emissions of both fuels were measured under laboratory conditions using the Worldwide Harmonized Light Vehicles Test Cycles at 7°C and 23°C for Euro 3, 4 and 5 cars. The emissions occurring between these temperatures were estimated via interpolation. The local temperature data were taken from the Finnish Meteorological Institute's (2018) Kaisaniemi measurement point in Helsinki. The actual mileage in 2018 was used to calculate the consumption of diesel fuel (Helsingin Kaupunki, 2018). The actual car fleet in the study area was derived from the Finnish Transport and Communications Agency (Traficom, 2019).

Table 3.2: Data sources in the case study presented in Publication I

Data		Source
Well-to-tank NO_x and $PM_{2.5}$ emissions		
	Baseline diesel	Literature (life cycle software database)
	Hydrotreated vegetable oil (HVO)	Manufacturer
Tank to wheel No_x and $PM_{2.5}$ emissions		Measured
Temperature		Measured (Finnish Meteorological Institute)
Mileage		Measured (City of Helsinki)
Car fleet		Statistics (Finnish Transport and Communications Agency)

3.6.2 Nitrogen handprint

Publication II focuses on developing the nutrient handprint approach from the N point of view. To modify the original carbon handprint framework to make it suitable for the N context, the specific nutrient requirements were reviewed in the literature, especially with regard to the suitable indicators. Additionally, criteria and preconditions for N handprint creation were formulated. To calculate the N footprints for handprint quantification, the nutrient footprint approach presented in section 3.2.2 was used as a starting point. As defined by Grönman et al. (2016), the nutrient footprint of a production chain is composed of virgin and recycled nutrient inputs and the outputs lost from and still part of the nutrient cycle. To add the environmental impact dimension to the assessment, the impact category of eutrophication potential (EP) was also included as it was identified as relevant in the context of nutrient flows.

A suggested framework for N handprint assessment (Publication II, Figure 1) was demonstrated with a case study of recycled N in an industrial symbiosis between a pulp and paper mill wastewater treatment plant (WWTP) and a biogas plant. In the case study, a recycled N product (ammonia water) derived from biogas production replaced virgin N in the pulp and paper mill WWTP, hence leading to a potential N handprint. In accordance with the novel N handprint framework, mandatory indicators of N balance and EP were included in the N handprint calculations, and global warming potential (GWP) was identified as a relevant optional indicator because urea production through the Haber–Bosch process is highly energy-intensive (Sutton et al., 2013). The EPs for the baseline and offered solutions were calculated using the CML2001 EP characterisation factors because the assumption was that both marine water and freshwater may be affected. Nevertheless, local EP characterisation factors should be used when available as eutrophication impacts depend on the local conditions and characteristics of the recipient water body (Henryson et al., 2018). Carbon footprint calculations were conducted using a CML2001 GWP100-year impact analysis method with the LCA modelling software GaBi and its database (Sphera, 2019).

In the case study, the offered solution was ammonia water, an N-rich recycled nutrient product made from digestate formed in biogas production. Regarding handprint contributors, it was assumed that the biogas producer would reduce the N footprint of a pulp and paper mill by providing recycled N for WWT instead of virgin urea. A pulp and paper mill was identified as the beneficiary in the case study as it uses supplementary N in its WWTP. The use of virgin urea in the WWTP was determined to be the baseline, and the daily quantity of wastewater treated in the WWTP (94,846 m^3) was determined to be the functional unit in the study. Both the biogas plant and the pulp and paper mill are located in southern Finland.

The system boundaries of the case study are presented in Figure 3.6. The N balance for footprint calculations was studied from cradle to grave for ammonia water and urea. However, the calculations related to ammonia water did not include biogas production because the digestate from the biogas process was identified as waste. Either N input in the wastewater from the pulp and paper mill processes was included because the N input was the same in both solutions. EP and GWP were calculated from cradle to gate as the customer processes were assumed to be similar in the baseline and offered solutions. Emissions from transportation were taken into account in the EP and GWP calculations, but not in the N balance calculations. It was assumed that urea was transported from Central Europe, which means distances of 1,300 km by ship and 100 km by truck. The transportation distance for ammonia water was assumed to be 100 km by truck.

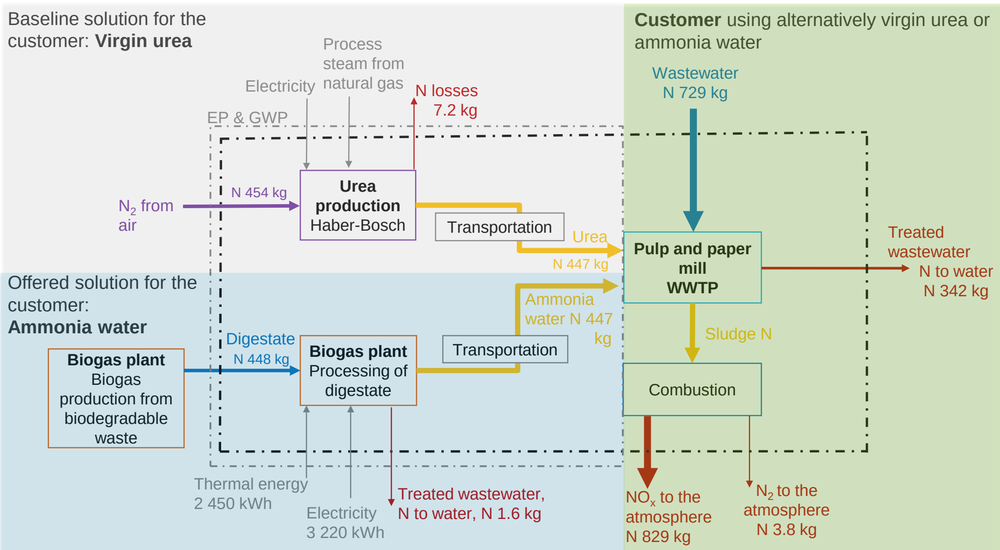

Figure 3.6: System boundaries of the case study in Publication II. Blue text and lines = recycled N inputs; purple = virgin N inputs; red = N outputs lost from the nutrient cycle; green = N outputs still part of the nutrient cycle; orange = intermediate N flows; grey = energy inputs; black dashed line = system boundaries in the N footprint assessment; grey dashed line = system boundaries for the eutrophication potential and global warming potential calculations. N masses and energy consumption are expressed per functional unit (reproduced from Publication II).

In biogas production, nutrient-rich digestate can be further processed through centrifuging, evaporation and stripping to ammonia water, NP concentrate and N containing dry matter. In the GWP calculation, the energy consumption of the digestate processing was allocated to the different N-containing fractions based on their N masses. Otherwise, NP concentrate and dry matter were excluded from the calculations. With regard to the other assumptions, the N content of biogas was assumed to be zero, and ammonia water was used in a 1:1 relationship in the WWTP to replace urea. Due to the complexity of the different forms and conversion processes of nitrogen, all the N was considered the same to simplify the calculations.

The data for the case study comprised primary and secondary data. The companies operating the biogas plant and the pulp and paper mill provided primary data for N flows and energy consumption for 2017–2020 and 2017–2019, respectively. For urea production, secondary data from the GaBi database for 2018–2020 were used (Sphera, 2019).

3.6.3 Water handprint

Publication III's content was divided as follows. Firstly, the framework for assessing environmental handprints across different impact categories is presented. The introduced framework pulls together all the studied environmental impact categories within the scope of the present study and thus aims to respond to RQ2. The presented framework is strictly based on the carbon handprint framework, with additional steps identified during the development of the work. As the framework is a compilation of Publications I–III, the method's aspects are addressed across chapter 3.

Secondly, Publication III demonstrates water handprint calculation with the case study of the novel water purification technology used in a mining company's water treatment plant. Similar to the other handprint assessments in the present study, water handprint calculations are based on footprint assessments, and in the context of water, the water footprint principles and guidelines described in ISO 14046 (2014) and 14073 (2017) apply. As stated in ISO 14046, water footprint assessment should include both the water quantity (scarcity) and quality aspects. Thus, both elements were also included in the case study.

The case study investigated whether a novel water purification technology would reduce the water scarcity footprint and improve the water quality (in terms of eutrophication) of a mining company located in northern Finland. In the baseline situation (without the use of a purification technology), water from the mining operations is directed to wetlands for biological treatment. To ensure sufficient removal of nutrients and impurities, large wetland areas are needed, but an additional challenge is that the purification potential is also largely dependent on the season and the outside temperature. Water purification technology, referred to herein as an offered solution, aims to remove solid matter, dissolved minerals and N compounds from mining wastewater before it is released to the wetlands, hence reducing the emissions to the receiving water bodies. As an example, a water quality handprint was demonstrated as a change in the EP achieved with the N removal technology. Other environmental impacts were excluded, although the comprehensive water quality footprint assessment should include all relevant compounds and impacts. Aside from water quality improvement, technology use also enables the recycling of wastewater through enrichment processes, thus decreasing the need for primary water intake and overall water consumption. The change between the baseline and offered solutions in water use was considered in the water quantity (scarcity) handprint assessment. Handprints were calculated as the difference between the water quality and quantity footprints.

In the case study, the beneficiary was identified as a mining company located in northern Finland. As a functional unit, the yearly quantity of extracted mining products without enrichment was used as a functional unit. It was assumed that no purification method other than wetlands was used in the baseline solution. The water handprint framework for the case study is presented in Publication III (Figure 3).

In the water scarcity handprint calculation, the data for the water streams of the mining operations and the amounts of water treatment chemicals used per year were collected from the mining company's environmental permit document. For one month, the chemicals were used in the following amounts: NaOH, 0.05 t; $Fe_2(SO_4)_3$, 1 t; and polyacrylamide, 0.05 t. The water consumption data related to the production of chemicals were acquired from the Ecoinvent database. The scarcity factors for each water consumption location were provided by Boulay et al.'s (2018) available water remaining (AwaRe) method. Local scarcity factors of 0.9 for the plant and 1.1 for chemicals were used.

In the water quality handprint assessment, it was assumed that in the baseline situation, the wetlands removed approximately 87% of the N bound in NH_4 (NH_4-N) and 3% of the nitrite and nitrate-N (NO_2+NO_3-N). The estimated baseline was 7,000 kg N emissions and 40 kg P emissions per year, which was converted to PO_4^{3-} eq. with the CML2001 general eutrophication impact factors. For the offered solution, the removal efficiency of the process was 75% of the NH_4-N and 78% of the NO_2+NO_3-N. (Kilpeläinen, 2020.)

3.6.4 Regional handprint

Publication IV differs from Publications I–III in scope. Although the main method that was used was the carbon handprint method, it was applied to cities and regions as an extension of the original application scope described by Grönman et al. (2019). This required defining a regional handprint and identifying the possible handprint contributors. As a starting point, a literature review concerning cities' climate work from different perspectives was conducted, and the existing standards were scrutinised. Secondly, discussions with city, regional council and voluntary sector representatives were held to clarify the practical need for and practical purpose of the regional handprint approach.

Thirdly, a case study concerning the handprint of the city of Espoo was conducted to demonstrate and test the framework under development. As a result, a step-by-step guide for regional handprint calculation was composed in line with the carbon handprint guidelines.

The case study comprised qualitative and quantitative parts. The potential carbon handprint-producing activities associated with the city were identified qualitatively according to the literature and discussions with city representatives. True to the nature of a case study, no exhaustive list was prepared, but relevant instances were collected for further method development. As a quantitative assessment, the carbon handprints of public electric vehicle (EV) charging stations built on city-owned land were calculated for Espoo. The hypothesis was that the availability of public EV charging stations has the potential to achieve a carbon handprint if the charging station uses renewable electricity and is used instead of a home charger using mixed electricity. The carbon handprint was calculated as the difference between the lifetime carbon footprints of the two solutions.

The data for the case study principally consisted of secondary data from the literature and from Espoo representatives. In the quantitative part of the case study, the use of public charging stations in Espoo operating with electricity from wind power was an offered solution, and EV charging at home with the national Finnish electricity mix was determined to be the baseline solution. A user was defined as a person who lives in Espoo and owns an EV. The carbon handprint calculation included all the life cycle stages of the baseline and offered solutions. However, the life cycle GHG emissions of an EV were excluded because they were assumed to be similar in both solutions. The system boundaries of the case study are shown in Figure 3.7.

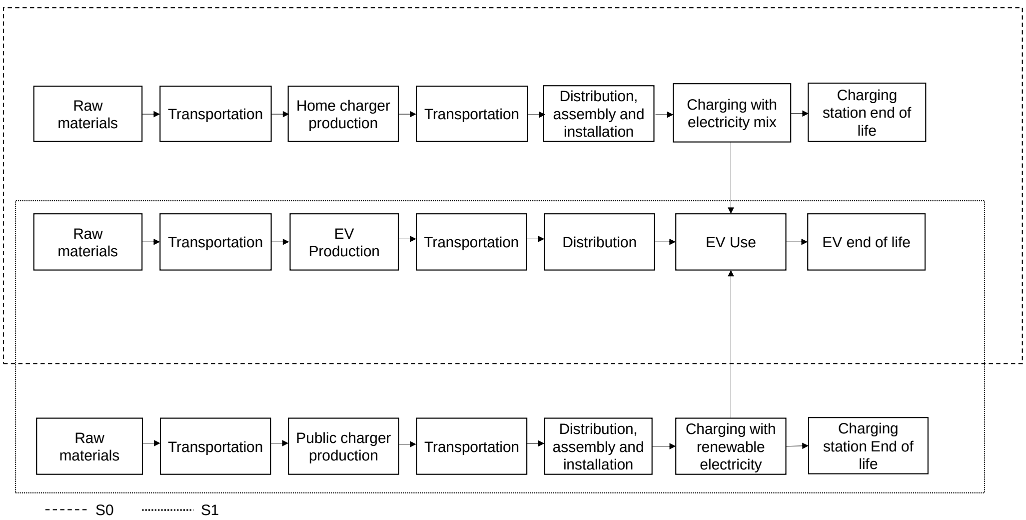

Figure 3.7: System boundaries of the baseline solution (S0) and offered solution (S1) (reproduced from Publication IV). EV = electric vehicle

The functional unit was determined to be the amount of energy consumed by driving an EV in one year. In Finland, the national average distance covered by a vehicle powered by a propulsion method using a material other than petrol or diesel in 2018 was 15,062 km (Statistics Finland, 2019). Typically, the energy consumption of an EV is 0.15–0.30 kWh/km (Motiva, 2021). In the assessment, an average value of 0.225 kWh/km was used. The carbon footprints were calculated using the CML2001 GWP100 approach, and the values for the Finnish electricity grid mix and electricity from wind power were derived from the GaBi LCA modelling software database (Sphera, 2019). The public charging stations in Espoo use alternating current, which produces 9.62 gCO_2eq/kWh more GHG emissions than a home charger when the lifetime of both charger types is assumed to be 8 years (Zhang et al., 2019). The difference is mainly due to the greater use of materials and energy during the material acquisition and manufacturing phases and to the higher electricity loss in the use stage of a public alternating current charging station (Zhang et al., 2019). In the calculation, it was assumed that 100% charging is carried out with a specific charger. To extrapolate the carbon handprint results to all the 18 public charging stations in Espoo in 2021, it was assumed that, on average, one public charging station is adequate for 10 EVs (European Commission, 2014). Thus, in 2021, the potential for charging 180 EVs was created.

4 Results

This chapter presents the results of the current study. Section 4.1 summarises the general elements that need to be considered when modifying the carbon handprint framework for application to other environmental scopes. The following sections provide more details and state the main findings of the case study in each publication.

4.1 Environmental handprint based on the carbon handprint

The application of different environmental scopes in handprint assessments requires the identification of the specific features of the studied environmental impacts. In the case studies presented in Publications I–III, several modification needs of the original framework were identified. Table 4.1 lists the identified features to be acknowledged when developing an environmental handprint framework.

Table 4.1 :Specific features of the handprint assessment in different scopes

Scope	Point of assessment		Extent of impacts		Appropriate indicators	Location of emission sources
	LCI	LCIA	Local	Global		
Air quality	X			X	X	X
Nitrogen	X	X	X		X	X
Water		X	X		X	X
Regions		X		X	X	

LCI = life cycle inventory; LCIA = life cycle impact assessment

Firstly, it was recognised that handprint assessment could be performed at the inventory or impact assessment level, depending on the studied environmental impacts. According to the LCA principles, in some cases, the goal of LCA can be attained by performing only an inventory analysis and an interpretation; such a study is referred to as an LCI study (ISO 14040, 2006). However, carbon handprint assessment is always performed at the LCIA level, with only one impact category: climate change (ISO 14067, 2018). Nevertheless, with regard to some environmental scopes, it is feasible to quantify and communicate the results only at the inventory level or separately for LCI and LCIA studies. This may be due to the challenges in assessing the actual environmental impacts or the need to understand both the quantitative and qualitative aspects of the studied flows and emissions. For instance, in the case study presented in Publication I, air quality handprint assessment was conducted only at the inventory level, which will be discussed in greater detail in section 4.2.1. For N handprint assessments, both the inventory and impact assessment levels are included, as shown in Publication II and further discussed in section 4.3.1.

Secondly, in the carbon handprint approach, the focus is on a single environmental issue, climate change, and GHG emissions, often GWP100, are used as indicators (Grönman et al., 2019). However, when assessing other environmental impacts, appropriate and relevant indicators must be selected. For example, in the case of N, several indicators must be simultaneously included in the handprint assessment. As concluded in Publication III, the impacts and indicators are case-specific and are chosen based on the identified handprint contributors. However, it is important to consider the whole life cycle of a studied offering because the relevance of different emissions may vary between life cycle phases. Suggestions of suitable indicators for different environmental scopes in handprint assessment are given in the following sections.

Environmental impacts may be local or global in nature. For example, GHG emissions have a global impact as they contribute to climate change. Conversely, with regard to some environmental issues, such as water, nutrients and air quality, the impacts of emissions are local rather than global. The locality of emissions is highlighted when the impacts of emissions are dependent on the local characteristics or when there is a direct relationship between the emissions and the midpoint or endpoint impacts. Publication I states that air quality impacts are often local, although long-range transport affects the locations of the final impacts. The environmental impacts of nutrients, such as eutrophication, are also site-dependent. However, in LCA, site-generic characterisation factors for eutrophication are commonly used (Henryson et al., 2018). When available, site-specific characterisation factors must be applied.

In cases in which there is a close connection to the locality aspects of emissions, it is important to determine whether the emissions during a product or service life cycle occur in different geographical locations. Publication I highlights the need to separately quantify and communicate emissions from different life cycle phases when considering air quality impacts. This is mainly because emissions with air quality impacts are highly local, and emissions at different life cycle points may occur in different locations. Similarly, considering the locations of emission sources may be important with regard to water scarcity and quality and nitrogen, due to the local impacts.

4.2 Environmental handprints: Air quality handprint

Publication I addresses specific features when considering the positive air quality impacts of products or services. The results of the case study presented in Publication I provide a background based on air quality handprint assessment for building the coherent framework presented in Publication III. Air quality handprint assessment was demonstrated in the case study of paraffinic renewable diesel fuels used in urban environments.

4.2.1 Identified requirements for air quality handprint assessment

Publication I addresses the modification needs of the carbon handprint framework for assessing the positive air quality impacts of products or services. Firstly, in air quality handprint assessment, it is important to identify the relevant indicators with regard to air pollutants. Air pollutants are a major threat to human health; thus, in addition to mere air pollutant emissions, harmfulness to health should be considered. Typically, the key outdoor air pollutants are particulate matter (PM_{10} and $PM_{2.5}$), O_3, NO_2 and SO_2 (World Health Organization, 2018). In addition, NH_3, NMVOCs, CO and Pb emissions may be relevant in the context of air quality. In Publication I, NO_x and $PM_{2.5}$ were identified as relevant in the conducted case study based on previous studies. Although the term 'air quality handprint' is used as an umbrella term for several indicators, in calculations and communications, indicators should be reported separately. That is to say, in Publication I, NO_x and $PM_{2.5}$ handprints were studied.

As stated in section 4.1, environmental handprint assessments can be conducted at the inventory or impact assessment level. In Publication I, an air quality handprint is assessed only at the inventory level, and environmental impact categories are excluded. This is mainly due to the challenge that in most cases, air quality impacts are related to the concentrations rather than quantities of emission outputs. However, putting the emission results into the context of concentrations will require using air quality dispersion models, which will also allow the inclusion of various local emission sources, long-range transport of emissions and local weather conditions. The understanding of the studied system's impacts on the ambient air pollutant concentrations will allow their extension to the midpoint and endpoint levels.

Publication I underlines the need to take into account the locality of emission release with regard to air quality because air quality impacts are highly local. As can be seen in Figure 4.1, which shows the system boundaries of the study, air pollutant emissions occur in different geographical locations during the life cycles of the studied fuels. However, the handprint assessment method emphasises the importance of including the whole life cycle in the examination to identify the life cycle stages at which the highest amounts of emissions are produced and the possible trade-offs.

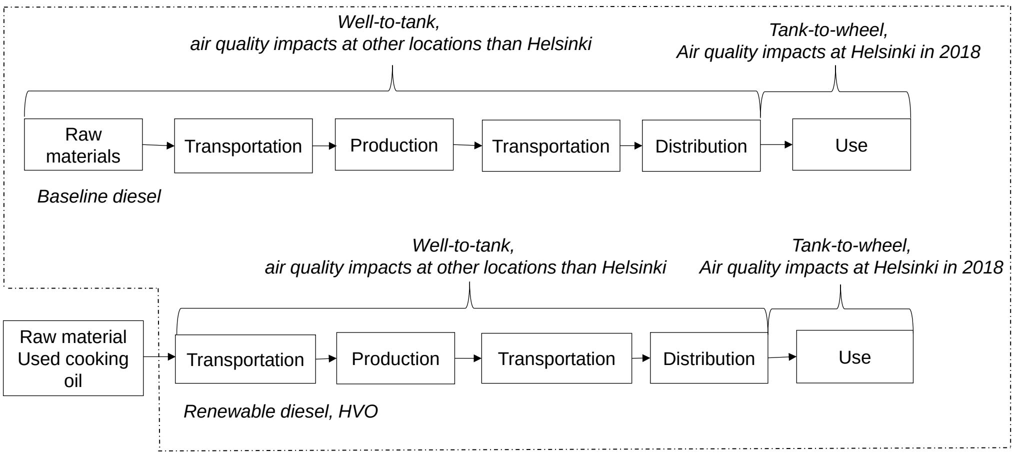

Figure 4.1: System boundaries and geographical locations of emissions (reproduced from Publication I).

In addition to geographical variation in air pollutant emissions, Publication I indicates that NO_x and $PM_{2.5}$ emissions are focused on the use phase (tank-to-wheel). Figure 4.2 illustrates the contribution of the well-to-tank and tank-to-wheel phases to the total life cycle NO_x and $PM_{2.5}$ emissions of the studied fuels. The tank-to-wheel phase was shown to be responsible for 92% of the conventional fuel emissions and 96% of the HVO life cycle NO_x emissions. With regard to the $PM_{2.5}$ emissions, tank-to-wheel emissions cover 84% of the life cycle emissions of conventional diesel and 77% of the life cycle emissions of HVO. This indicates that fuel selection may have an impact on the local air quality. Thus, it is recommended that well-to-tank and tank-to-wheel emissions be calculated and communicated separately. However, the communication of a handprint always requires the inclusion of the product's entire life cycle.

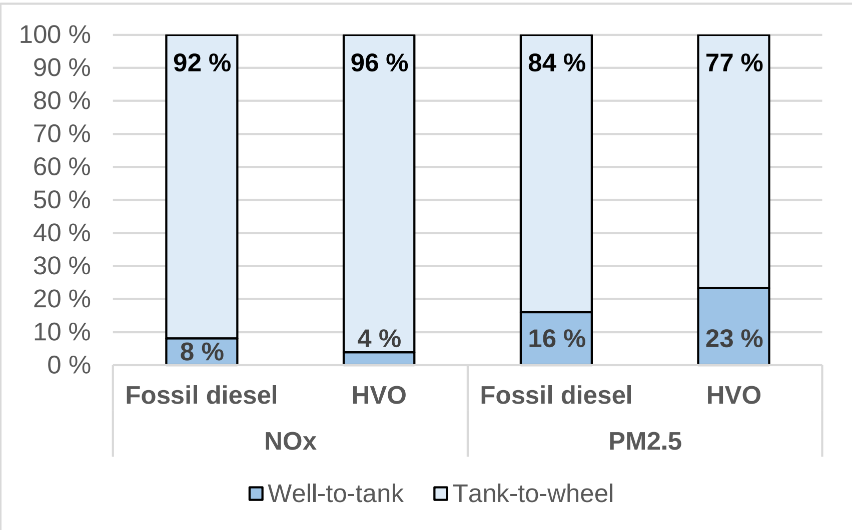

Figure 4.2: Contribution of different life cycle phases to NO_x and $PM_{2.5}$ emissions (reproduced from Publication I).

4.2.2 Air quality handprint assessment for paraffinic renewable diesel fuel

As stated in section 4.2.1, it is recommended that the emissions for different life cycle phases be calculated and communicated separately. Thus, the results of the air quality handprint assessments for the well-to-tank and tank-to-wheel phases are presented herein. Regarding the tank-to-wheel phase, the NO_x and $PM_{2.5}$ exhaust emissions in the defined Helsinki (2018) fleet were calculated separately for both fuels. For NO_x, its exhaust emissions were 283,000 kg for conventional diesel and 264,400 kg for HVO. As for the $PM_{2.5}$ exhaust emissions, they were 3,000 kg for conventional diesel and 1,600 kg for HVO. In the case of air quality, the local emission reduction potential of emissions is relevant due to the locality of air quality impacts. The annual reduction potential of exhaust emissions is examined annually in Helsinki based on the 2018 values in the studied fleet due to the replacement of conventional diesel with HVO. For the NO_x tank-to-wheel emissions, the annual reduction potential was 18,500 kg (7%). For the $PM_{2.5}$ exhaust emissions, the calculated reduction potential was 1,500 kg (49%). Figure 4.3 shows the tank-to-wheel NO_x and $PM_{2.5}$ emissions of the studied fuels and the emission reduction potentials due to the replacement of conventional diesel with HVO in the studied fleet based on the 2018 values.

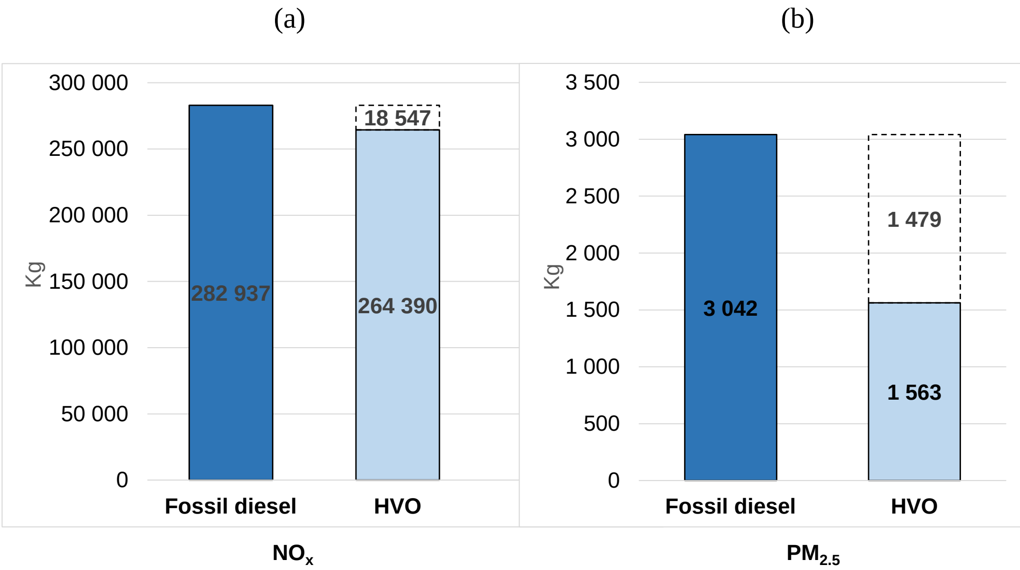

Figure 4.3: Annual (a) NO_x and (b) $PM_{2.5}$ exhaust emissions and reduction potentials in Helsinki based on the 2018 values (reproduced from Publication I).

The air quality handprint of HVO can be derived from the total life cycle reduction potential of NO_x and $PM_{2.5}$ emissions by comparing the well-to-wheel NO_x and $PM_{2.5}$ emissions of the studied fuels. According to the results, the NO_x emissions are 32,700 kg, and the $PM_{2.5}$ emissions are 1,580 kg lower for HVO than for conventional diesel (Figure 4.4). In percentages, the life cycle reduction potential of NO_x is 11%, and that of $PM_{2.5}$ is 44%.

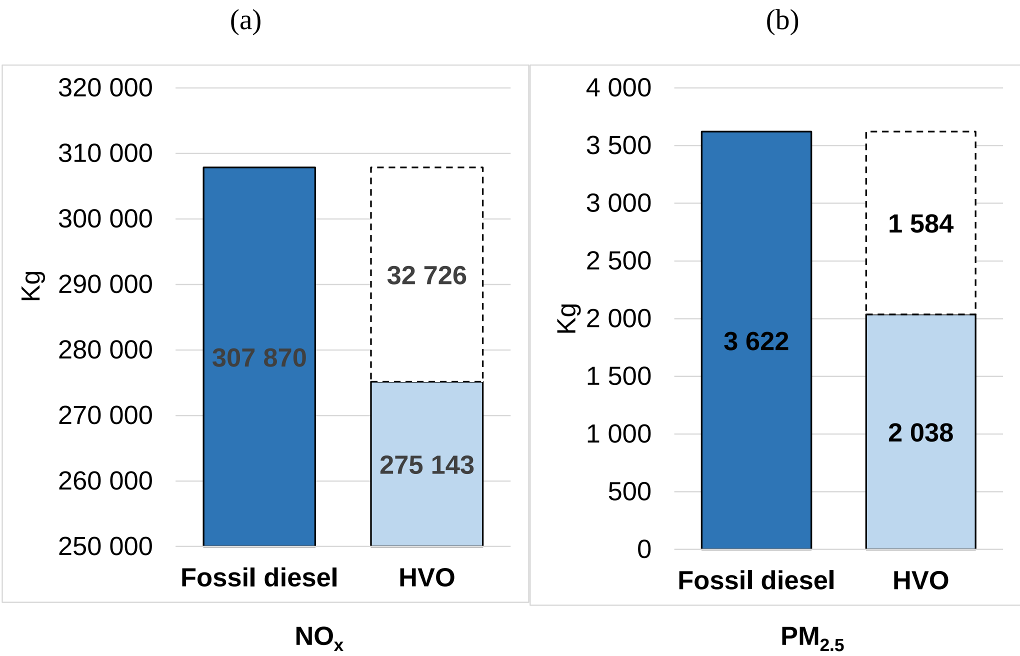

Figure 4.4: Life cycle (a) NO_x and (b) $PM_{2.5}$ emissions and handprints in the studied fleet in Helsinki in 2018 (reproduced from Publication I).

According to the results of the case study in Publication I, the provider of HVO can communicate an NO_x handprint of 32,726 kg (11%) and a $PM_{2.5}$ handprint of 1,584 kg (44%) for the defined customer and fleet. However, the results highlight that the emission reduction potential is most significant in the tank-to-wheel phase when considering the entire life cycles of the fuels.

4.3 Environmental handprints: N handprint

Publication II applies the handprint concept to nutrient use from the N point of view. The specific characteristics of N handprint calculation are identified, and an approach to assessing positive impacts on N cycles is presented. The results of the case study in Publication II further contributed to the development of the more extensive environmental handprint approach presented in Publication III, which is discussed in section 4.4.

4.3.1 Identified requirements for N handprint assessment

Performing N handprint assessment requires identifying the relevant indicators. According to the results of the case study presented in Publication II, on the subject of indicators, N handprint assessment should include two levels: the inventory and impact assessment levels. At the inventory level, the changes in the nutrient balance between the baseline and offered solutions are assessed, whereas the impact assessment level describes the potential environmental impacts due to the emissions from the studied systems.

(1) Inventory level

In the assessment of the changes in the N balance between the baseline and offered solutions, the N balance needs to be evaluated from three different aspects: the quantity and quality of the input N resources (virgin and recycled inputs), the quantity of the N emissions to the environment (the N outputs lost from the nutrient cycle) and the N recovered for further nutrient use (the N outputs still part of the nutrient cycle).

(2) Impact assessment level

At this level, the environmental impacts of N emissions and, optionally, the impacts of other relevant emissions are assessed. As a mandatory indicator, the changes in EP between the baseline and offered solutions must be included in every assessment. Other optional indicators may also be relevant for the assessment on the grounds of the assumed or identified environmental impacts related to the studied solutions. The potential optional indicators in the nutrient context may include the acidification potential or GWP due to the energy intensity of fertilizer production processes.

As stated in the carbon handprint guidelines, the handprint can be calculated as the difference between the footprints of the baseline and offered solutions. The calculation of the N handprint follows the same rule, but due to the multi-indicator nature of the N handprint, clear criteria and preconditions are needed to identify the indicator values that determine the magnitude of the handprint. The criteria are related to the aspects in the N balance that determine the magnitude of the N handprint. The preconditions must be met before an N handprint can be created, but they do not affect the magnitude of the handprint. Thus, the quantitative N handprint refers to an N resource handprint based on the changes in the N balance (inputs and outputs) of a system. The criteria and preconditions are discussed in greater detail in Publication II (Table 1 and Supplementary Materials).

With regard to other specific requirements of N handprint assessment, it is recommended that the locality of environmental impacts be taken into account in the calculations. In particular, within the bounds of possibility, local EP characterisation factors must be used, and the geographical locations of the emissions must be acknowledged.

4.3.2 N handprint assessment for a recycled N product

In the case study, the N handprint for a recycled N product used in the pulp and paper mill WWTP was calculated as the difference between the N footprints of the baseline and offered solutions. The baseline solution was the virgin N product used for the pulp and paper mill WWT, and the offered solution was a recycled N product used in the same process.

(1) Inventory level

In the baseline solution, a 454 kg virgin N input was needed to meet the urea requirement of WWT. In the offered solution, 448 kg of recycled N was used as an input. In percentages, 100% of input N in the baseline solution was of virgin origin, and 100% of input N in the offered solution was recycled. In both solutions, all the input N was lost from the nutrient cycle after WWT; that is, no N was left in the nutrient cycle. However, when considering quantities, 1.2% less N was lost in the offered solution due to the lower N input compared to the baseline solution. The inventory-level N balances of the baseline and offered solutions are presented in Figure 4.5.

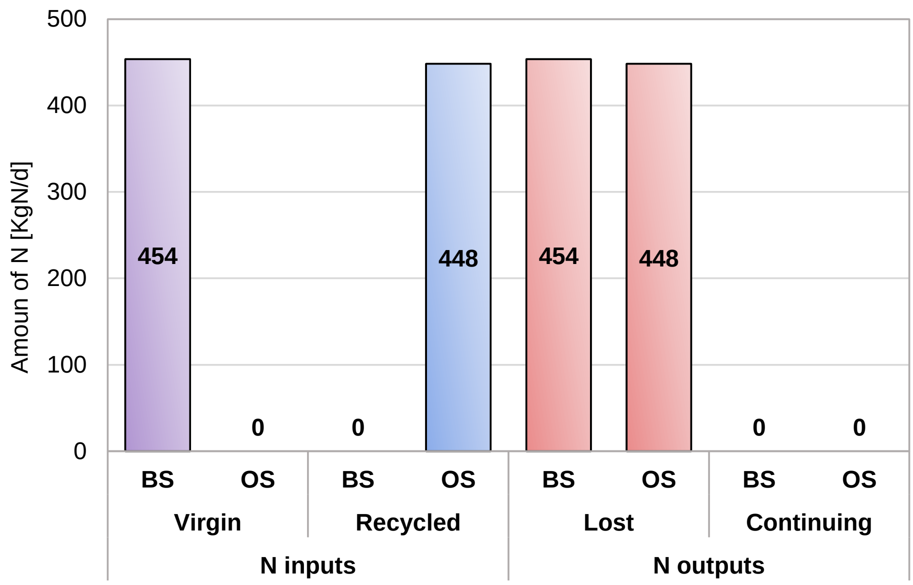

Figure 4.5: N balances of the baseline and offered solutions in kgN/d (reproduced from Publication II). BS = baseline solution; OS = offered solution

(2) Impact assessment level

At the impact assessment level, EP is a mandatory indicator. It was 1.76 $kgPO_4^{3-}eq/d$ in the baseline solution and 0.92 $kgPO_4^{3-}eq/d$ in the offered solution. The EP of the offered solution was thus 48% lower than that of the baseline solution. The main reason for this difference was that renewable thermal energy is used in ammonia water production as the biogas plant uses its own biogas in heating processes. The EPs of the baseline and offered solutions are presented in Figure 4.6 as percentages, along with the GWP calculation results.

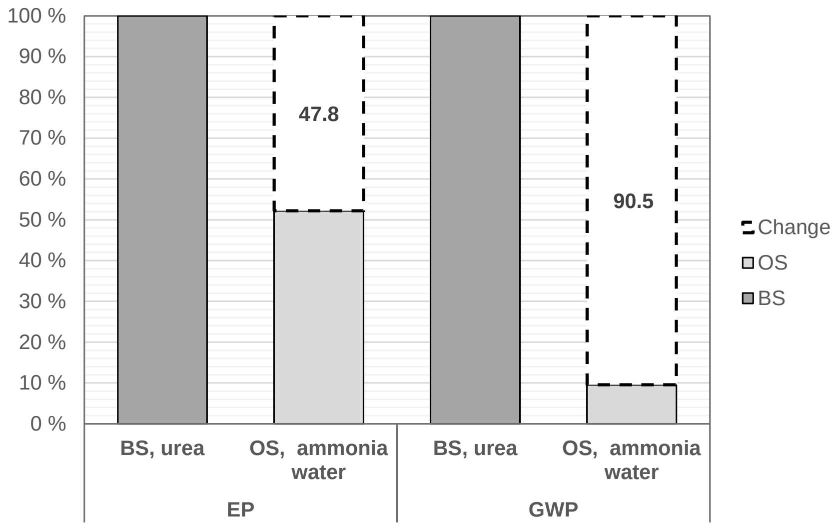

Figure 4.6: Eutrophication potential (EP) and global warming potential (GWP) of the baseline and offered solutions (reproduced from Publication II). BS = baseline solution; OS = offered solution

From the optional impact assessment indicators, GWP was identified as a relevant indicator. The carbon footprint for the baseline solution was 2,686 kgCO_2eq/d, and that for the offered solution was 256 kgCO_2eq/d. Thus, the GWP for the offered solution was 2,430 kgCO_2eq/d or 90.5% lower than that for the baseline solution (Figure 4.6).

According to the N handprint preconditions, the EP of the offered solution must be equal to or lower than that of the baseline solution. Similarly, the specified optional environmental impact indicators are not allowed to show worse performance for an offered solution compared to the baseline solution. However, in the case study, both the EP and GWP were lower in the offered solution than in the baseline solution, which means that the environmental impact preconditions for the N handprint calculation were met.

When considering the N balance, the input side was more closely examined as it was hypothesised that the use of a recycled N in the offered solution was the main handprint mechanism. According to the results, the handprint criteria were met as the total need for N inputs was lower in the offered solution than in the baseline solution. Additionally, the virgin N inputs in the baseline solution were completely replaced by recycled N in the offered solution. When considering the output situation, it was better in the offered solution than in the baseline solution because less N in total was lost in the offered solution.

As the results show that the N handprint criteria and prerequisites were met in the case study, the N handprint was created. The magnitude of the N handprint could be derived from the differences in N balance between the baseline and offered solutions. Thus, the N handprint equalled a 5.6 kg (1.2%) reduction in total N (virgin + recycled) inputs and a 454 kg (100%) reduction in virgin N inputs due to the replacement with recycled N inputs.

4.4 Environmental handprints: Water handprint

Publication III reviews water handprint assessment and demonstrates it with a case study of a water purification technology. The case study of water handprint assessment affected the development of an environmental handprint framework.

4.4.1 Identified requirements for water handprint assessment

Similar to other handprint assessments, water handprint calculations are based on water footprint assessments. ISO 14046 (2014) 'Environmental management—Water footprint—Principles, requirements and guidelines' and 14073 (2017) 'Environmental management—Water footprint—Illustrative examples on how to apply ISO 14046' provide guidelines for water footprint calculations. According to ISO 14046, two aspects of water use must be included in the assessment: water scarcity impacts (water quantity) and water quality impacts. Thus, indicators describing these two aspects must also be included in handprint assessment. The water scarcity footprint is related to the water volumes used. Water quality can be measured using water-related environmental impacts employed in LCA, such as by measuring the acidification potential, EP or water toxicity potential. Local impacts should be considered in the context of water quality and scarcity issues.

4.4.2 Water handprint assessment for a water purification technology

The results of the water handprint calculation showed that the water scarcity handprint was 94 m^3 world eq/year, corresponding to 34% of the annual water demand of the baseline solution. According to the results, the water quality handprint in terms of eutrophication was 460 $kgPO_4^{3-}eq$/year, corresponding to a 63% reduction in EP compared to the baseline solution. Both the water scarcity and water quality handprints are presented in Figure 4.7.

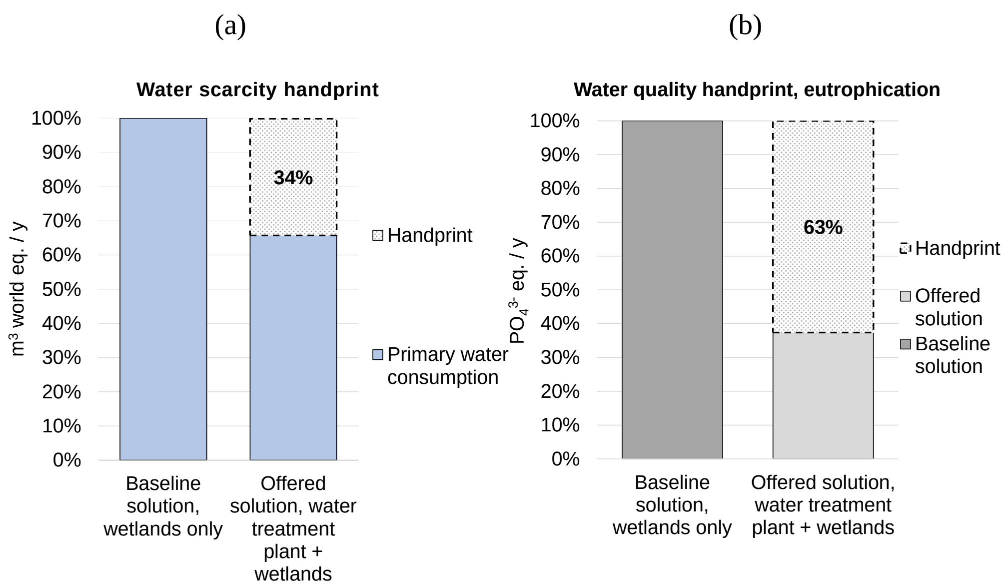

Figure 4.7: (a) Water scarcity and (b) water quality handprints in the case study of a water purification technology.

4.5 Regional approach to handprinting

Publication IV widens the application scope of the carbon handprint approach to include the regional level and identifies the specific requirements of regional-level assessments. In Publication IV, the carbon handprint for cities and regions is defined, and the focal potential handprint contributors in city- or regional-level assessments are identified and categorised. Finally, a framework guiding the assessment procedure is presented, briefly tested and demonstrated, with Espoo as a case study. The regional approach is applicable only in the impact category of climate change.

4.5.1 Identified requirements for regional carbon handprint assessment

Several specific requirements for regional handprint assessment are presented in Publication IV. Firstly, separating a city's carbon footprint from its carbon handprint is essential. The GHG inventory (i.e. calculation of a city's carbon footprint) forms a basis for cities' climate work by contributing to the understanding of emission sources and quantities. Thus, cities' climate work efforts are concentrated on minimising their carbon footprints and, often, striving for carbon neutrality. However, more widespread GHG-reductive actions are often excluded or ignored, even though the carbon footprints of other actors within and outside cities and regions can also be reduced. Consequently, the carbon handprints of cities and regions should communicate the GHG emission reductions achieved in the carbon footprints of other actors due to the city measures. To avoid misunderstandings, a city's carbon handprint is calculated not by comparing the city's own carbon footprints in different temporal phases but by comparing the carbon footprints of an offered and a baseline solution when used by a defined actor. In the regional context, a city or region is a provider of solutions with climate benefits and can communicate potential handprints.

Secondly, understanding the difference between a city as a geographical area and as an organisation is important. Cities' GHG inventories are prepared based on the geographical city boundaries, by summing up the emissions and deducting the removals. In contrast, in handprint assessment, a city as an organisation is an executive organ that implements climate actions. Actions producing handprints and reducing other actors' footprints can occur either within or outside a city's geographical boundaries. However, handprint contributors may also reduce a city's own carbon footprint, but importantly, a city's carbon handprint can never be subtracted from its carbon footprint. The relationship between the city as an organisation and the geographical boundaries of the footprint and handprint assessments is illustrated in Figure 4.8.

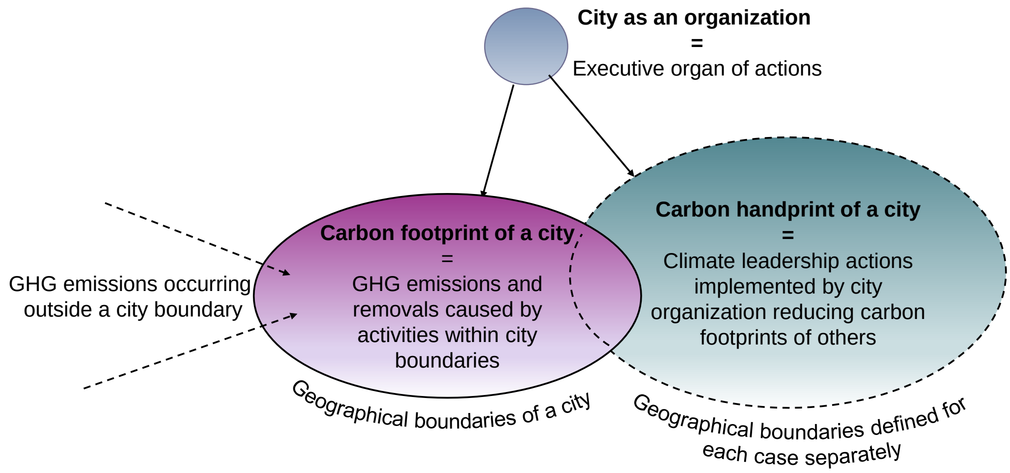

Figure 4.8: Distinction between a city's carbon footprint and carbon handprint and between a city as an organisation and as an area (reproduced from Publication IV).

4.5.2 Framework for assessing the carbon handprints of cities and regions

As one of the major aims of Publication IV, a framework for assessing cities' and regions' carbon handprints according to the perceived carbon handprint framework modification needs introduced by Pajula et al. (2018) and Grönman et al. (2019) is presented. The framework for assessing the carbon handprints of cities and regions comprises four stages: (1) identification of the handprint requirements; (2) identification of the additional LCA requirements; (3) quantification of the handprint and (4) communication of the handprint results. Compared to the original framework, changes to stage 1 (definition of the handprint requirements) were required. Stage 1 of the carbon handprint framework for cities and regions is discussed in greater detail in the following paragraphs, whereas stages 2–3 follow the original framework and are explained in section 4.6. Figure 4.9 presents the framework for assessing the carbon handprints for cities and regions.

Stage 1	**Define the scope of the offered solution**	**City/region** Acknowledging the climate leadership initiatives of the city in order to maximize their positive impact			
Stage 1	**Identify potential handprint contributors**	**Ownership** Providing footprint reducing solutions through city owned companies or property	**Operating environment** Providing a climate-friendly operating environment for a business or a resident	**Projects** Piloting and participating in innovative climate projects/initiatives; Being followed on its pioneering example	**Companies – other aspects** Companies in the region providing handprint solutions without any contribution of the city
Stage 1	*Guidelines to be referred to*	*Product/company handprint guidelines*	*Product/company handprint guidelines*	*Project handprint guidelines*	*Product handprint guidelines*
Stage 1	**Identify the environmental impacts in question and their potential indicators**	**Climate change** GHG emissions			
Stage 1	**Identify the users and beneficiaries of the offered solution**	Company, organization or a resident in or outside the city	Current and potential companies, organizations or residents in the city	Parties that benefit from the project; Parties that benefit from the replicated project	Customers of the companies
Stage 1	**Define the baseline**	GHG emissions of the beneficiary without the offered solution	GHG emissions of the beneficiary in its current or alternative location or its existing value chain	GHG emissions of the beneficiary without the project/initiative	GHG emissions of the customer without the offered product or service
Stage 2	**Define the functional unit**	The measure of the function the offered solution delivers in a relevant time frame in use			
Stage 2	**Define the system boundaries**	The relevant and similar life cycle stages of the offered and the baseline solution			
Stage 2	**Define data needs and sources**	Identifying representative and accessible data of the offered and baseline solution representing the similar time-related coverage			
Stage 3	**Calculate the footprints**	Calculate footprints of the offered and baseline solution based on relevant ISO-standards where applicable			
Stage 3	**Calculate the handprint**	Difference of the footprints calculated			
Stage 4	**Identify the relevant indicators to be communicated**	Carbon dioxide equivalents per functional unit			
Stage 4	**Consider critical review of the handprint**	Mandatory if the results are intended for comparative assertions to be disclosed to the public as instructed in the ISO standards 14044 and 14026			
Stage 4	**Communicate the results**	Communicating the results respecting appropriateness, clarity, credibility, and transparency. Communicate results tailored to recognized beneficiaries. Communication units: in kgCO_2eq./a and in %.			

Figure 4.9: Carbon handprint framework for cities and regions (reproduced from Publication IV).

Stage 1 comprises five steps to identify the detailed requirements of handprint assessment. In the first step, the scope of the offered solution is defined. The carbon handprints of cities and regions are calculated through the climate leadership initiatives implemented by such cities or regions. Thus, a defined solution implemented by a city and bringing potential carbon footprint reductions for the beneficiaries is considered an offered solution.

Stage 2 identifies the potential handprint contributors; that is, it defines how the city- or region-driven actions achieve reductions in other actors’ carbon footprints. Handprint contributors can be recognised and classified through three main mechanism categories presented in Publication IV: ownership, operating environment and projects. In addition, the mechanism category of companies–other aspects was recognised but was recommended to be reported separately. The first mechanism category (ownership) refers to GHG-reductive actions that can be implemented through city- or region-owned properties or companies. The second mechanism category (operating environment) includes actions in which a city or region offers a climate-friendly operating environment for a company, resident or other actor. The third mechanism category (projects) refers to GHG-reductive projects or other initiatives in which the city or region plays an important role or acts as a facilitator. In the context of projects, a city or region can obtain direct benefits by participating in projects that lead to GHG emission reductions for the project beneficiaries, or indirect benefits if some other actor follows its pioneering example and replicates the climate-friendly initiative elsewhere. Under the additional mechanism category of companies–other aspects, a city or region can report the carbon handprints produced by companies within it. Although in these cases the city or region does not necessarily have any role in the handprint creation, it may be relevant to acknowledge such carbon handprints in the strategic planning not only to increase the city's handprint potential but also to attract new businesses to the area. After the categorisation of actions, more detailed guidelines for assessment can be found in the product (Pajula et al., 2021) or company handprint guidelines (Vatanen et al., 2021). The mechanism category of projects follows the guidelines for project handprint assessment described by Vatanen et al. (2021). Additionally, in the context of companies–other aspects, the product handprint guidelines (Pajula et al., 2021) must be referred to.

In the third step, the environmental impact category and its indicators are identified. Carbon handprint assessment for cities and regions is intended for assessing only positive climate impacts; thus, the impact category of climate change is included.

In the fourth step, the users or beneficiaries of the offered solution are specified as a focal part of the handprint assessment. A user or beneficiary refers to an actor whose carbon footprint is lowered due to a city action. In the context of cities, beneficiaries may vary from individual residents to companies and other cities. Other beneficiaries can also be recognised, and they may be located within or outside the city. Figure 4.10 provides examples of different beneficiaries of a city with spatial diversity.

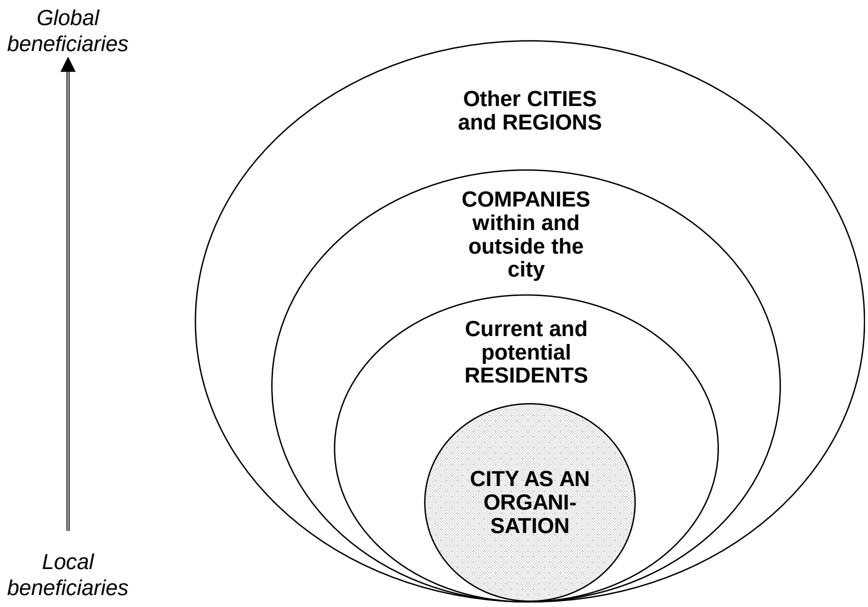

Figure 4.10: Examples of beneficiaries of cities in carbon handprint assessment and their spatial variability.

In the fifth step, the baseline for an offered solution is defined. In general, a baseline represents a situation without the offered solution provided by the city. However, in the context of the regional handprint, choosing a baseline also depends on the mechanism category, in line with Figure 4.9. Defining a baseline is crucial for the quantitative result of the assessment and should be performed accurately by following the instructions for a baseline setting given in Carbon Handprint Guide v. 2.0 (Pajula et al., 2021).

4.5.3 Regional carbon handprint assessment for the city of Espoo

In Publication IV, regional carbon handprint assessment was briefly demonstrated through the case study of the city of Espoo. As a first phase, the carbon handprint contributors in the city were surveyed and divided into the mechanism categories described in section 4.5.2. According to Publication IV, the total carbon handprint of a city or region is the sum of all the identified handprint actions, which requires a very broad calculation. Thus, only one exemplary calculation case is presented.

The results of the case study carbon handprint calculation of public EV charging stations show that for one EV with 100% charging with a specific solution, the carbon footprints for home charging and public charging are 671 $kgCO_2eq/a$ and 62 $kgCO_2eq/a$, respectively. Thus, the carbon handprint derived as the difference between the carbon footprints is 609 $kgCO_2eq/a$, in favour of public charging. When extrapolated for the potential of 18 installed charging stations, the maximum carbon footprints for home charging and public charging were 121 tCO_2eq/a and 11 tCO_2eq/a, respectively. The carbon handprint potential thus corresponded to up to 110 tCO_2eq/a, which equalled a 91% GHG emission reduction potential, as shown in Figure 4.11.

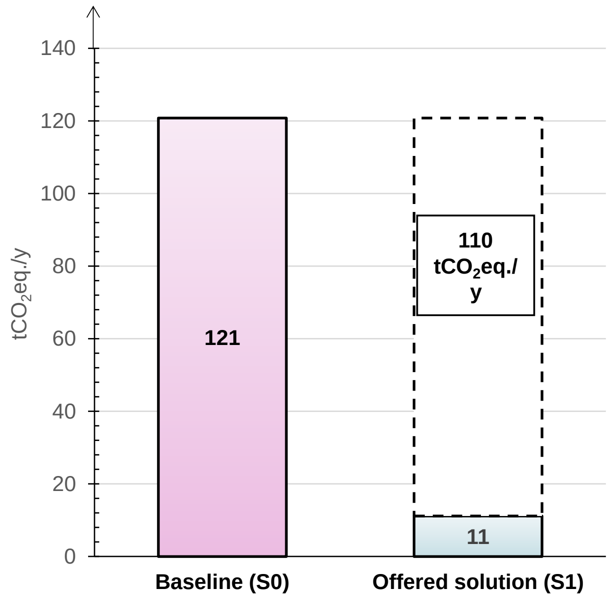

Figure 4.11: Carbon footprints and carbon handprints of the baseline and offered solutions in the case study in Publication IV (reproduced from Publication IV).

The presented results were calculated for a situation in which 100% EV charging is carried out in either a public charging station or at home. In a scenario in which the EV is charged both at home and at a public charging station, the handprint of EV charging in the 18 new public charging stations will be between 0 tCO_2eq/a (0% charging at a public charging station) and 110 tCO_2eq/a (100% charging at a public charging station).

4.6 Summary of results

With contributions from Publications I–III, the studied environmental and application scopes of handprint assessment were combined in the same framework. Publication III focuses on the key issue of the present study: presenting a framework for assessing the positive environmental impacts for several impact categories with different application scopes. Publication III aims to respond to RQ1 by providing a coherent framework for assessing the positive environmental impacts of products, services, organisations and projects compared to the baseline solution. In addition to climate change, the framework covers the environmental impact categories of air quality and use of nutrients, water and resources. However, the carbon handprint for cities and regions presented in Publication IV is not embedded in the environmental handprint framework introduced in Publication

III as it covers only the impact category of climate change. Nevertheless, it provides an important extension of the application scope of the carbon handprint approach.

Based on the previous carbon handprint framework and the existing ISO LCA standards, a four-stage framework was composed, taking into account the specific requirements of different environmental and application scopes. The four main stages of the framework are as follows: (1) identification of the handprint requirements; (2) identification of additional LCA requirements; (3) quantification of the handprint and (4) communication of the handprint results. Each stage consists of several more detailed steps, which are introduced in the following paragraphs. The framework for assessing environmental handprints is presented in Figure 4.12.

Figure 4.12: Framework for assessing environmental handprints. The grey texts are outside the scope of the present study but are included in the environmental handprint framework presented in Publication III (modified from Figure 2 in Publication III).

Stage 1. Identification of handprint requirements

The first stage of the framework specifically applies to handprint assessments, and it plays an important role in defining the operating environment for the calculation (Pajula et al., 2018). Stage 1 includes five steps: defining the scope of the offered solution, identifying the potential handprint contributors, identifying the environmental impacts in question and their potential indicators, identifying the users and beneficiaries of the offered solution and defining the baseline.

Step 1: Definition of the scope of the offered solution

In the first step, the application scope of the offered solution is defined and described. In general, the offered solution refers to a solution that brings environmental benefits compared to a BAU solution. Its application scope is divided into the main categories of products and services, organisations and projects. However, organisational and project-level handprint calculations were not considered as they were outside the scope of the present study. In the case of the first group (products), the offered solution can be, for instance, a product, service, technology, component or raw material.

Step 2: Identification of potential handprint contributors

In the second step, the objective is to identify potential handprint contributors or mechanisms through which the offered solution will provide environmental benefits compared to the baseline. Potential mechanisms that may lead to a reduction in the footprints of other users should be clearly stated and described. Handprint contributors depend on the offered solution and may be derived, for example, from the use of recycled, renewable or less polluting materials and energy or by providing energy-efficient solutions or products with prolonged lifetimes. Although handprint contributors are often based on identified improvements in products and services, preliminary assessments are sometimes based on rough data, and modelling may be needed to recognise the mechanisms. As step 2 aims to identify the potential handprint contributors to provide a basis for further calculation, only an actual handprint calculation will show if the handprint is actually achieved with an offered solution. However, step 2 is crucial for selecting suitable indicators, defining a baseline for calculations and setting system boundaries.

Step 3: Identification of the environmental impacts in question and their potential indicators

In the third step, relevant impact categories and indicators are selected according to the identified handprint contributors of an offered solution. As presented in Publications I–III, the environmental handprint framework currently covers the environmental impacts of climate change, air quality, nutrients and water scarcity and quality. Additionally, outside the scope of the present study, the environmental handprint project developed guidelines for assessing resource handprints. After identifying the relevant impact categories, the framework gives suggestions for suitable indicators to be used in each context, but some other indicators may also be used. Again, the main foundation for the selection of appropriate indicators is the identified handprint contributors. As an exception, in the impact category of climate change, GHG emissions are always used as an indicator, and in nutrient handprint assessment, it is suggested that some obligatory indicators always be included in the calculation.

Step 4: Identification of the users and beneficiaries of the offered solution

The fourth step involves identifying the named users or beneficiaries of the offered solution. Identifying the beneficiary is focal in handprint assessments as the main purpose is to provide footprint reductions for the user; thus, the calculations are primarily user-specific. Users or beneficiaries can be recognised by investigating who benefits from the improved environmental performance or whose footprint will be decreased. However, always naming a specific beneficiary is not possible, or there are several beneficiary groups. In such cases, a representative average user may be used, or it is possible to examine handprint creation from a wider point of view by conducting the study at the system level through system expansion.

Step 5: Definition of the baseline

In step 5, the baseline solution is determined to set a point for comparison. The baseline solution must provide the same functions to beneficiaries and must be used for the same purposes as an offered solution. According to the definition by Pajula et al. (2018), baseline refers to "a reference case that best represents the conditions most likely to occur in the absence of an offered solution".

The chosen baseline affects the magnitude of the positive impact that may be achieved through an offered solution; hence, guidelines for baseline selection are needed to ensure the reliability of the handprint assessment. Generally, two different situations in a baseline setting may exist, depending on the offered solution. When an offered solution is new to the market, the current situation without an offered solution must be used as the baseline. If an offered solution replaces an existing product in the market, the users of the offered solution must be identified. When the users can be specified, their current product or another option available in the market must be chosen as the baseline. In cases where the named users are not available, the market leader or typical or average product or service in the identified area and time must be chosen as the baseline. In other respects, the selected baseline must be in line with the offered solution in terms of delivered functions, use purposes and availability in the market. Both solutions must also be used in the same defined time period and geographic region, and similar calculation principles must be used, such as regarding data quality, system boundaries and assumptions.

It is recommended that the baseline be communicated transparently and accurately, with a description of the included activities, system boundaries and technological, geographical and temporal scope. To increase the transparency of an assessment, the assumed or perceived uncertainties must be estimated along with the validity of the selected baseline.

Stage 2: Identification of additional life cycle assessment requirements

This stage comprises three steps: definition of the functional unit, definition of the system boundaries and definition of the data needs and sources. Stage 2 is closely linked to the ISO standards for LCA (Pajula et al., 2018).

Step 6: Definition of the functional unit

A functional unit is defined and used in line with the guidelines given in ISO 14040-44 (2006), which define a functional unit as 'quantified performance of a product system for use as a reference unit'. Thus, in the handprint context, a functional unit refers to the measure of the function delivered by the offered solution to the beneficiary in a relevant time frame. Functional units act as references to which resource use or emissions are related, thus enabling the comparison of the footprints of an offered solution and a baseline solution.

A functional unit is selected according to the application and use purpose of the offering.

Step 7: Definition of the system boundaries

System boundaries define the unit processes included in a study, and they must be modelled and described clearly. In handprint assessments, all the life cycle stages of the studied solutions must be incorporated, including the processes at the use phase, as the customer is very important in the handprint assessment approach. However, some life cycle stages, processes, inputs or outputs within the system can be excluded when they do not significantly affect the overall results of the assessment. The system boundaries of the baseline and offered solutions must be similar and consistent with the goals of the study and must be set in line with the definitions in ISO 14040-44 (2006), 14046 (2014) and 14067 (2018).

Step 8: Definition of the data needs and sources

After the identification of the handprint contributors and baseline and the setting of the system boundaries, the data needs can be identified and defined. According to ISO 14040-44 (2006), 14046 (2014) and 14067 (2018), the data must be representative in terms of geographical, temporal and technological coverage and must be precise and complete. As a specific feature of handprint assessments, the data must also reflect an actual operating environment for both the baseline and offered solutions based on the recognised handprint contributors. The temporal period of the collected data can be defined depending on the case studied, but overall, it must be long enough to cover the variation in operations so that the average outcome of the selected indicator can be established.

Stage 3: Quantification of the handprint

At this stage, the footprints of the baseline and offered solutions are quantified, and the handprint is subsequently calculated.

Step 9: Calculation of the footprints

The footprints of the baseline and offered solutions are calculated based on the selected indicators of different environmental impact categories, using equal functional units. Footprint calculations are conducted throughout the life cycles of the studied solutions or according to the defined and justified system boundaries. Each indicator identified as relevant earlier (in the step of scope definition) must be quantified separately.

Nutrient footprint calculation requires quantification of a nutrient footprint profile, which consists of the four nutrient balance indicators (virgin and recycled inputs, lost and continuing outputs) and the EPs of the baseline and offered solutions. Other environmental impact indicator values can also be relevant in the studied case. Carbon and water footprint calculations follow the guidelines given in ISO 14067 (2018) and 14046 (2014).

Step 10: Calculation of the handprint

The potential handprint of an offered solution is calculated as the difference between the footprints of the baseline and offered solutions. Consequently, a handprint is created if the footprint of the offered solution is lower than that of the baseline solution in terms of its use by a beneficiary.

Regarding some environmental impacts, such as water and nutrient impacts, several indicators are used to quantify the footprint; thus, the handprint is not a single indicator. In the water context, handprints can be divided into water scarcity handprints (water quantity handprints) and water quality handprints, which can be further specified with a qualifier, such as a water quality handprint in terms of eutrophication. In the case of nutrients, the use of multiple indicators requires clear criteria for defining when an N handprint must be created (Publication II: Table 1 and Supplementary Materials).

Stage 4: Communication of the handprint results

The fourth and last stage provides guidelines for communicating the handprint results and identifying the need for a critical review of the handprint.

Step 11: Identification of the relevant indicators to be communicated

The first step at the communication stage is to confirm the most relevant indicators to be communicated. The selected indicators must accurately represent the results and real situation; thus, the possible negative changes must also be transparently communicated.

Step 12: Critical review of the handprint

The purpose of the critical review is to verify the handprint assessment process and the given results. In line with ISO 14044 (2006) and 14026 (2017) on the communication of footprints, a critical review is required when the results are used for comparative assertions to be disclosed to the public.

Step 13: Communication of the results

In the last step, the results are communicated respecting the principles of appropriateness, clarity, credibility and transparency. With regard to appropriateness, it must be considered whether the intended audience is familiar with the offered solution, LCA and the footprint and handprint concepts. As for clarity, appropriate communication units must be selected according to the indicators identified in step 11. The quantity and unit of the calculated handprint, the used baseline scenario, the identified handprint contributors, the temporal coverage of the data and the geographical boundaries of the assessment, which are all central issues, must be included. In business-to-business and business-to-consumer communications, from the point of view of the beneficiary, it may also be appropriate to communicate the emission reduction potential (i.e. footprint reduction potential) of a customer. To ensure credibility, the methods and standards used can be attached to the communications, together with the information regarding the performer of the study and a possible critical review. For transparency, it is also important to communicate how additional information will be provided to interested parties.

5 Discussion

This chapter discusses both the theoretical and practical implications of the results of the present study, evaluates the validity and reliability of the research done and reviews the limitations of the publications. The chapter ends with recommendations for further research.

5.1 Theoretical implications

The need for methods for estimating and quantifying potential beneficial environmental impacts has been recognised in the scientific literature, but is also called for on the part of businesses. The environmental handprint framework presented in Publication III provides an important addition to the existing methods, which mainly concentrate on measuring the harmful lifetime impacts of products and systems. The field of positive assessments has been seen as scattered and incoherent, and clear and consistent definitions have been missing. This dissertation contributes to the knowledge on positive impact assessment by defining and unifying the terms and principles used and providing stepwise calculation guidelines for assessing positive impacts for several environmental and application scopes. Although a few approaches other than the existing carbon handprint framework have introduced principles for estimating positive environmental impacts, the method presented in this dissertation is the first to provide comprehensive guidelines for quantitative assessments.

From the perspective of method, the results of the present study provide novel extensions to both the environmental and application scopes of the carbon handprint framework. Publication I focuses on the air quality handprint and offers specific requirements for conducting air quality-related handprint assessments. In the case study in Publication II, the handprint method is applied in the N context to enable the evaluation of the positive impacts of products and services on N cycles. Publication III gives an example of water scarcity and quality handprint calculations based on the existing water footprint calculation practices. The regional carbon handprint approach introduced in Publication IV defines a carbon handprint in the context of cities and regions and provides guidelines for assessing the positive climate impacts of cities and regions. Thus, Publication IV provides a novel application of the handprint approach and a necessary method-based framework for cities' climate work when aiming beyond climate neutrality.

There are various challenges to the assessment and communication of positive environmental impacts. One challenge is that in the sustainability context, what are considered positive environmental impacts are often only those that are perceived as being less harmful to the environment than the negative impacts (Dijkstra-Silva et al., 2022). However, positive impacts are often highly context-related issues and are linked to the surrounding conditions and practices (Di Cesare et al., 2018; Grönman et al., 2019). In addition, especially from an environmental point of view, novel solutions with beneficial environmental impacts usually replace worse alternatives, which is ultimately the reason for the novel solutions' positive impacts on the environment. As production and consumption always have absolute negative impacts on the environment at some level, the use of a handprint as an indicator can show the relative positive impacts in the decision-making context. Furthermore, a handprint acts as an incentive for the development and implementation of novel innovative solutions that have the potential to gain widespread environmental benefits.

Attempts to include assessment of potential positive impacts in LCA have raised the concern that the results might be used in greenwashing or in justifying or covering up the adverse impacts of the studied offerings. The environmental handprint framework presented in this dissertation aims to address this problem by providing an LCA-based method with additional stages defining a real operating environment to ensure the assessment's transparency and reliability. It is stated that to ensure credibility, the inclusion of a real operating environment is focal when estimating beneficial impacts (Kasurinen et al., 2019). The environmental handprint framework aims to address the issue of credibility by defining the actual, specified beneficiary of a studied offering and by requiring the use of a functional unit. Accurate selection and description of a baseline solution also increase the reliability of handprint assessment as the baseline has a significant impact on the magnitude of a potential handprint. Consequently, the first stage of the environmental handprint framework, in which the handprint requirements are described, is crucial for the reliability of the results. In addition to precise guidelines and definitions, proper communication is important to ensure the truthful dissemination of the results. Transparency is important at every stage.

5.2 Practical implications

The environmental handprint framework can be used in several contexts for different purposes, but mainly in decision-making to support environmentally beneficial choices of customers, companies and policymakers. Whereas products and services usually have absolute negative lifetime impacts on the environment, decisions related to the selection of products, services and practices can be either negative or positive from the environmental point of view. A handprint makes positive contributions visible and enables justified decision-making from an environmentally beneficial perspective. Thus, rather than estimating and communicating absolute positive impacts, a handprint aims to show the relative superiority of environmentally beneficial products and services.

Aside from aiding in decision-making, a handprint aims to encourage companies and cities to develop and implement more sustainable innovative solutions by offering a reliable measurement and communication tool for this purpose. The previous indicators have not offered a tool for showing environmental benefits, which may have restricted the implementation and communication of good practices. In addition, without science-based methods, the measurement and communication of beneficial impacts may be misleading and based on companies' own marketing strategies, at worst leading to greenwashing. Thus, transparent and reliable indicators are needed for companies to show their positive contributions.

For companies, handprints provide possibilities at two levels. On the one hand, they can allow companies to reliably measure, communicate and market the environmental benefits of their products and services to consumers. Unlike communicating the absolute environmental burdens of their offerings to consumers, a handprint offers the possibility of comparing different options and, based on this, making environmentally beneficial decisions. On the other hand, companies can use a handprint in their own processes, such as in product development and decision-making in procurement, and when selecting suitable subcontractors. By selecting products and services with a handprint, companies may be able to decrease their own footprints and, in the case of climate impacts, scope 2 and 3 emissions. Similarly, the regional-level carbon handprint may help companies detect a low-carbon operating environment that can further lower their carbon footprints. Reductions in carbon footprints may lower the need to compensate for residual emissions when aiming at carbon neutrality.

The framework for assessing regional handprints presented in Publication IV encourages cities and regions to widen their climate work from only reducing their own GHG emissions to developing and implementing innovative climate actions. Thus, the carbon handprint provides an essential addition to the traditional climate work of cities and regions and complements the existing instrumentation. In the future, carbon handprint assessment can also be integrated into international commitment frameworks, such as the Covenant of Mayors and C40 Cities. To widen the practical adaptation of the carbon handprint framework of cities and regions, the framework should be included in the climate work of cities to reliably show the GHG emission reduction potentials of climate interventions. Through systematic and long-range strategic planning, cities and regions can develop carbon handprint potential and, more importantly, manage to have an impact on climate change mitigation. The carbon handprint can also be used by cities or regions as a communication, marketing and branding tool for enhancing their viability and attractiveness.

Recent events have shown that even at the global level, sudden and unexpected crises can occur, and geopolitical situations can suddenly change. Thus, a discussion on countries' interdependence, such as in raw material acquisition, energy and products, has arisen. The environmental handprint approach can help identify solutions that can reduce these dependencies and find novel solutions with positive contributions to sustainability. For example, with regard to nutrients, fertilizer prices have increased drastically along with energy prices, which may lead to food crises and even famines in developing countries (Food and Agriculture Organization, 2022). As shown in Publication II, recycled nutrient products can help reduce both virgin N and energy consumption but can also help utilise local resources and decrease the dependency on industrially produced fertilizers. Similarly, water insufficiency is a real problem in several areas, even in Europe (European Environment Agency, 2021), and the water handprint enables a comparison of different solutions and helps point out the most efficient ones in terms of water scarcity and quality. Across the different environmental impact categories, the environmental handprint approach presented in this dissertation can help in developing, identifying and implementing solutions promoting circular economy targets.

5.3 Reliability and validity

The environmental handprint framework is built on the LCA method, which increases the reliability of the approach. The handprint approach includes the use of functional units and the setting of convenient system boundaries by complementing the given LCA principles with the inclusion of real operating environments, which is important in handprint studies. In addition, step-by-step guidelines for calculation and communication increase the transparency and validity of the method when conducted by different users.

Handprint assessments require much data as the calculation comprises quantifying two separate footprints, and when considering system-wide changes, the need for data is even higher. The use of primary data increases the validity of the assessment, but the availability of such data is often limited, especially for the baseline solution. In these cases, secondary and average data need to be used. When a handprint is quantified for a named customer, primary data from customer processes are more often available. However, the altogether high need for data and time resources may limit large-scale handprint calculations in companies.

When considering different environmental impact categories, the complexity of natural processes may require simplification of the studied systems. In the case study presented in Publication II, all N flows were considered the same as acknowledging changes in different forms of N would make the assessment overly complex. In the case study presented in Publication I, air quality handprint assessment was conducted only at the inventory level to make the conduct of the study feasible. To conclude, simplifications need to be done to ensure the usability of the method, although the results do not completely represent real-world processes.

The scope of the handprint assessment is selected according to the hypothesis of potential handprint contributors and other relevant factors related to the offered solution. However, as the study concentrates on a specific environmental impact category, some impacts may show worse performance for the offered solution compared to the baseline solution. When aiming for real environmental sustainability, one must minimise the negative burdens (e.g. footprints) and maximise the positive impacts (e.g. handprints). To achieve these goals, the use of LCA and footprinting methods combined with handprint assessments is recommended for a broad understanding of environmental performance. Transparent communication of both negative and positive aspects can also increase reliability and validity and reduce the risk of greenwashing.

5.4 Limitations

The publications included in this dissertation have several limitations. The environmental handprint framework does not include all the existing environmental impact categories; rather, it provides examples of how to conduct handprint studies for different impacts and application scopes. Similarly, the case studies presented in Publications I–IV represent only a limited share of the possible scopes. For example, in the nutrient context, the handprint method is currently limited to N. Assessing a handprint in terms of other nutrients requires acknowledging the specific characteristics of different nutrients.

Air quality handprint assessment covers only the inventory level and does not include the potential midpoint or endpoint impacts. With regard to air quality, the challenge is to relate air pollutant emissions to ambient air pollutant concentrations, which are instead related to potential impacts, mainly on human health (Liu et al., 2017; Rybarczyk and Zalakeviciute, 2018; Shimadera et al., 2016). This has also been perceived as a challenge when aiming to include the health effects of $PM_{2.5}$ in emission-based LCA (Fantke et al., 2015). Although air pollutant-related impact categories have been developed for LCA (Jolliet et al., 2014; van Zelm et al., 2016), differences and inconsistencies in the impact scores for the same LCA case study appear (Lopes Silva et al., 2019). In addition, it has been perceived that there is a need to regionalise data for LCIA when it concerns the PM formation impact category (Fantke et al., 2015). However, while relating local air pollutant emissions to ambient concentrations and, further, to human exposure to intake will be informative, without reliable characterisation factors, misleading results may be obtained. An alternative option is the use of air pollution modelling, which helps in understanding not only the relevant processes between emissions and concentrations but also the interactions between emissions, weather conditions, geographical features and long-range transportation of emissions (Rybarczyk and Zalakeviciute, 2018; Shimadera et al., 2016).

The regional handprint assessment framework provides an overview of the calculation of the regional handprint through defined actions. However, estimating the total handprint of a city or region requires the assessment of all the recognised climate actions implemented by a defined region, which is a very extensive and laborious task. Currently, the regional handprint assessment framework only provides calculation guidelines for individual actions and presents the principles of city-level calculations.

5.5 Recommendations for further research

This dissertation presents a framework for assessing environmental handprints for different environmental and application scopes and demonstrates the assessment through case studies. However, the case studies represent only a minor share of the potential application targets; thus, more practical case examples are suggested to test the feasibility of the framework in terms of different indicators in various sectors and systems with diverse solutions.

In the present study, the use of the N handprint approach was demonstrated only for industrial symbiosis. Thus, it is recommended that criteria and preconditions in other contexts, such as the agri-food sector and other nutrients, be set for further studies to test the feasibility of the N handprint framework. In the regional context, a calculation example is only briefly discussed in this dissertation; additional qualitative and quantitative case studies are suggested. In addition, air quality and water handprint studies need further case applications, especially in terms of different indicators and solutions.

As the publications do not accurately consider the communication stage of handprint assessment, a closer examination of and future research on this topic is needed.

As shown in this dissertation and related publications, the handprint approach has important applications for companies. In the future, it can be used to evaluate environmental performance and corporate social responsibility from a wider viewpoint. Especially when companies use the handprint approach in combination with city-level handprint strategies, their potential to produce handprint solutions may rise considerably. However, further research is needed to understand the role of companies in society as producers of large-scale environmental benefits and their positive contributions at the societal level.

The assessment of the potential negative impacts of product systems and processes has been standardised by ISO in ISO 14040 and 14044 (LCA), 14067 (product carbon footprint) and 14046 (water footprint). In the future, the assessment of the potential positive impacts of product systems and processes must also be standardised in line with the existing ISO standards on LCA. However, further harmonisation is needed for this step.

6 Conclusions

The main objective of the present study was to determine whether the environmental benefits of products and services could be evaluated by applying the handprint approach. Attaining this objective required answering RQ1 and recognising the specific characteristics of different environmental impacts in the context of handprint assessment. The case studies presented in Publications I, II and III identified the modification needs of the original carbon handprint framework in the context of air quality, N and water-related issues, respectively. As an outcome, general and conjunctive issues that are important to consider in handprint assessment were derived (see the Results chapter). In particular, the need to recognise relevant indicators, the selection between LCI and LCIA studies and the consideration of the locality versus globality of emissions were highlighted.

Answering RQ1 enabled proceeding to RQ2 and developing a coherent framework across the different environmental scopes to assess the positive impacts of products and services. Publication III presents the overall framework and shows that the handprint calculation can be conducted with similar guidelines for different environmental impacts by acknowledging the suitable indicators for each category. By providing step-by-step calculation guidance, Publication III paves the way for the quantitative assessment of handprints.

As a third step, Publication IV answers RQ3 by using the carbon handprint approach at the city and regional levels. According to Publication IV, regional handprints aim to communicate the innovative climate actions implemented by cities and regions. City-level consideration opens new opportunities for cities to enhance their climate work beyond aiming at climate neutrality by offering them indicators to systematically increase their handprint potential in the years to come. Through handprint actions, cities can attract new taxpayers and companies, thus increasing their viability and attractiveness.

Developed frameworks, both for assessing environmental handprints and for regional-level consideration, originate from the recognised need to quantify and communicate the positive environmental impacts of products, services and cities. This dissertation contributes to the present relevant knowledge by providing an important addition to the existing methods, which have mainly captured the environmental burdens of offerings. Thus, the handprint approach has a large and diverse application potential as it is a useful and feasible indicator for different actors aiming to show their offerings' and actions' positive contributions to the environment.

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Publication I

Lakanen, L., Grönman, K., Väisänen, S., Kasurinen, H., Soininen, A., and Soukka, R.
Applying the handprint approach to assess the air pollutant reduction potential of paraffinic renewable diesel fuel in the car fleet of the city of Helsinki

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Applying the handprint approach to assess the air pollutant reduction potential of paraffinic renewable diesel fuel in the car fleet of the city of Helsinki

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ABSTRACT

Ambient air pollution is a global environmental challenge, especially in densely populated regions. In urban areas, road traffic is an important source of fine particulate matter ($PM_{2.5}$) and nitrogen oxide (NO_x) emissions, primarily due to exhaust gases. The adoption of paraffinic renewable diesel fuels for urban transportation has been suggested as a more sustainable and less air polluting alternative to conventional fossil fuels. The aim of this study is, therefore, to examine whether the transition from the conventional fossil fuel diesel to paraffinic renewable diesel (hydrotreated vegetable oil [HVO] according to the EN 15940 standard) can reduce $PM_{2.5}$ and NO_x emissions in an urban environment. The life cycle assessment-based handprint approach is utilized to calculate and demonstrate the emissions reduction. The reduction potential is quantified for Euro 4, 5 and 6 passenger diesel cars using actual car fleet, mileage, local temperature, and laboratory emissions measurements for 2018 in Helsinki, Finland. Our study shows that the use of HVO can reduce $PM_{2.5}$ and NO_x emissions in urban areas. According to our results, $PM_{2.5}$ emissions could be reduced by 49% for the defined location and car fleet by replacing conventional fossil-fuel diesel with HVO. In the case of NO_x emissions, the local reduction potential is 7%. Overall life cycle emissions reduction potentials of NO_x and $PM_{2.5}$ emissions are 11% and 44%, respectively, if conventional diesel is replaced by HVO. Thus, the manufacturer of HVO can communicate the air quality handprint, and in particular, the NO_x and $PM_{2.5}$ handprints, that their product can achieve.

1. Introduction

Outdoor air pollution is a significant environmental health risk that is estimated to have caused approximately 4.2 million premature deaths worldwide in 2016 (WHO, 2018). Air pollutants increase cases of respiratory, vascular and heart diseases and have adverse effects on ecosystems and the climate (EEA, 2018a). Air pollution is closely related to global climate change because the combustion of fossil fuels is the main anthropogenic source of greenhouse gases, airborne particulate matter, sulphur and nitrogen oxides, and short-lived air pollutants such as black carbon and methane (Landrigan et al., 2018; Perera, 2017; Scovronick et al., 2015). Ambient (outdoor) air pollutants are typically particulate matter (PM), ozone (O_3), nitrogen dioxide (NO_2) and sulphur dioxide (SO_2) (WHO, 2018).

The adverse health impacts of poor air quality are concentrated in urban areas, which are not only population centres but also emissions hotspots, primarily due to traffic emissions. The main air pollutant compounds in cities that adversely affect human health are fine particulate matter and nitrogen oxides (NO_x) (EEA, 2019). Fine particulate matter with a diameter of 2.5 μm or less ($\leq PM_{2.5}$) has been recognized as having the most significant effect on human health as it can penetrate the lung barrier and enter the blood system (Anderson et al., 2012; Hänninen et al., 2014; WHO, 2018). Additionally, $PM_{2.5}$ emissions include various substances harmful to human health, such as heavy metals (Mazziotti-Tagliani et al., 2017; Soleimani et al., 2018), carbon compounds (Park and Lee, 2015) and sulphurs and carcinogens (WHO, 2003). Nitrogen

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oxides (NO_x) comprise nitric oxide (NO) and nitrogen dioxide (NO_2) (EEA, 2019). At high concentrations and under long-term exposure, NO_2 can cause inflammation of the airways, reduced lung function and other respiratory symptoms (WHO, 2003). Nitrogen oxides also have detrimental effects on environment, such as ozone layer depletion and acidification when dissolved in water bodies (Boningari and Smirniotis, 2016; Sepehri et al., 2020).

Road traffic is the biggest source of NO_x in EU-28 countries, and it was responsible for 39% of all NO_x emissions in 2017 (EEA, 2019). NO_x emissions from road vehicles are problematic since they are released near ground level, often in densely populated areas where the number of exposed citizens is high. The transportation sector is also an important contributor to fine particulate emissions, although sources of $PM_{2.5}$ emissions vary considerably depending on location, geographical characteristics and meteorological conditions (Vallius, 2005; WHO, 2018). $PM_{2.5}$ emissions from road traffic derive from exhaust gases but also from non-exhaust sources, such as brake wear, road wear, tyre wear and road dust resuspension (Amato et al., 2014). In European cities, road transport is assumed to be responsible for around 12% of primary fine particulate matter emissions (EEA, 2018b), and in OECD countries the proportion can be much higher (OECD, 2020). Nevertheless, emissions from vehicle exhausts have decreased significantly in recent years due to tightened emission legislations (EEA, 2019). At the EU level, this includes stricter emission standards (e.g. Euro 1–6) (EC, 2018, 2007) and the imposition of requirements for fuel quality (EC, 2009). However, the overall emissions from the transport sector have decreased less than expected because of the increase in passenger and freight volumes (EEA, 2018b). Furthermore, NO_x emissions under real driving conditions, particularly from diesel-powered passenger cars and vans, have shown to be higher in many cases than is permitted under European (Euro) emission regulations (EEA, 2018b; Kadijk et al., 2016). One explanation for this is that previously used test cycles did not represent real driving practices; hence, more accurate test cycles have since been developed and adopted for emissions measurement (Degraeuwe and Weiss, 2017).

As well as being responsible for a substantial amount of greenhouse gas emissions, diesel-powered vehicles have traditionally been significant sources of both NO_x and $PM_{2.5}$ emissions (Prasad and Bella, 2010; Reşitoı;lu et al., 2015). As an alternative to conventional fossil-fuel diesel, bio-based diesel has shown to offer advantages in terms of greenhouse gas and pollutant emissions (Naik et al., 2010). It is assumed that due to the properties of biofuel, the combustion process in the engine produces less air pollutant compounds than the combustion of conventional diesel and may thus reduce local air pollution. However, the characteristics and amount of air pollutant emissions from bio-based diesel vary depending on the composition of the fuel and the source of the raw materials (Lapuerta et al., 2008; Suarez-Bertoa et al., 2019). Bio-based diesel can be produced, for example, from different types of vegetable oils, used cooking oils and animal fats (Dimitriadis et al., 2018). The combustion of first-generation biodiesels produced from esterified vegetable oils (FAME) showed a reduction in particulate matter, hydrocarbon and carbon monoxide emissions but an increase in NO_x emissions compared to conventional diesel (Giakoumis et al., 2012; Hoekman and Robbins, 2012; Hutter et al., 2015; Torregrosa et al., 2013; Wu et al., 2009).

More advanced biofuels, such as hydrotreated vegetable oil (HVO), Fischer-Tropsch (FT) diesel and dimethylether (DME), were developed to offer a more sustainable alternative to first-generation biodiesels. The usage of HVO has been shown to result in reduced particulate matter, hydrocarbon and carbon monoxide emissions compared to conventional diesel (Happonen et al., 2013; Kuronen et al., 2007; Pflaum et al., 2010; Pirjola et al., 2019; Sugiyama et al., 2012). Reductions in particulate matter and carbon monoxide emissions are mainly due to the high cetane number and zero aromatics of HVO (Pflaum et al., 2010; Sugiyama et al., 2012). Research results concerning NO_x emissions from HVO combustion are not consistent and unequivocal since NO_x emissions vary for different types of engine technology, fuel properties, test cycles, type of fuel injection system and other engine parameters (Aatola et al., 2009; Erkkilä et al., 2011; Pechout et al., 2019). Some studies have observed NO_x reductions for HVO compared to conventional diesel (Aatola et al., 2009; Bohl et al., 2018; Hemanandh and Narayanan, 2017; Ogunkoya et al., 2015; Pechout et al., 2019; Pflaum et al., 2010), whereas other studies have shown comparable or increased NO_x emissions from HVO combustion (Dimitriadis et al., 2018; Happonen et al., 2013; Kousoulidou et al., 2014; Millo et al., 2015; Sugiyama et al., 2012). Regarding carbon dioxide emissions, HVO has shown to have lower global warming potential (GWP100) when taking the whole life cycle into account (Arvidsson et al., 2011; Grönman et al., 2019) as well as lower tailpipe carbon dioxide emissions (Nylund et al., 2011).

Although numerous studies have examined air pollutant emissions from different bio-based and fossil fuels, there is still a lack of understanding of how the transition from fossil fuels to renewables would affect emissions and air quality in cities. The potential for a reduction in $PM_{2.5}$ and NO_x emissions when transitioning to renewable diesel is usually studied based on laboratory emissions measurements, and transition effects in a real operating environment are often neglected. To our knowledge, only a few studies have assessed the change in the emission levels at the urban scale when bio-based diesel fuel is used instead of conventional diesel (Dias et al., 2019; Hutter et al., 2015; Pino-Cortés et al., 2015; Ribeiro et al., 2016). Furthermore, these studies focused on FAME and not HVO.

Hence, this paper aims to identify and quantify whether using HVO in passenger diesel cars can reduce NO_x and $PM_{2.5}$ exhaust gas emissions in an urban Nordic city (Helsinki, Finland), and if so, by how much. In the study, we combine the laboratory measurement of emissions data with local car fleet, vehicle mileage, and weather observations. Life cycle NO_x and $PM_{2.5}$ emissions are also taken into account to observe possible trade-offs in emissions between life cycle stages. Previous studies have mainly concentrated on tank-to-wheel emissions since their impact on local air quality has been recognized to be the most significant. In this work, however, we also include well-to-tank life cycle analysis. One aspect of the novelty of this article is that our study combines emissions from Euro 4, 5 and 6 diesel passenger cars operating under different ambient temperatures because previous studies have shown a clear temperature-dependency for vehicle emissions (Grange et al., 2019; Ko et al., 2019; Suarez-Bertoa and Astorga, 2018). Laboratory measurements on emissions are conducted using the Worldwide Harmonized Light Vehicles Test Cycle (WLTC) (EC, 2017; EU, 2017), which more closely resembles real driving conditions – and hence, emissions – than the previously used New European Driving Cycle (NEDC) (Degraeuwe and Weiss, 2017).

The research presented in this paper adopts the guidelines for handprint thinking presented by Grönman et al. (2019) and Pajula et al. (2018). The handprint approach offers guidance on how to set up a comparison between a novel solution and the business-as-usual situation. This allows the change, or preferably the reduction, in emissions to be seen when the new solution is introduced in the same operating environment as the baseline solution. The handprint approach is based on the standardized life cycle assessment (LCA) method and was originally developed to quantify the greenhouse gas reduction potential of products when used by a customer; this is the first attempt to utilize the handprint guidelines in an outdoor air quality setting.

2. Methods

The carbon handprint assessment approach for a product is structured on a framework with step-by-step guidance (Pajula et al., 2018), which is slightly modified here for the assessment of air quality changes. These modifications to the original carbon handprint approach are presented in yellow in Fig. 1. The right-hand side in the same figure outlines the paraffinic renewable diesel case examined in this study using the modified handprint approach for air quality.

The fuel examined here is HVO made from used cooking oil. HVO is a paraffinic renewable diesel fuel with zero aromatics and meets the requirements of the EN 15940 standard. The city of Helsinki, Finland, was assumed to be the customer in this case, meaning the assessment examined how a change of diesel fuel would affect the amounts of selected air pollutants in the Helsinki region. The examination covered the entire year of 2018, which was the most recent year for which representative data were available. The handprint approach, when applied to air quality, requires an additional step to identify the relevant indicators, in this case, airborne pollutants. This paper investigates $PM_{2.5}$ and NO_x emissions because they have been identified as important contributors

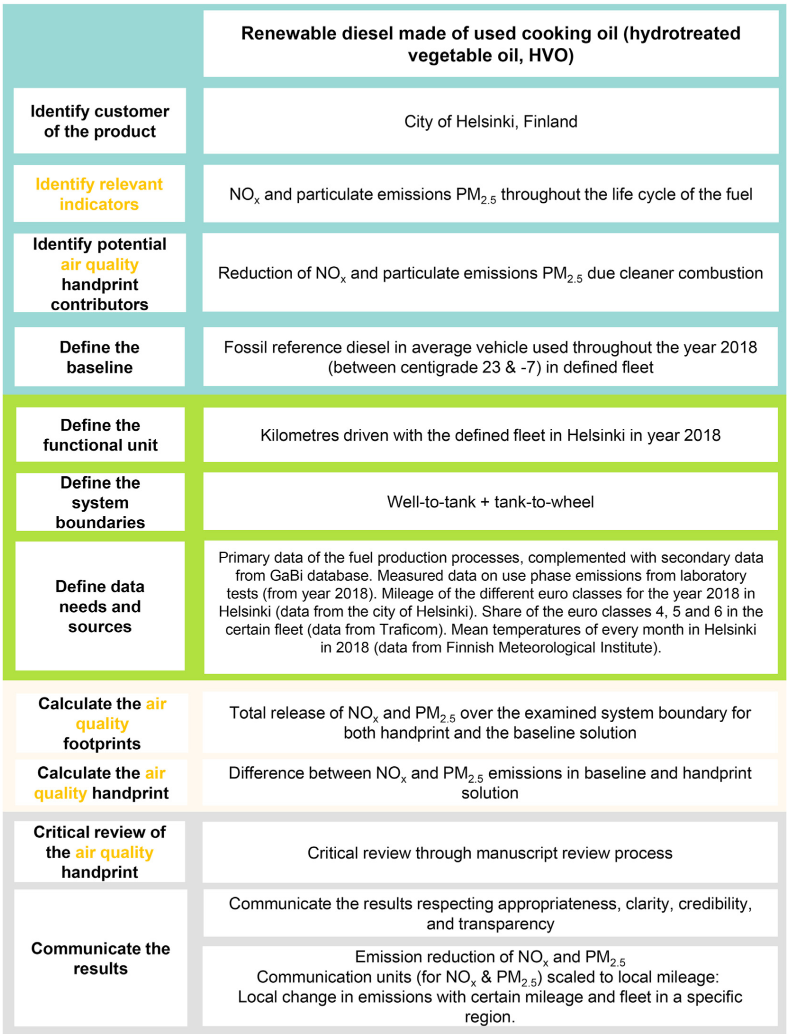

Fig. 1. Framework for the air quality handprint approach using the case study of replacing conventional diesel with paraffinic renewable diesel in passenger cars in Helsinki in 2018.

to ambient air quality in cities (Martínez-Bravo and Martínez-del-Río, 2020). Additionally, traffic exhaust emissions, especially from diesel-powered vehicles, are a major source of these compounds in urban areas (EEA, 2019; Karagulian et al., 2015; Prasad and Bella, 2010). Moreover, $PM_{2.5}$ has been identified as being very harmful to human health, and NO_x also adversely impacts on health (Anderson et al., 2012; Hänninen et al., 2014; WHO, 2003). Sulphur oxide and ground-level ozone were excluded from the study as, as in most of Europe, legislation in Finland sets limits on the sulphur content of road fuels. Hence, SO_x emissions from road traffic have declined markedly since the early 1990s and SO_x levels in Finland are well below the limit set to protect human health (Finnish Environment Institute, 2015; IEA, 2016). Ground-level ozone was excluded because it is formed in photochemical reactions involving volatile organic compounds and NO_x and does not itself occur in emissions (Zhang et al., 2019).

The hypothesis for creating an air quality handprint is that the transition from conventional fossil fuel diesel to HVO decreases NO_x and $PM_{2.5}$ emissions due to the cleaner combustion process in the vehicle's engine. In this study, the 100% conventional diesel used in Helsinki was substituted with 100% HVO. Thus, conventional diesel serves as the baseline product in this case. The baseline diesel contained 7% biocomponents, in this case FAME, which is in line with current European fuel standards that allow up to 7% biodiesel volume in fossil fuel diesel (EN 590:2013, 2017). The replacement of conventional diesel was studied for a defined fleet representing diesel-powered passenger cars from three different Euro regulation tiers (Euro 4, 5 and 6). Euro 4 regulations came into effect in 2005, Euro 5 in 2009 and Euro 6 in 2014 (DieselNet, 2020).

In 2018, the total vehicle mileage in the Helsinki city area was 2463 million kilometres. The calculated share of passenger vehicles was 1645 million kilometres and the share of diesel passenger vehicles was 420 million kilometres. Euro 4, 5 and 6 diesel-powered passenger cars corresponded to 26% of all passenger vehicles and 17% of all vehicles in Helsinki. The proportions of Euro 4, 5 and 6 of all diesel passenger vehicles in Helsinki were 17%, 35% and 42%, respectively (Fig. 2).

The functional unit used in the study was kilometres driven by the defined diesel-powered passenger vehicle fleet in the Helsinki city area in the year 2018. A more detailed depiction of the vehicle fleet is presented in Table 1.

The examination included the entire well-to-wheel life cycle of the studied fuels. However, the results are presented separately for the production phase (well-to-tank) and use phase (tank-to-wheel) as those emissions occur in different geographical locations (Fig. 3). Use phase covers exhaust emissions that are emitted during the drive.

The well-to-tank emissions of the renewable diesel were derived from the manufacturer; in the case of conventional diesel, the LCA modelling software GaBi's database was used (Sphera, 2019). The tank-to-wheel emissions of the conventional and renewable diesel were quantified under laboratory conditions using the WLTC test cycle at −7 °C and 23 °C. Emissions occurring between these temperatures were estimated via interpolation. The impacts of temperature on the formation of NO_x and $PM_{2.5}$ were taken into account using the mean temperatures of each month in 2018, taken from the Finnish Meteorological Institute's (Finnish Meteorological Institute, 2018) Kaisaniemi measurement point in Helsinki. Based on the average temperatures, the coldest month in Helsinki in 2018 was February, where the average temperature was −7 °C, and the warmest was July, with the average of 21.1 °C. The consumption of diesel fuel was assessed based on the data considering the actual mileage during the year 2018 (Helsingin kaupunki, 2018). Mileage was assumed to be shared evenly across each month of the year. The number of diesel cars and the proportions of Euro 4, 5 and 6 vehicles in the study area were based on vehicle data from the Finnish Transport and Communications Agency (Traficom, 2019).

The subsequent steps in the framework required the calculation of the air pollutant emissions both for the renewable diesel and for the baseline diesel. Any reduction in air pollutants using renewable diesel would result in an air quality handprint — in this case specifically NO_x and $PM_{2.5}$ handprints. The results and the appropriate way to communicate them are presented in the following section.

3. Results

The NO_x and $PM_{2.5}$ exhaust emissions in Helsinki based on the year 2018 fleet are presented in Fig. 4. The NO_x exhaust emissions for conventional and HVO diesel were 283 000 kg and 264 400 kg, respectively. The annual $PM_{2.5}$ exhaust emissions in Helsinki were 3000 kg for conventional diesel and 1600 kg for HVO. Fig. 4 also shows how the emissions in the studied fleet were distributed among the included Euro regulated car groups. In the defined Helsinki (2018) fleet, Euro 5 cars were responsible for 66% of conventional diesel and 65% of HVO NO_x exhaust emissions. When considering $PM_{2.5}$ exhaust emissions, the share of Euro 4 cars was 94% and 89% for conventional diesel and HVO, respectively.

The reduction potentials of NO_x and $PM_{2.5}$ exhaust emissions due to the replacement of conventional diesel with HVO in Helsinki based on 2018 values in the studied fleet are presented in Fig. 5. The reduction potential is highest for $PM_{2.5}$ emissions, which are reduced on average by 49% when compared to conventional diesel. In the case of NO_x emissions, the reduction potential is 7%. However, when communicated in kilograms, the NO_x reduction potential in Helsinki based on the year 2018 fleet proved to be highest, at 18 500 kg, and the $PM_{2.5}$ exhaust emissions reduction potential is 1500 kg. In the Helsinki (2018) fleet, the highest NO_x reduction

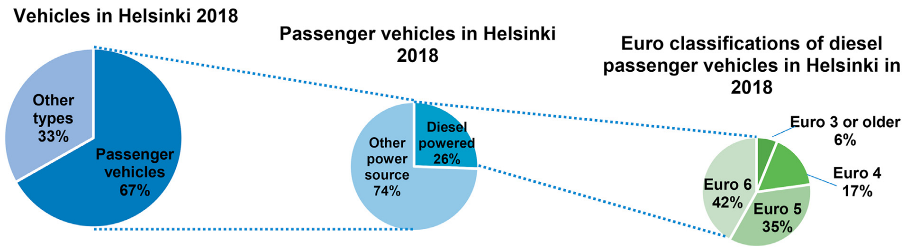

Fig. 2. Examined vehicles in Helsinki in 2018.

Table 1
Number of passenger vehicles and driven kilometres in Helsinki in 2018.

	Diesel passenger vehicles					Other passenger vehicles	All passenger vehicles
	Euro 4	Euro 5	Euro 6*	Other Euro classes	In total	In total	
Number of passenger vehicles	8341	17 744	20 961	3068	50 114	146 110	196 224
Million kilometres	69.74	148.73	175.62	26.05	420.13	1224.87	1645.00

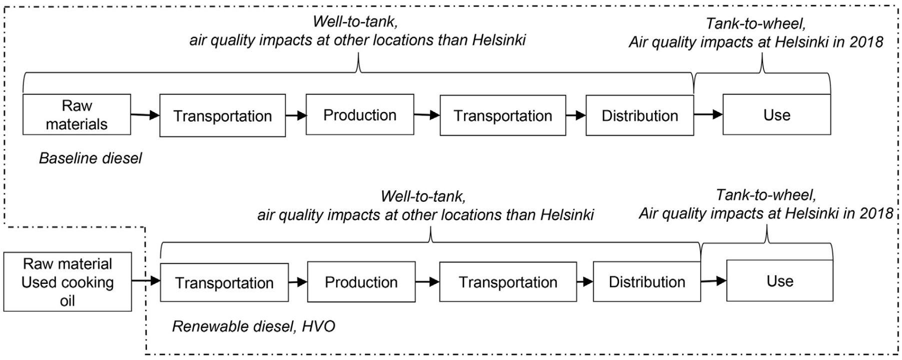

Fig. 3. System boundaries.

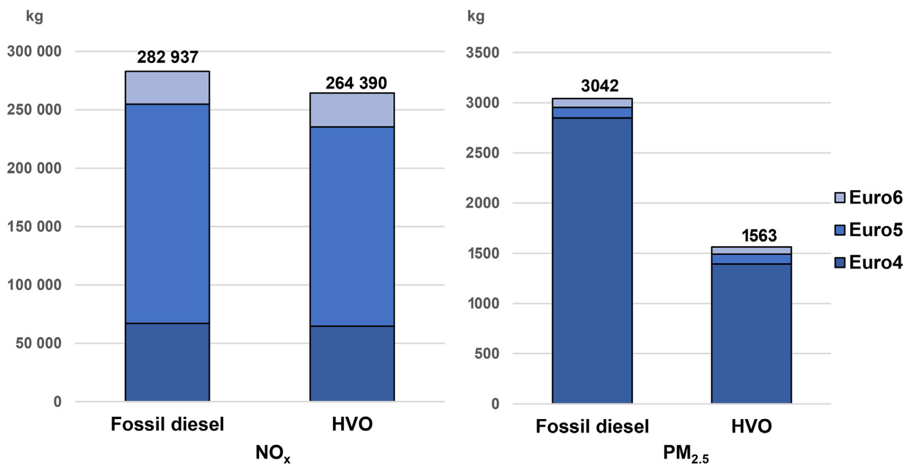

Fig. 4. Annual NO_x and $PM_{2.5}$ exhaust emissions in Helsinki based on 2018 values.

potential is for Euro 5 cars, at 9%, and in the case of $PM_{2.5}$ exhaust emissions, for Euro 4 cars, at 50%.

In this study, local NO_x and $PM_{2.5}$ exhaust emissions in Helsinki represent the tank-to-wheel phase of the studied fuels' life cycles. However, in the handprint methodology, it is important to examine the whole life cycle to identify the most emission-producing life cycle stages and examine possible trade-offs. Hereby, it should be noted that the well-to-wheel and tank-to-wheel emissions occur at different geographical locations. Local air quality impacts can only be identified through a separate calculation of the different life cycle stages. Fig. 6 shows the contribution of well-to-tank and tank-to-wheel phases to the total life cycle NO_x and $PM_{2.5}$ emissions of the studied fuels. The results show that the tank-to-wheel phase dominates in every studied case. When considering NO_x life cycle emissions, the tank-to-wheel phase covers 92% of conventional fuel and 96% of HVO life cycle emissions. In the case of $PM_{2.5}$ emissions, tank-to-wheel emissions account for 84% of life cycle emissions in conventional diesel and 77% in HVO.

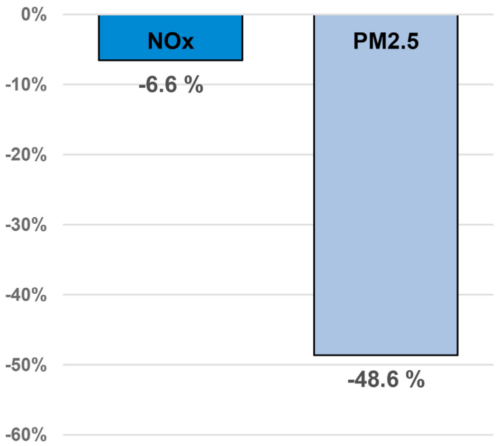

Fig. 5. Annual reduction potential of NO_x and $PM_{2.5}$ exhaust emissions in Helsinki based on the year 2018 values for diesel-powered passenger cars.

As mentioned previously, the total life cycle reduction potential of NO_x and $PM_{2.5}$ emissions can be considered as the air quality handprint. The emissions reduction, i.e. the NO_x and $PM_{2.5}$ handprint, can be calculated by comparing the well-to-wheel NO_x and $PM_{2.5}$ emissions of the studied fuels. Fig. 7 demonstrates the total life cycle NO_x and $PM_{2.5}$ emissions of the studied fuels based on the fuel consumption of the Helsinki (2018) fleet. The results show that NO_x emissions are 32 700 kg lower when HVO is used instead of conventional diesel. Similarly, $PM_{2.5}$ emissions are 1580 kg lower with HVO. As a consequence, the emissions reduction could be considered as a handprint, which means that a manufacturer of the HVO could communicate the handprint of 32 700 kg, or 11%, for NO_x in this case with the studied fleet as they have enabled an equivalent footprint reduction of the customer. The $PM_{2.5}$ handprint would be 1580 kg, or 44%, for the defined fleet in Helsinki in 2018.

4. Discussion

The results show that paraffinic renewable diesel has the potential to reduce NO_x and $PM_{2.5}$ emissions in a city such as Helsinki with its average fleet and climatic conditions. The paraffinic renewable diesel fuel may offer a way to decrease $PM_{2.5}$ emissions, especially from older cars without advanced emissions cleaning technologies; hence, the biggest emissions reduction can be achieved in areas where the car fleet is relatively old. Our findings are in line with previous studies, which have shown a reduction in $PM_{2.5}$ emissions for paraffinic renewable diesel combustion compared to conventional fossil-fuel diesel (Bortel et al., 2019; Nylund et al., 2011; Pflaum et al., 2010; Sugiyama et al., 2012). $PM_{2.5}$ emissions were 49% lower in the case of paraffinic renewable diesel compared to conventional diesel when observing the use-phase emissions. According to our results, the reduction potential for $PM_{2.5}$ emissions is higher for Euro 4 diesel passenger cars than newer cars. The reason for the improvement in the particulate emissions reduction rate originates from the introduction of diesel particulate filters (DPF) in Euro 5 diesel passenger cars (EC, 2007). While many previous studies (Dias et al., 2019; Hutter et al., 2015; Kousoulidou et al., 2014) proved that the use of first-generation biodiesel will increase the NO_x emissions of transportation, our results highlight that NO_x emissions may also decrease through the use of paraffinic renewable diesel instead of conventional fossil-fuel diesel. NO_x emissions in the use phase are tightly linked to the outside temperature and vehicle model, and consequently, it is important to examine NO_x emissions with the actual car fleet and climatic conditions in a certain location. The NO_x emissions reduction corresponds to the NO_x emissions produced by 40.9 million kilometres driven with conventional diesel when calculated with the average emissions from Euro 4–6 diesel passenger cars at an ambient air temperature of 7 °C, which was the annual average temperature in Helsinki in 2018. For Euro 4 specifically, the $PM_{2.5}$ reduction is similar to the $PM_{2.5}$ emissions caused by 113.1 million kilometres driven with conventional diesel.

Our results do not include emissions from Euro 0–3 passenger diesel cars. The share of Euro 0–3 diesel cars in the studied fleet was 6.5% and if all the vehicles in the study area were included, the results may change. Additionally, according to scientific evidence, NO_x reductions are higher in heavy-duty than in light-duty diesel vehicles when using HVO as a fuel instead of conventional diesel (Aatola et al., 2009; Bohl et al., 2018; Neste, 2016). This is mainly due to differences between engine sizes and engine properties,

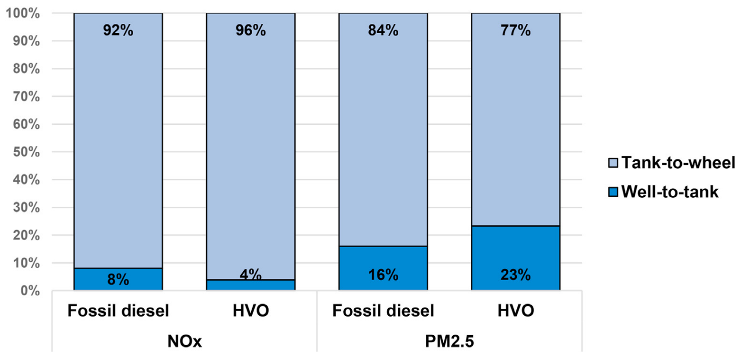

Fig. 6. Share of the different life cycle phases of NO_x and $PM_{2.5}$ emissions.

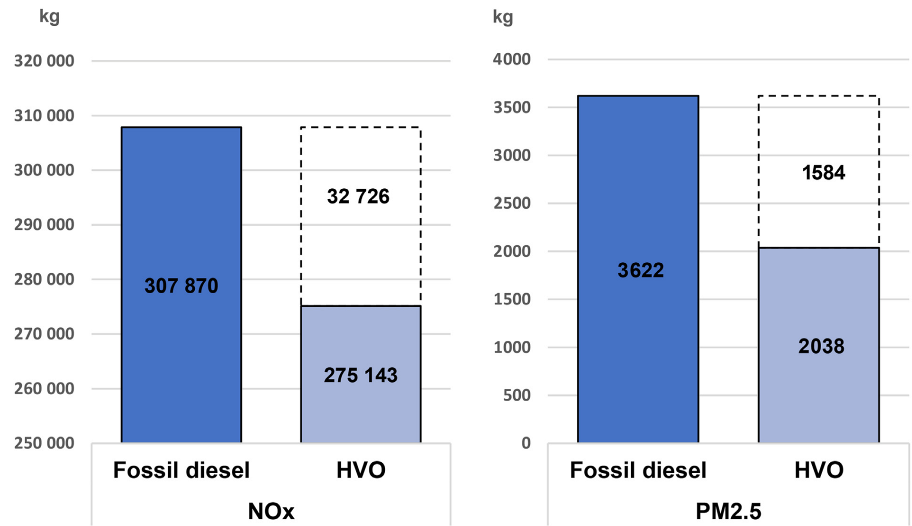

Fig. 7. Total life cycle NO_x and $PM_{2.5}$ emissions of the studied fuels and their NO_x and $PM_{2.5}$ handprints.

especially higher cycles and loads in heavy-duty engines (Muncrief, 2016; Neste, 2020). Heavy duty vehicles cause greater amount of NO_x emissions due to higher temperatures in the engine. However, ignition and combustion properties of HVO result in a smaller share of premixed combustion, thus causing less NO_x emissions (Neste, 2020). Heavy traffic was excluded from our study because no recent laboratory emissions measurements were available. Including Euro 0–3 passenger vehicles and heavy traffic to the calculation would offer a better understanding of diesel cars' air pollutant impacts on local air quality and would also help to examine the whole potential to reduce local air pollution through fuel replacement. It is also important to conduct the study in areas besides Helsinki because local emissions and conditions along with the local vehicle fleet affect the air pollutant reduction potential. In addition, laboratory measurement data for temperatures below −7 °C would be interesting to study because particularly use phase NO_x emissions increase when ambient temperature decreases (Grange et al., 2019; Suarez-Bertoa and Astorga, 2018). Also, further measurements with different vehicles, including heavy traffic, different velocities, and stop-and-go driving, would provide important data.

As the tank-to-wheel phase proved to be the most significant emission source of $PM_{2.5}$ and NO_x, the choice of fuel may have an impact on local air quality. Nevertheless, it is essential to recognize in which locations the emissions from different life cycle stages occur. Further studies are required to put the results into the context of local air pollutant concentrations or to proportion the results to air quality limits. Using dispersion models of air pollutants is necessary to recognize different emission sources affecting local air quality, as is taking weather conditions and other relevant factors into account. Influencing local emissions has traditionally been beyond the reach of individual citizens, but the choice of fuel may give an opportunity to enhance local air quality. In addition to decreased air pollutant emissions, paraffinic renewable diesel has been claimed to have other advantages over conventional diesel. For instance, it has been shown to have lower life cycle and use-phase greenhouse gas emissions than conventional fossil-fuel diesel (Arvidsson et al., 2011; Grönman et al., 2019; Nylund et al., 2011).

Replacing conventional diesel with renewable diesel may bring about positive environmental impacts if NO_x and $PM_{2.5}$ exhaust gas emissions are decreased. Our results highlight that the emissions reduction potential is significant in the tank-to-wheel phase when considering the whole life cycle of the fuels. According to Grönman et al. (2019) and Pajula et al. (2018), a handprint refers to the beneficial environmental impacts of a product when used by a customer. Thus, the well-to-wheel emissions reduction potential could be interpreted as the handprint of the renewable diesel fuel. However, the different life cycle stages must also be studied separately since emissions occur at different geographical locations, meaning it is not appropriate to observe only the total well-to-wheel emissions. Our results show that the handprint approach can also be applied to environmental impacts other than greenhouse gas reduction, and only a slight modification to the approach allowed the specifics of air quality handprint assessment to be tackled. These modifications were identifying the relevant indicators in terms of air pollutants and communicating the results taking into account the locality of emission release.

5. Conclusions

The need to improve urban air quality has led to the search for solutions to reduce traffic-related emissions. On the other hand, the initiators of these solutions require a sound, science-based method with which to calculate and communicate the benefits their product offers in reducing pollution. This study presents the results of how a paraffinic renewable diesel can reduce the annual NO_x and $PM_{2.5}$ emissions in the Helsinki area. The handprint calculation approach is implemented in the scope of outdoor air quality.

Based on the concluded air quality handprint assessment, wherein the lifetime emissions of a paraffinic renewable diesel (HVO) are compared to those of baseline conventional diesel, the results give a strong indication that by choosing the paraffinic renewable diesel, the NO_x and $PM_{2.5}$ emissions can be significantly reduced, especially in the use phase of the fuel. The emissions reduction potential is noteworthy, especially in older diesel vehicles with no novel filtration or other emissions reduction system. Using HVO-based renewable diesel in Euro 4 (or older) vehicles can reduce $PM_{2.5}$ emissions in particular. Also, NO_x reduction is possible and indeed significant when considering absolute NO_x kilograms. Accordingly, manufacturers of paraffinic renewable diesel can communicate that if all the Euro 4–6 diesel vehicles in Helsinki were to shift to their paraffinic renewable diesel, they would gain an annual NO_x handprint of 32 700 kg and a $PM_{2.5}$ handprint of 1600 kg based on Helsinki year 2018 data.

Despite the findings on the reduction potential of NO_x and $PM_{2.5}$ demonstrated here, the effect is less significant for modern diesel vehicles. As car fleets are updated, the benefit of using renewable diesel instead of fossil diesel diminishes in terms of air quality. This indicates that the best results for improving air quality can be achieved when using paraffinic renewable diesel in areas where the fleet uses older technology. However, using paraffinic renewable diesel instead of conventional diesel also decreases the burden on exhaust gas cleaning systems in newer cars while reducing the overall air pollutant emissions of the car fleet.

CRediT authorship contribution statement

Laura Lakanen: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Preparation, Writing - review & editing, Visualization. **Kaisa Grönman:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - original draft, Preparation, Writing - review & editing, Visualization, Project administration, Funding acquisition. **Sanni Väisänen:** Software, Formal analysis, Data curation, Writing - review & editing. **Heli Kasurinen:** Conceptualization, Methodology, Writing - review & editing, Funding acquisition. **Asta Soininen:** Conceptualization, Resources, Data curation, Writing - review & editing, Supervision, Funding acquisition. **Risto Soukka:** Conceptualization, Methodology, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Publication II

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Developing the nitrogen handprint approach to quantify the positive impacts of industrial symbiosis on nitrogen cycles

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Developing the nitrogen handprint approach to quantify the positive impacts of industrial symbiosis on nitrogen cycles

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ABSTRACT

Excessive nitrogen (N) uptake for nutrient use in food production and industry and increased N losses to the environment severely interfere with nutrient cycles and harm the environment and thus, closing N cycles through N recovery and recycling is required to improve N use efficiency. To quantify positive impacts enhancing N cycles, this study suggests a novel N handprint approach, which combines life cycle assessment based nutrient footprint and carbon handprint approaches. The N handprint comprises of a set of indicators providing a wide systemic view on changes in N cycles. The case study demonstrates that the N handprint is created when a recycled N nutrient product is used instead of a virgin N nutrient for the needs of a pulp and paper mill wastewater treatment. According to our results, the handprint equals a reduction of 454 kg of virgin N inputs, and 5.6 kg of total N inputs for daily treated wastewater. Additionally, global warming potential is 91%, and the eutrophication potential 48% lower for the recycled N nutrient than for the virgin N nutrient. These results can be used to promote the use of recycled N on similar occasions in order to improve nutrient use efficiency.

1. Introduction

Nitrogen (N) nutrients are required in large quantities, mainly as a fertilizer for the food system (Sutton et al., 2013; Kahiluoto et al., 2014). Rockström et al. (2009) and Steffen et al. (2015) stated that human activities severely interfere with global and local nutrient cycles. N resources in the atmosphere are abundant; however, the safe boundary for introducing new atmospheric N_2 to the nutrient cycle as reactive N (N_r) has been transgressed (Steffen et al., 2015) mainly due to highly inefficient use of N as a nutrient. Sutton et al. (2013) stated that, on average, over 80% of consumed N nutrient is lost to the environment. Galloway et al. (2004, 2014) defined N_r as any form of N except N_2. N_r release into the environment from the nutrient cycle takes several forms and has various adverse and sequential environmental impacts, known as the nitrogen cascade (Galloway et al., 2003). For example, the airborne emissions of greenhouse gas (GHG) N_2O accelerate climate change and NO_x emissions from combustion processes decrease air quality and cause health risks. In addition, while NO_x emissions have a negative terrestrial and aquatic eutrophication and acidification impact and damage vegetation, they also contribute to tropospheric ozone formation and harm biodiversity. Furthermore, nitrates (NO_3^-) may have a toxic impact on aquatic environments, and ammonia (NH_3) volatilization causes a deterioration in air quality (De Vries et al., 2013; Sutton et al., 2013.) The energy-intensive Haber–Bosch process to convert atmospheric N_2 to N_r accounts for 2% of global energy consumption (Sutton et al., 2013), causing further environmental impacts. A necessary solution is to increase N use efficiency by closing N cycles through nutrient recovery and recycling (De Vries et al., 2013; Kahiluoto et al., 2014).

To date, nutrient use has been mainly evaluated by using nutrient footprints and nutrient use efficiencies (Grönman et al., 2022). Many of the methods – such as the N-Calculator (Leach et al., 2012; Noll et al., 2020), the nutrient use efficiency of the full chain (Sutton et al., 2013), the N use efficiency of a food chain (Erisman et al., 2018), the N use efficiency of the life cycle (Uwizeye et al., 2016), and the N food-print (Chatzimpiros and Barles, 2013) – might be suitable for assessing food products only. More importantly, their aim is to understand the nutrient flows on a national or local scale rather than to improve the nutrient balance of a specific product system. In contrast, the nutrient footprint presented by Grönman et al. (2016) and further applied by Joensuu et al. (2019) offers a tool to identify the nutrient hotspots in bio-based product

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chains by providing a resource efficiency indicator, which focuses on the nutrient flows and nutrient balance of a system. However, the environmental impacts of nutrient emissions, such as eutrophication, are outside the scope of the nutrient footprint assessment. When necessary, combining the nutrient footprint with environmental impact indicators would give a comprehensive picture of the sustainability of nutrient use.

Nutrient footprint and nutrient use efficiency methods concentrate on assessing nutrient use but ignore the positive impacts provided by new products or solutions improving nutrient cycles. Recently, handprints have become important indicators beside footprints since they can highlight the positive environmental impacts products or services can produce (Guillaume et al., 2020). Norris et al. (2021) defined an actor's handprint "as a net positive change relative to business as usual, measurable in footprint units, of which the actor is a cause." According to Pajula et al. (2021), "a handprint refers to the beneficial environmental impacts that organizations can achieve and communicate by providing products and services that reduce the footprints of others." Grönman et al. (2019) and Pajula et al. (2018) also defined more specific carbon handprint approach to assess and communicate the positive climate impacts of products when used by a customer and compared to a business-as-usual solution. The carbon handprint approach is based on standardized life cycle assessment (LCA) methodology and utilizes footprint calculations to make the comparisons. The carbon handprint framework provides a systematic way to assess life cycle climate benefits at system level in a comparative manner. Thus, it is a useful indicator for comparing the climate impacts of different solutions and identifying improvement potential in product systems or processes. The carbon handprint approach has been applied by, for example, Jenu et al. (2020) and Kasurinen et al. (2019).

The sustainable use of nutrients is increasingly integrated into different sectors through circular economy targets (European Commission (EC), 2020). The benefits of circular solutions improving nutrient cycles have been recently discussed in the food sector by, for example, Koppelmäki et al. (2021) and Harder et al. (2021). The EC has recognized the potential for a 30% reduction of non-renewable resources in fertilizer production, and the regulation of fertilizers aims to, for example, ease the access of organic and waste-based fertilizers to the market (EC, 2016). In Finland, biowaste and biomass side-streams contained 95 000 tonnes of N annually in 2014–2016. Of this, 34 700 tonnes per year were soluble N, which could be used as a nutrient. Simultaneously, however, 152 000 tonnes of inorganic N fertilizers were used per year (Marttinen et al., 2018.) Thus, the potential for utilizing recycled nutrients is assumed to be comparatively high. As recent geopolitical instabilities have led to restricted availability of synthetic fertilizers and a steep increase in prices, the rationale for finding ways to recycle nutrients is even stronger.

Industrial symbioses play a crucial role in increasing the rate of waste and by-product circulation in industries. Besides, they may have many other benefits, including reduction of environmental impacts, GHG emissions, and the use of fossil fuels as well as creation of economic value (Fertilizers Europe, 2019). Aho et al. (2015) offered the sustainability benefits and risks of recycled nutrients produced at a biogas plant and used at an industrial wastewater treatment plant (WWTP). They concluded that the greatest sustainability benefit of nutrients results from the use of waste as a raw material instead of a virgin product. The production of a recycled nutrient product consumed less energy, water, and mineral resources than a similar product made of primary raw materials. Additionally, recycled nutrients caused lower health and environmental threats linked to chemical use (Aho et al., 2015.)

The objective of this study is to develop and test a novel N handprint approach to assess positive impacts enhancing N cycles by combining two LCA-based tools: the nutrient footprint method (Grönman et al., 2016; Ypyä et al., 2015) and the carbon handprint approach, which aims to quantify context-specific positive climate impacts (Grönman et al., 2019; Pajula et al., 2018). N footprint methodologies have concentrated on assessing absolute N flows, but they do not include assessment of potential positive impacts achieved with novel or alternative solutions. Nor do footprints enable a comparison between different solutions. The N handprint presented in this paper aims to overcome these deficiencies by providing a comparative indicator which acknowledges the real operating environment of the solutions under consideration. As is typical of handprint methodology, the benefits brought about for a user in terms of enhanced N cycles are included in the N handprint assessments. According to Zhang et al. (2020), consistent and structural multi-system and multi-spatial scale approaches with systemic-level examination to quantify nutrient budgets still lack. The N handprint approach presented in this paper aims to fill this gap by providing a systematic framework to quantify and communicate positive impacts on nutrient cycles at a systemic level. Whereas previous research has concentrated mainly on developing methods to quantify nutrient use in various food supply systems at different geographical boundaries (e.g., Chatzimpiros and Barles, 2013; Leach et al., 2016; Uwizeye et al., 2016; Erisman et al., 2018), our study aims to amplify understanding of assessing nutrient flows more widely, including in contexts other than food production.

The N handprint approach is applied and tested in a case study of an industrial symbiosis between an industrial WWTP and a provider of a recycled nutrient product to quantify the potential positive impacts on N cycles. To our knowledge, this is the first attempt to assess positive impacts on nutrient cycles by applying the handprint methodology. Previously, the handprint approach has been modified to quantify an air quality handprint (Lakanen et al., 2021) and for the use of cities and regions to quantify their positive climate actions (Lakanen et al., 2022). This study was conducted as a part of the Environmental Handprint Project by the research institution VTT and LUT University during the years 2018–2021 (Vatanen et al., 2021), and it constitutes an essential part of the extensive methodological entity of the environmental handprint introduced by Pajula et al. (2021) and Lakanen et al. (2022a).

2. Methodology

In this paper, we present an approach whereby two previously published assessment methods, the carbon handprint (Section 2.1) and the nutrient footprint (Section 2.2), are combined to form the N handprint approach. The novel N handprint approach and guidelines as to how the evaluation should be carried out are presented in Section 2.3. The N handprint approach is then applied to the case study considering N recycling as part of the needs of the WWTP of a pulp and paper mill (Section 2.4).

2.1. Carbon handprint

The carbon handprint approach provides a step-by-step procedure to assess the positive climate impacts enabled by a novel product, service, or product chain replacing a business-as-usual solution in a certain area and for certain users (Grönman et al., 2019; Pajula et al., 2018). The carbon handprint assessment compares the life-cycle carbon footprints of a baseline and a novel (i.e., offered) solution, and a handprint is created when a carbon footprint of an offered solution is less than a carbon footprint of a baseline solution. However, the key issue is that reducing own carbon footprint only is not a handprint; instead, for an offered solution to achieve a carbon handprint, it should bring about reductions in the GHG emissions of others.

A carbon handprint enables a comparison of two different products, services, or product chains. Consequently, setting a baseline essentially affects the magnitude of a potential handprint. Based on carbon handprint guidelines, a baseline should be a product, service, or product chain which delivers the same function to the user as the offered solution and is used for the same purpose by the users within a specific time period and region (Pajula et al., 2018).

2.2. Nutrient footprint

The nutrient footprint proposed by Grönman et al. (2016) is a resource efficiency indicator which focuses on nutrient flows and the nutrient balance of a system by combining nutrient intake and nutrient use efficiency. The indicator can be applied to assess the N or phosphorus (P) balances of food chains and other bio-based production chains. As based on LCA, the nutrient footprint takes into account the entire life cycle of the offered production chain. However, examination of nutrient flows is only performed at inventory level, and the amounts of nutrients are not characterized to represent different environmental impact categories.

The nutrient footprint considers virgin and recycled nutrient inputs into a system, the utilization of nutrients in product(s) of the system, and nutrient outputs as nutrient emissions, wasted nutrients, or nutrients in by-products from the system. Virgin nutrients are defined as nutrients extracted from natural resources and converted to a reactive form for human use. Recycled nutrients are already in the nutrient cycle and are recycled for human use in the system. Recycled nutrients can be, for example, waste flows or side streams whose nutrient content is further utilized. Utilized nutrients are bound to the product. Nutrients may be lost as emissions to air or water systems or as part of material that is incinerated, placed in landfill, or used for other purposes so that its nutrient content is no longer utilized for human purposes (e.g., building material) (Grönman et al., 2016).

2.3. Nitrogen handprint

This study modifies the carbon handprint approach (Grönman et al., 2019; Pajula et al., 2018) for an N context by utilizing a previously published nutrient footprint approach (Grönman et al., 2016). The N handprint approach developed is presented in Fig. 1, below. It consists of 13 steps, divided into four stages, which guide the performance of an N handprint assessment. Compared to the original carbon handprint guidelines by Pajula et al. (2018), additional steps are included in the N handprint framework (steps 1, 3, and 11), and some terms are replaced or specified to better fit the N context, especially in step 10.

The *first stage, handprint requirements*, is specific to handprint assessments, as opposed to other LCA studies (Pajula et al., 2018, 2021). In the carbon handprint assessment, the first stage includes three steps: identifying customers, identifying potential handprint contributors, and defining the baseline (Pajula et al., 2018), which requires the purpose of the N handprint assessment to be modified. First, the offered solution should be clearly specified (step 1). The offered solution refers to a product or service that can enable positive environmental impacts for its user, in this case improvement in N balance. Thereafter, potential contributors should be identified, or, in other words, a hypothesis should be made about how the offered solution could help N cycles in comparison

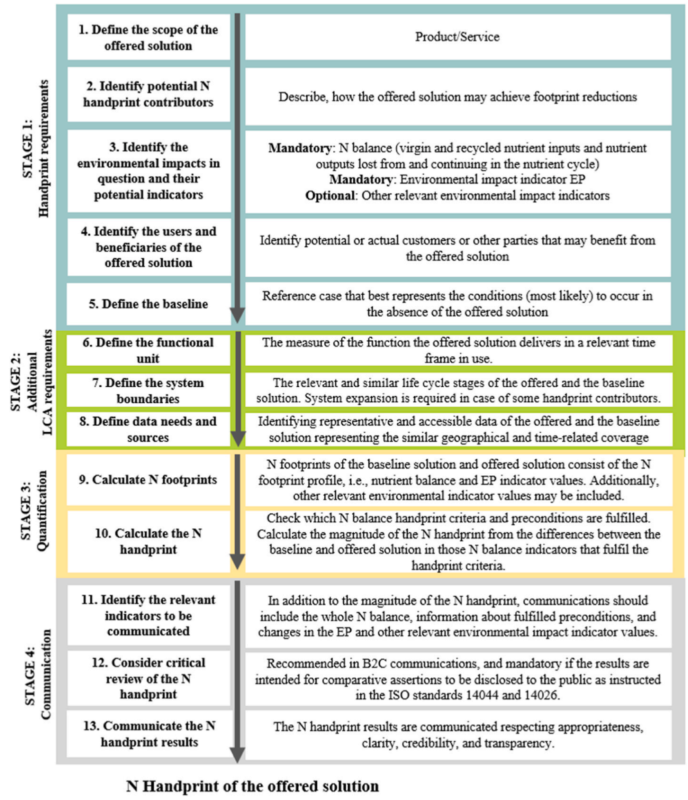

Fig. 1. The framework for an N handprint assessment.

to the baseline solution (step 2). In the context of N, potential handprint contributors can, for instance, lead to reductions in the use of virgin N or an increase in the use of recycled N. N recycling may also be enhanced through, for example, lower N losses from the studied system. N handprint contributors may also refer to the introduction of novel sources of recycled N or to novel use purposes of output N, such as in the case of industrial symbiosis enhancing a circular economy. New solutions and technologies may also help to optimize the use of N or prevent N losses to the environment, hence lowering environmental impacts.

In the first stage, an additional step is required in which the relevant indicators are selected and clearly indicated (step 3). As regards the indicators, it is suggested that an N handprint assessment should include two levels:

1. Assessment of changes in the **N balance** of the baseline vs. the offered solution (inventory level). As defined by Grönman et al. (2016), the nutrient balance provides information about the quantity and quality of the nutrient resources used (virgin and recycled inputs) and about the quantity of the nutrient emissions into the environment as well as the nutrients recovered for further nutrient use (the nutrient outputs lost from the nutrient cycle and continuing in the nutrient cycle).
2. Assessment of the **environmental impacts of N emissions** (impact assessment level).
   a. Mandatory: Assessment of changes in the eutrophication potential (EP) of the baseline vs. the offered solution.
   b. Optional: Assessment of other relevant environmental impact indicators. Optional indicators are selected based on assumed or identified environmental impacts related to studied solutions. For example, acidification potential may be locally important, or global warming potential (GWP) relevant as fertilizer production may be an energy-intensive process.

As the fourth step in the N handprint assessment, identifying customers requires consideration of those parties that benefit from the change in N cycles from a wider perspective (step 4). Similarly to the carbon handprint assessment (Pajula et al., 2018), an offered solution should bring about N footprint reductions for a user or beneficiary. Specification of beneficiaries is important for the inclusion of an operating environment in an assessment (Pajula et al., 2021).

Defining the baseline solution is one of the most critical steps in handprint assessment as it sets a point for a comparison (step 5). The baseline can be defined as "the reference case that best represents the conditions most likely to occur in the absence of an offered solution" (Pajula et al., 2021) and thus, it includes functions replaced by the offered solution. In general, a baseline selection depends on two fundamental questions: whether an offered solution is new on the market or replaces an existing product. In a case of the first scenario, the current situation without an offered solution is used as a baseline. The second scenario requires identifying the users of an offered solution, and if the users can be specified, their current product or another option available on the market acts as the baseline. Otherwise, the market leader or typical or average product or service in the identified area and time is chosen to be the baseline. Importantly, the baseline and the offered solution must deliver the same functions, be used for the same purpose, be available in the market, and be used in the defined time period and geographic region. An assessment must be conducted similarly for both solutions, for example in terms of data quality, system boundaries, and assumptions (Pajula et al., 2021.) These general guidelines for baseline determination in the context of a carbon handprint apply in N handprint assessment.

The *second stage, additional LCA requirements*, has three steps: defining the functional unit, defining system boundaries, and defining data needs and sources. This stage is largely based on the international standards of LCA (Pajula et al., 2018, 2021). All three steps are also essential in N handprint assessments, and the general guidelines provided in LCA standards ISO 14040 (2006) and ISO 14044 (2006) and by Pajula et al. (2018, 2021) apply in the N context. However, N handprint studies have some specific features and fundamental differences from carbon handprint studies. The climate change impact considered in a carbon handprint is global, while nutrients have a more local importance. Carbon handprints can be associated with any product or service, while N handprints are restricted to N flows, such as those related to the food system, fertilizer industry, or nutrient side streams and waste flows. Evaluating nutrient cycles may require wider system boundaries or system expansion to identify truly beneficial changes in N cycles between the offered and baseline solution.

The *third stage of the N handprint assessment requires N footprint and handprint calculations*. The greatest difference from the carbon handprint approach is that the N handprint has multiple indicators whereas carbon handprint has only one, namely CO_2-equivalent. The N footprint results, consisting of multiple indicator values, do not unambiguously indicate whether an N handprint is created and which indicators contribute to its magnitude. The basic principle of how the magnitude of the N handprint is determined is the same as for the carbon handprint: It is calculated from the difference between the N footprint indicator values of a baseline solution and the offered solution when the alternative solution is used by the same beneficiary (Grönman et al., 2019). However, clear criteria are required as to when the N handprint is created and the indicator values which determine its magnitude.

Table 1 summarizes the aspects included in the N handprint assessment as well as related N handprint criteria and preconditions. Criteria and preconditions are differentiated as follows. Criteria are related to aspects in the N balance that determine the magnitude of the N handprint. Preconditions do not affect the magnitude of the N handprint but must be fulfilled before an N handprint can be created. In other words, the N handprint means a nutrient resource handprint based on changes in the N balance (inputs and outputs) of a system. For example, the EP is used as an additional confirmation that the offered system does not adversely affect the environment; it is not used as a component of the N handprint. The N handprint is, thus, in line with the air quality handprint, which only considers changes in the mass balance of air pollutants and not, for example, midpoint environmental impacts or endpoint health impacts of air pollutants (Lakanen et al., 2021).

The N handprint is created when

- Either one or both input criteria (1, 2) are fulfilled while the output situation is at least equal in the offered solution to that in the baseline solution
- OR the output criterion (3) is fulfilled while the input situation is at least equal in the offered solution and the baseline solution
- AND the eutrophication precondition is fulfilled
- AND, if relevant, other environmental impact preconditions are fulfilled.

When determining whether the N balance allows the creation of the N handprint, the conductor of the assessment may adopt either an input or an output approach. The choice of approach may originate from identifying potential handprint contributors on the input or output side before making the calculations. For example, if a decrease in virgin N inputs in the offered solution is identified as a potential N handprint contributor, the input approach is a natural choice. Additional preconditions are needed to define the input or output situation as at least similar or equal between the baseline and offered solution. Worse situations hinder the creation of the handprint.

Supplementary materials, "N balance situations, handprint criteria, and preconditions," describe situations in which either the input or output handprint criteria are fulfilled in combination with possible simultaneous output or input situations. These materials further describe additional N balance preconditions in each situation.

As regards the input preconditions, potential alternative uses of recycled N inputs should be included in the assessment. If more virgin N

Table 1
N handprint assessment, criteria, and preconditions. Text in italics details situations that fulfill the criteria.

N handprint assessment indicators		
N balance		**Criteria: N balance**
Mandatory	Assessment of changes in the nitrogen balance of the baseline vs. offered solution.	**INPUT CRITERIA** **1** Fewer nitrogen inputs in total are required in the offered solution than in the baseline solution. *inputs in offered solution < inputs in baseline solution* **OR 2** Virgin N inputs in the baseline solution are partly or totally replaced by recycled N in the offered solution or decreased without replacement. *virgin inputs in offered solution < virgin inputs in baseline solution **and** recycled inputs in offered solution ≥ recycled inputs in baseline solution* **Preconditions:** The output situation is better or equal in the offered solution compared to the baseline solution. Additional preconditions define equality. **OUTPUT CRITERION** **3** The ratio of the N outputs that continue in the nutrient cycle to the N outputs lost from the nutrient cycle is larger in the offered solution than in the baseline solution. The increase in the ratio must not be pursued by increasing the total amount of N inputs and outputs. *lost outputs in offered solution < lost outputs in baseline solution **and** continuing outputs in offered solution ≥ continuing outputs in baseline solution **or** lost outputs in offered solution < lost outputs in baseline solution **and** continuing outputs in offered solution < continuing outputs in baseline solution **and** the ratio of continuing to lost N is larger in offered solution than in baseline solution **or** lost outputs equal 0 in offered solution* **Preconditions:** The input situation is better or equal in the offered solution compared to the baseline solution. Additional preconditions define equality.
Environmental impacts		**Preconditions: Environmental impacts**
Mandatory	Assessment of changes in the EP of the baseline vs. offered solution.	The EP does not increase in the offered solution in comparison to the baseline solution.
Optional	Assessment of other relevant environmental impact indicators.	Other relevant environmental impact indicators do not show worse impacts in the offered solution in comparison to the baseline solution.

and less recycled N is used in the offered than in the baseline solution while total N inputs decrease, one should ensure that better uses for the recycled N justify the decrease in the ratio of recycled to virgin N in the offered solution. Similarly, when less virgin N and more recycled N is used in the offered than in the baseline solution while the total amount of N inputs is decreased, maintained, or increased, one should ensure no alternative uses for the recycled N exist. Alternative uses of recycled N in the offered solution may be included within the baseline system boundaries through system expansion. Alternative uses should be economically justified. Increasing the use of recycled N is acceptable if, for example, the recycled N is waste in the baseline solution. A further question is how better, or equal, uses should be defined and who is eligible to define uses. A general guideline, which applies well to industrial symbioses, is that using recycled nutrients that would otherwise be waste is a positive development. Otherwise, the precondition is inevitably open to discussion and discretion. A critical review of the handprint assessment adds credibility to the decision about better uses in the N handprint assessment. However, further research that leads to refining the precondition is needed.

As regards the output preconditions, first, the ratio of continuing to lost N should be at least equal in the offered and baseline solution. This might be the situation, for instance, when decrease in total N input to the system causes a decrease in both lost and continuing N outputs. In this case, decreasing the amount of N lost to the environment is a positive change, but decreasing the continuing N outputs is a negative change. However, as fewer inputs in total lead to fewer outputs in total, the negative change in continuing N should not directly hinder the handprint creation. Instead, a check should be made that the decreased total outputs are at least equally divided between the categories of continuing and lost N in the offered solution and baseline solution. For instance, if the ratio of continuing to lost N equals 0 in both the baseline and offered solution, the ratio is equal in both, and the outputs do not affect the magnitude of the handprint. Secondly, when a decrease in the total N inputs between the offered and baseline solution shows on the output side as a reduction in continuing N, the amount of lost N should equal 0 in both solutions.

Conducting an N handprint assessment and creating the assessment framework involve an iterative process. The N handprint criteria could help in stating the initial hypothesis about N handprint contributors. Some contributors set further requirements on system expansion which affect the system boundaries and baseline.

Returning to the N handprint framework, as presented in Fig. 1, the *fourth stage* deals with appropriate, clear, credible, and transparent *handprint communications*. First, it is worth identifying the relevant indicators to be communicated. In addition to the magnitude of the N handprint, communications should include the whole N balance including virgin, recycled, lost, and continuing N, as well as changes in the EP and other relevant environmental impact indicator values, preferably numerically. To be transparent, the communications should also clearly indicate, which N handprint criteria and preconditions are fulfilled, and which changes in the N balance contribute to the magnitude of the N handprint. As stated earlier, the magnitude of the N handprint is calculated from the differences between the baseline and the offered solution for those N balance indicators that fulfill the N handprint criteria (Table 1).

Second, a critical review is highly recommended, or mandatory if the results are intended to be used for a comparative assertion intended to be disclosed to the public (Pajula et al., 2018; ISO 14026; ISO 14040; ISO 14044). Appropriate and clear communication units should be used.

2.4. Case study: recycled N nutrient product in wastewater treatment

The presented N handprint approach was applied to the case study, which quantifies the potential beneficial impacts on nutrient cycles that can be achieved through industrial symbiosis. In the case study, the biogas plant provides a recycled N nutrient product for a pulp and paper mill WWTP to be used instead of a virgin N nutrient product. The biogas production process from biodegradable waste generates nutrient-rich digestate, which can be re-processed to N-rich ammonia water. Ammonia water can be used as a supplement N in wastewater treatment (WWT). In this case, the customer is a pulp and paper mill-activated sludge WWTP, where virgin urea is typically added to the WWT process to ensure a sufficient concentration of N.

To conduct an N handprint assessment, the N handprint framework was applied in the case study as presented in Fig. 2. The scope of the offered solution is ammonia water (step 1), which is assumed to reduce

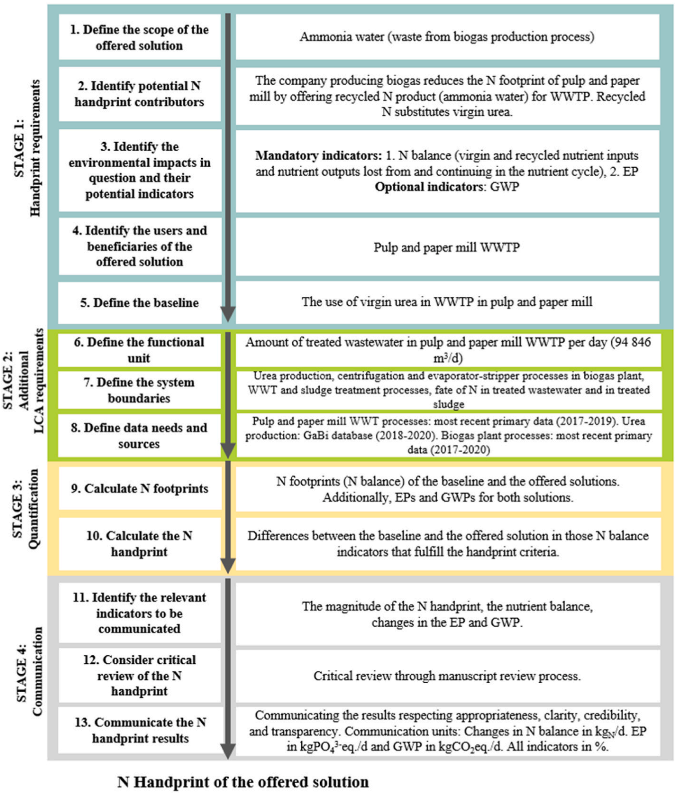

Fig. 2. Framework for the N handprint approach in the case study of the recycled nutrient product in the WWTP.

the N footprint of a pulp and paper mill by offering recycled N nutrient to WWT instead of virgin urea (step 2). As a decrease in virgin N inputs in the offered solution is identified as a potential N handprint contributor, the input approach for the N handprint assessment is selected for use, as recommended in Section 2.3. According to the N handprint framework, mandatory indicators of N balance and EP are included in the assessment. Additionally, among optional indicators GWP was identified as relevant, as urea production through Haber–Bosch is highly energy-intensive (step 3). In the case study, the beneficiary is a pulp and paper mill, which needs supplementary N for its WWTP (step 4). The baseline was defined as the use of virgin urea in the WWTP (step 5). The daily quantity of treated wastewater in the WWTP (94 846 m^3) was determined to be a functional unit in a study (step 6).

Fig. 3 presents the system boundaries as well as the N and energy flows of the case study (step 7). N flows and energy consumption were examined per wastewater treated in 1 day at the WWTP, which corresponds to 94 846 m^3 wastewater. Calculations did not include biogas production because digestate from the biogas process was identified as waste. N input in wastewater from the pulp and paper mill processes was also excluded, as it is the same in the offered and baseline solutions. Transportation was included in the EP and in the GWP calculation but not in the N balance calculation. Typically, the urea used in Finland is produced in Central Europe; hence, the transportation distance was assumed to be 1300 km by ship and 100 km by truck for urea. For ammonia water, the transportation distance was assumed to be 100 km by truck. System boundaries for EP and the GWP were calculated from cradle to gate, as the customer processes were assumed to be similar in both solutions. For the N footprint, all life cycle stages from cradle to grave were included in calculations.

It was assumed that ammonia water replaces all the urea in the offered solution in a 1:1 relationship. Ammonia water is produced from digestate that is generated in the biogas production process. Digestates need to be further centrifuged, evaporated and stripped. In addition to ammonia water, N containing dry matter and NP-concentrate from centrifuged digestate are generated in the biogas plant. NP-concentrate contains P and N and can be used as a fertilizer. The energy consumption of the digestate processing was allocated to ammonia water and other N-containing outputs (sludge and NP-concentrate) based on their N masses. However, NP-concentrate was otherwise excluded from the calculations as it is not utilized in the processes described in the case study but, rather, as a separate product in other locations. The N content of biogas was assumed to be zero. As N occurs in many different forms and conversion processes are very complex, all the N was considered to be the same in the calculation.

For biogas plant and pulp and paper mill WWT processes, the most recent primary data –from the periods 2017–2020 and 2017–2019, respectively – were used. Data for urea production were secondary data from the GaBi database from the period 2018–2020 (step 8). N footprints

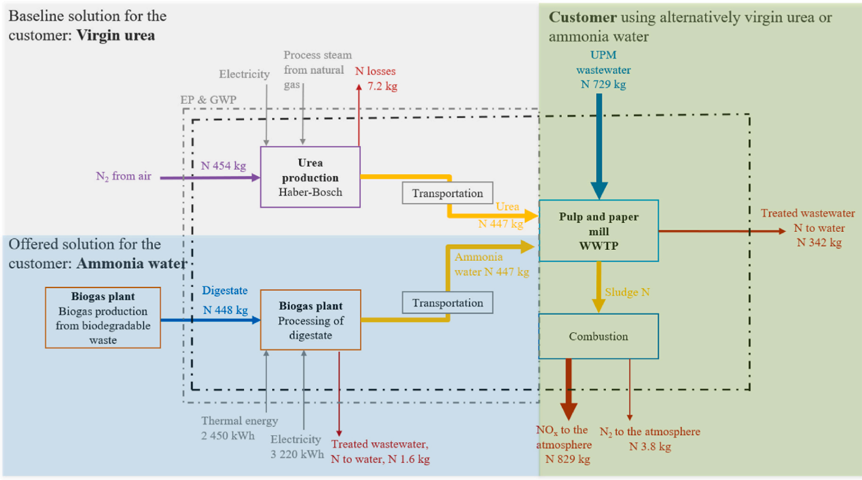

Fig. 3. System boundaries of the case study. Blue text and lines = recycled N inputs; purple = virgin N inputs; red = N outputs lost from the nutrient cycle; green = N outputs that continue in the nutrient cycle; orange = intermediate N flows; gray = energy inputs; black dashed line = system boundaries in the handprint assessment; and gray dashed line = system boundaries for the EP and GWP calculation. N masses and energy consumption are expressed per functional unit. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

for the offered and baseline solutions were calculated according to Grönman et al. (2016) (step 9). In footprint calculations, virgin and recycled N inputs, as well as the N outputs lost from the nutrient cycle and continuing in the nutrient cycle, were assessed through the life cycles of solutions. EPs for both solutions were calculated by using CML 2001 EP characterization factors, since it was assumed that both marine and freshwater may be affected. When possible, local EP characterization factors should be used. Carbon footprint calculations were conducted using a CML 2001 GWP 100-year impact analysis method with the LCA modeling software GaBi and its database (Sphera, 2019). The N handprint was calculated as the difference between the baseline and offered solutions in those N footprint indicators shown to fulfill the handprint criteria presented in Table 1 (step 10).

At the communication stage, the magnitude of the N handprint, the N balance, EP, and GWP were identified as relevant to be communicated (step 11). A critical review was assumed to be conducted through the manuscript review process (step 12). Finally, it was considered that suitable communication units for indicators would be kg_N/d for the N balance, kg phosphate equivalents/d ($kgPO_4^{3-}eq./d$) for EP, and $kgCO_2eq./d$ for the GWP (step 12). Additionally, all indicators should be communicated in %.

3. Results

The N footprint for the offered and baseline solutions consists of four separate indicators: virgin N inputs, recycled N inputs, N outputs lost from the nutrient cycle, and N outputs continuing in the nutrient cycle. The total N balance of the baseline and offered solutions in kilograms of N per wastewater treated in a day at the WWTP (94 846 m^3) is presented in Fig. 4.

In the baseline solution, 453.8 kg of virgin N are needed to produce enough urea to meet the N requirements of the WWTP. Correspondingly, in the offered solution, 448.2 kg of recycled N are used for ammonia water production. The total N input is reduced by 5.6 kg_N/d in the offered solution compared to the baseline solution. This reduction fulfils the first input N handprint criterion, which states that fewer N inputs in

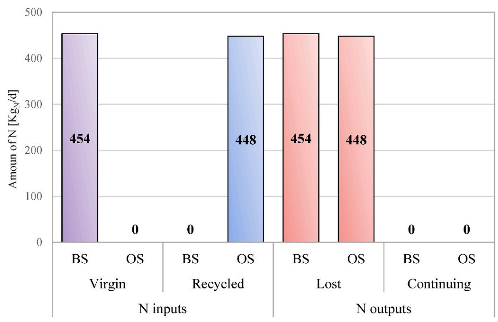

Fig. 4. N balances of the baseline and offered solutions in [kg_N/d]. BS refers to the baseline solution and OS to the offered solution.

total are required in the offered than in the baseline solution. In the baseline solution, all the N used in urea production is atmospheric N (N_2), which has been converted to a more reactive form (N_r) and can be considered a virgin nutrient. In contrast, in the offered solution, all the input N is recycled from another process (biogas production). This leads to a reduction in virgin N input of 453.8 kg/d in the offered compared to the baseline solution, which fulfills the second input N handprint criterion.

On the output side, all the N is lost from the nutrient cycle in both solutions mainly due to the WWTP of the customer. The results show that in the baseline and offered solution, 98.4% and 99.6% of N losses occur from the WWTP, respectively. However, 5.6 kgN/d more N is lost in the baseline than the offered solution because the N input is higher in the baseline solution. In percentage terms, 1.2% less N is lost from the nutrient cycle from the offered than from the baseline solution. Due to 100% N losses in both solutions, no N continues in the nutrient cycle in either solution.

Fig. 5 presents the EP and GWP of the baseline and offered solutions as percentages. The EP of the offered solution is 48% lower than that of the baseline solution. In kilograms, the EP for the baseline is shown to be 1.76 $kgPO_4^{3-}$eq./d, while that for the offered solution is 0.92 $kgPO_4^{3-}$eq./d. Thus, in kilograms the EP is shown to be 0.84 $kgPO_4^{3-}$eq./d lower for the offered solution than for the baseline. The difference is mainly due to the renewable thermal energy used in ammonia water production, as the biogas plant uses its own biogas in heating processes. Regarding GWP, the carbon footprint for the baseline solution is 2686 kg CO_2eq./d and for ammonia water it is 256 kg CO_2eq./d. Thus, the GWP for the offered solution is 2430 kg CO_2eq./d lower than in the baseline. In percentage terms, the offered solution has a 90.5% lower lifetime GWP than the baseline.

The N handprint preconditions on environmental impacts state that the EP is not allowed to increase in the offered solution in comparison to the baseline solution. Neither are other relevant environmental impact indicators allowed to show worse impacts in the offered than in the baseline solution. As the EP and GWP are not higher in the offered than in the baseline solution, the environmental impact preconditions for the N handprint calculation are fulfilled.

In summary, the N handprint prerequisites are fulfilled in the case study, as presented in Table 2. The input approach for an N handprint assessment was observed to be suitable for the case study, according to the identified handprint contributors. In other words, in the input side, either one criterion or both criteria should be fulfilled while the output situation should remain at least equal in the offered to that in the baseline solution.

Fulfillment of N handprint criteria and preconditions indicates that the N handprint is created in the case study to the benefit of a producer of an ammonia water. The N handprint in the symbiosis between the WWTP and biogas plant equals a 5.6 kg (1.2%) reduction in total N (virgin + recycled) inputs and a 454 kg (100%) reduction in virgin N inputs due to replacement by recycled N inputs. At the same time, the N balance on the output side remains at least equal; there are no identified better uses for the recycled N that replaces virgin N, and the additional precondition on not increasing EP is met. However, even small negative changes in the nutrient balance in comparison to the current calculations could hinder the creation of the nutrient handprint.

4. Discussion

Understanding the harmful impacts of nutrients in the environment is of primary importance (Rockström et al., 2009; Steffen et al., 2015). However, as with N, previous nutrient budgeting methods do not often include impact assessment and have been criticized by the LCA community for this deficiency (Einarsson and Cederberg, 2019). LCA is a widely used tool to assess circular solutions (Corona et al., 2019; Sassanelli et al., 2019). Improvement actions on nutrient cycles, as one example of circular solutions, can be assessed with LCA. However, LCA, too, has limitations on measuring the circularity of systems (Rigamonti and Mancini, 2021). Inconsistencies have been identified in modeling open loops in LCA (Peña et al., 2021), using materials multiple times with changing material qualities requires further guidance (Haupt and Zschokke, 2017), and LCA indicators may not consider the anthropogenic stocks available (Sonderegger et al., 2020). The N handprint approach presented in this paper is LCA-compliant and includes an environmental impact assessment as well as a life cycle perspective. Besides including environmental impact categories in the context of the studied nutrients, our approach enables incorporation of nutrient origin and destination at inventory level by adapting the nutrient footprint approach. Separating the input N into virgin and recycled N improves the transparency of the assessment and allows credit to be given to recycled nutrients that are already in the anthropogenic stock and utilized multiple times.

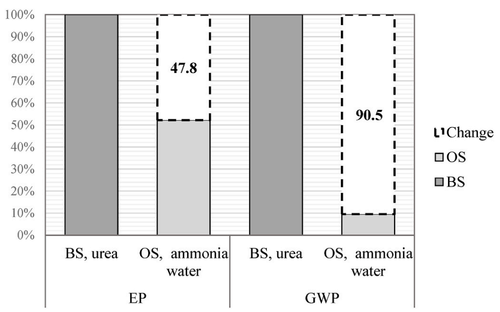

Fig. 5. EP and GWP of the baseline and offered solutions in [%]. BS refers to the baseline solution and OS to the offered solution.

Table 2
N handprint assessment, criteria, and preconditions in the case study.

N handprint assessment indicators		Case study: Ammonia water in WWTP
N balance		**Criteria: N balance**
Mandatory	Assessment of changes in the N balance of the baseline vs. offered solution.	**FULFILLED INPUT CRITERIA** **1.** Fewer N inputs in total are required in the offered than in the baseline solution. **2.** Virgin N inputs in the baseline solution are totally replaced by recycled N in the offered solution. **FULFILLED PRECONDITIONS:** The output situation is better in the offered than in the baseline solution.
Environmental impacts		**Preconditions: Environmental impacts**
Mandatory	Assessment of changes in the EP of the baseline vs. offered solution.	The EP does not increase in the offered solution in comparison to the baseline solution.
Optional	Assessment of GWP of the baseline vs. offered solution.	The GWP does not increase in the offered solution in comparison to the baseline solution.

According to our results concerning the case study of ammonia water, the recycled N product has the potential to reduce the N footprint of a customer, which, in this case, was a pulp and paper mill WWTP. In other words, the provider of the ammonia water thus creates an N handprint with this solution. The ammonia water provider can utilize these results in a trading situation with a potential customer to prove, on the basis of scientific fact, that environmental benefits will follow. If, for example, no environmental benefits had accrued from using the offered solution compared to the baseline product, the solution provider could have used these results to identify product or process development needs. The customer, on the other hand, can utilize these results to make informed decisions regarding their choice of N provider.

The positive nature of the results is in line with the results of Aho et al. (2015), who concluded that the greatest sustainability benefit of recycled nutrients is produced when the waste is used as a raw material in a nutrient product. Their study also found that less energy is needed to process a recycled nutrient product than that produced from virgin raw materials. In our study, this is valid as the ammonia water has minor processing needs other than transportation to the WWTP. In fact, transportation distances may become the limiting factor on the economic feasibility of the use of ammonia water. Transporting high volumes of liquid in trucks limits the potential users of ammonia water to a distance of about 100 km. Our results also indicate that ammonia water has GHG emission reduction potential of 90.5% compared to virgin urea.

The recent literature shows that reducing the environmental impacts and increasing the use efficiency of urea use are important, for example through polymer coatings (Xie et al., 2019) or Blue Urea (Driver et al., 2019).

Unlike previous nutrient indicators, the N handprint approach aims to quantify the positive impacts of products and services on N cycles based on the carbon handprint approach. As a response to a call for transparent communication with stakeholders in the field of nutrient budgeting (Zhang et al., 2020), our framework provides a novel way of messaging enhanced N cycles in business-to-customer as well as business-to-business communications. Moreover, the approach enables comparison of different products or services, indicates the need for improvements, and helps to show the most critical life cycle stages for preserving N in the cycle.

5. Conclusions and future challenges

In this article, a detailed methodological approach to calculate the positive environmental impacts of novel solutions closing, narrowing, and slowing N cycles called N handprint approach is presented. The N handprint approach was built as a combination of two existing LCA-based methods: the nutrient footprint and the carbon handprint. Then, we demonstrated the approach on a case study of the WWTP of a pulp and paper mill, which has traditionally used virgin urea to cover its N needs but could also utilize ammonia water, which is considered waste from biogas production. Our results indicate an N handprint for the ammonia water due to the daily reduction of 454 kg of virgin N inputs and 5.6 kg of total N inputs when compared to urea.

This study has applied handprinting in the nutrient context for the first time. Extending the scope of the handprint assessment from climate impacts is especially important when considering the circularity of provided solutions. Assessing only the carbon footprint of a solution may not allow some benefits of circular solutions to be brought forward, such as utilizing anthropogenic deposits available, extending the life cycle of products, or utilizing the goods multiple times.

The N handprint approach supplements existing N footprint methodologies by providing systematic guidelines to assess, at system level, positive changes occurring in N utilization throughout the life cycles of products or services. As the N handprint acknowledges the real operating environment in which the products or services are used, more realistic results can be expected than those derived from traditional LCA and footprint assessments. Additionally, the comparative character of handprinting allows diverse analyses when promoting N cycling and circular economy targets.

This study suggests that the N handprint is a suitable approach – albeit, with its multiple indicators, a laborious one – and indicator to quantify and communicate the potential positive impacts of industrial symbioses on nutrient cycles. The clear criteria and preconditions presented in this paper are needed to determine when the N handprint is created. Furthermore, creating a N handprint requires the sustainable use of nutrients and system-level nutrient balance optimization from the offered solution provider pursuing the N handprint. Our study is limited to N, but future research should include other nutrients among the handprint family as well. For example, P would be a feasible addition to the nutrient handprint approach as the calculation for the P balance is in line with that of N. However, additional environmental impact categories, such as abiotic depletion potential (ADP), should be considered in the context of P. The case study presented in this paper concentrates only on industrial symbiosis, although the applicational scope of the N handprint is much wider. Thus, further studies to test the suggested N handprint framework, criteria, and preconditions are highly encouraged in other contexts, such as the agri-food sector and for other nutrients.

CRediT author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cesys.2022.100090.

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Publication III

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Approach for assessing environmental handprints

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Approach for assessing environmental handprints

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Abstract. The need to reveal positive environmental consequences of offerings has risen as urgent climate actions are needed from companies. The environmental handprint approach was developed to indicate the positive environmental impacts of a solution offered to a client. The environmental handprint approach builds upon the previously published carbon handprint approach. The approach follows the guidelines of ISO standards on Life Cycle Assessment (LCA) but complements them with instructions for calculating positive environmental impacts. The environmental handprint framework allows consideration of several different environmental impacts including climate impacts, air quality, and utilization of nutrients, water and resources, and it can be applied to products, services, organisations and projects. The framework consists of four main stages: 1. Handprint requirements, 2. Additional LCA requirements, 3. Quantification, 4. Communication. The handprint approach provides an important addition to life cycle studies. Handprints can be used by organizations to communicate the environmental benefits of their products, services, and technologies. They also serve as an aid to identify improvement potential throughout the life cycle of an offering, thus supporting product development and decision making. Case studies supported the methodology development. A case related to water handprint in water treatment in the mining industry is presented in this paper.

1 Introduction

In recent years, sustainability goals have become increasingly important to steer companies' actions. Measuring the environmental performance of products and services has concentrated on negative life cycle impacts, and there has been an increasing interest for indicators that reveal positive environmental consequences of offerings. Various companies and organizations that have already minimized their own footprint have been lacking the means to showcase the environmental benefits their offerings can enable to their customers. LCA studies, based on ISO LCA standards [1,2], provide valuable information of the environmental burden of a product system from cradle to grave. However, specifications to these general LCA standards are needed to improve the accuracy of assessments and to widen the scope of studies towards assessing positive impacts. For example, ISO 14067 [3] on the carbon footprint of products specifies the principles, requirements and guidelines for the quantification and reporting of the carbon footprint of a product, thus complementing ISO 14040 and ISO 14044 standards. However, the guidelines for assessing positive environmental impacts of offerings have been lacking. Approach to measure positive impacts

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of actions has been recently introduced by Norris et al. [4]. The Sustainability and Health Initiative for NetPositive Enterprise (SHINE) handprint framework developed by Norris et al. aims to quantify environmental, economic, and social positive changes caused by an actor when compared to business-as-usual situation. Biemer [5] has also presented the ideas of handprints by emphasizing a positive way of thinking and well-meant actions to promote sustainability. The carbon handprint approach by research institution VTT and LUT university introduced by Grönman et al. [6] and Pajula et al. [7] provided general principles and instructions for assessing the carbon handprint of a product or service. Based on the most up-to-date definition [8] a handprint refers to *the beneficial environmental impacts that organizations can achieve and communicate by offering products and services that reduce the footprints of others.*

Footprints, in general, describe the environmental burden throughout the life cycle of a product system. Carbon footprint, for example, is usually calculated based on actualized data on company's or product's greenhouse gas emissions and removals. Handprint, however, 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. Thus, the handprint is equal to the possible or actualized reduction in the footprint of the user of the offering. The handprint can be created by two means: Using an offering that carries a lower environmental burden than the baseline offering (cradle to gate processes), e.g., through improved resource efficiency in manufacturing; or through the environmental impact reduction which actualizes while using the offered solution (gate to grave processes), for example through energy efficient products. Also, a combination of both means is possible in order to create a handprint, see Figure 1.

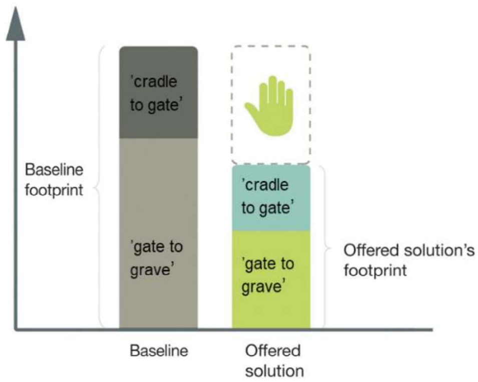

Fig. 1. Handprint is created if the footprint of the offered solution is lower than that of the baseline solution while used by the same customer (modified from [8]).

The carbon handprint approach gives guidelines only for assessing positive climate impacts, i.e., reduction in greenhouse gas (GHG) emissions. However, a framework for evaluating positive environmental impacts for other impact categories with wider application options has been lacking. The environmental handprint approach presented in this paper, aims to respond to the need for specific guidelines to assess positive impacts of products, services, organizations, and projects for several environmental impact categories including climate change, air quality along with nutrient, water, and resource use. The environmental handprint approach from the air quality perspective recently presented by Lakanen et al. [9] is another example for an environmental handprint besides the handprint presented in this present article.

2 Materials and methods

The framework is based on the carbon handprint approach introduced by Grönman et al. [6] and Pajula et al. [7]. The environmental handprint approach is also closely linked to the standardized LCA method with some specific complements for assessing positive environmental impacts. Environmental handprint is an umbrella concept including various positive environmental impacts. The framework for the environmental handprint is presented in Figure 2.

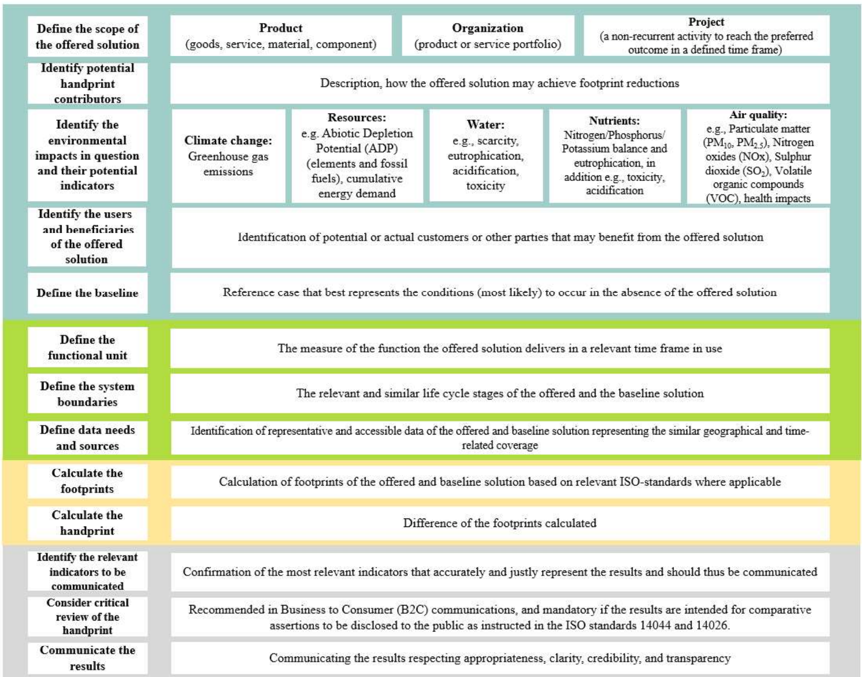

Fig. 2. The framework for the environmental handprint.

The framework consists of four main stages, which are: 1. Handprint requirements, 2. Additional LCA requirements, 3. Quantification, 4. Communication. Each stage comprises several steps, which guide in quantifying and communicating the handprint more precisely. Especially the first stage is specific to a handprint assessment when compared to a traditional LCA assessment, and thus explained here briefly.

In Stage 1, one must first define, whether the handprint assessment is done in a product or an organizational level, or if a project's positive environmental impacts are evaluated. Next, a hypothesis is made about how the offered solution would contribute to reducing footprint of its users. These mechanisms may be derived, for example, from the use of recycled, renewable, or less polluting materials and energy, from increased lifetime or performance, reduced waste or losses or through increased carbon capture and storage. The choice of these mechanisms in question determines which environmental impacts are relevant to be included in the study. Figure 2 presents the recommended indicators when assessing the handprint related to climate change, resources, water, nutrients, and air quality. Further guidelines for conducting the handprint assessment for these different environmental impacts can be found from the final report of the environmental handprint project [10].The fourth step is to identify the users of the studied offering. The handprint calculation always includes the use phase either through an actual or potential user using the studied offering compared to a baseline offering. Thus, handprint studies are always user specific. However, in situations where specific user cannot be identified, e.g., in the case of bulk products or heterogenous customers for the offering, a representative average user may be used in the assessment. However, also in these cases, geographical boundaries need to be kept similar. The final step at Stage 1, defining the baseline, is presumably the most critical on the results of the handprint assessment. The baseline sets the point of comparison, and it should be selected with conservative justifications and reported transparently. For more detailed guidance on the baseline determination procedure, the reader is advised to refer to the Carbon Handprint Guide v. 2.0 [8], which was composed in tight connection to the environmental handprint approach work presented in this paper. In the guide, the following Stages 2-4 of the handprint assessment are also presented.

Case studies, representing several Finnish companies with different offerings from varying industrial sectors, were done to support the framework development. Case studies were performed for all impact categories and applications described in the environmental handprint framework. The case study of water handprint assessment for a water purification technology used in the mining industry is presented in the following subsection.

2.1 Case study: Water handprint of water purification technology

In the case study, the environmental handprint approach from the water quantity and quality perspective was considered to assess potential water handprint of water purification technology. The water handprint approach described in the environmental handprint framework may consist of many indicators, which can be divided into two main categories, as in the water footprint standard ISO 14046 [11]: water scarcity impacts (water quantity) and water quality impacts. In the presented case study, a water scarcity handprint, and a water quality handprint in terms of eutrophication were quantified.

In this case study, the novel water purification technology is used in a water treatment plant in a mining company located in Northern Finland. In a baseline situation, water from underground and open mining operations can be directed to wetlands to be biologically treated. However, the area of the wetlands must be large enough to ensure sufficient removal of nutrients and impurities and moreover, purification potential of the wetlands is strongly dependent on the season and outside temperature. Novel water purification technology, referred here as the offered solution, aims to remove solid matter, dissolved minerals, and metals as well as nitrogen compounds from wastewater before it is released to the wetlands, which reduces emissions to receiving water bodies. Additionally, the share of the purified water from the water treatment plant can be recycled and used in enrichment processes of the mining company, which replaces the primary water intake and decrease overall water consumption. The framework for the case of the water purification technology is presented in Figure 3.

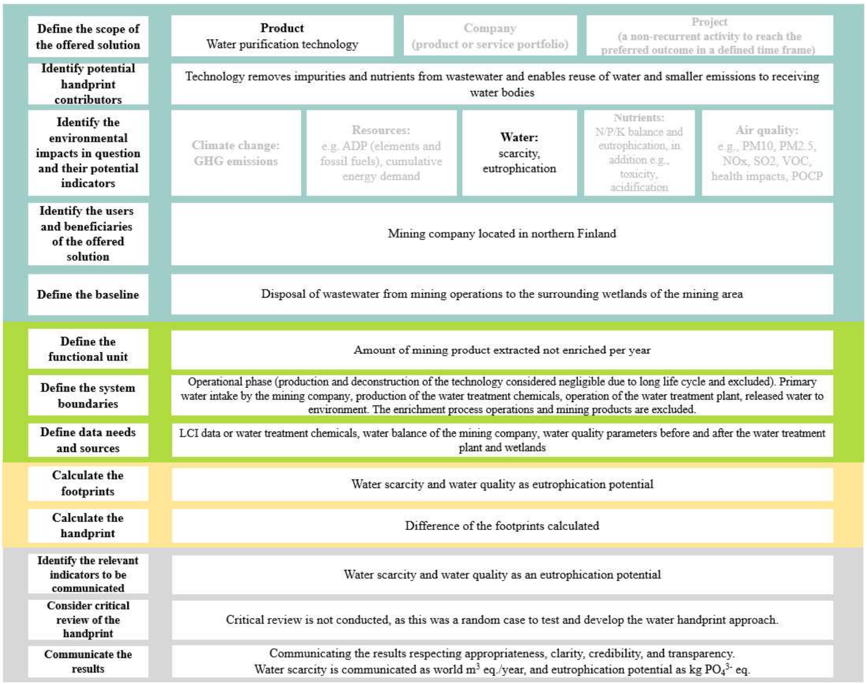

Fig. 3. The water handprint framework for the case of the water purification technology.

To quantify potential water handprint for the water purification technology, water scarcity and water quality footprints for the baseline and offered solutions were determined. The handprint was calculated as a difference between the footprints. The data for water streams of the mining operations were acquired from the environmental permit document of the mining company, which also stated the amounts of water treatment chemicals used per year. The amounts of chemicals used in one month were as follows: Sodium hydroxide (NaOH) 0.05 tonnes (t), ferric sulfate ($Fe_2(SO_4)_3$) 1 t, and polyacrylamide 0.05 t. Water consumption during the production of chemicals was taken from the Ecoinvent database. Table 1 illustrates water consumption volumes used for water scarcity handprint calculation.

Table 1. Water consumption volumes of the baseline and offered solution in water scarcity handprint calculation.

Water consumption / hour	Direct primary water consumption, m^3/h	Recycled water, m^3/h	Indirect primary water consumption, m^3/h
Baseline solution	35	0	0
Offered solution	23	12	0.035

The scarcity factors for each water consumption location are derived from AWaRe (Available Water Remaining) methodology by Boulay et al. [12], which also defined the calculation unit of cubic meters of world equivalent per year (m3 world eq. /y) for scarcity assessment. Local scarcity factors of 0.9 for the plant and 1.1 for chemicals were used.

In the quality assessment, for the baseline it was assumed that the wetlands remove approximately 87% of nitrogen which is bound in NH_4 (NH_4-N) and 3% of nitrite and nitrate-N (NO_2+NO_3-N). The estimated baseline is 7,000 kg N emissions and 40 kg P emissions per year, which were converted to PO_4^{3-} eq. with the CML 2001 general eutrophication impact factors. For the studied solution, the removal efficiency of the process is 75% of nitrogen bound in NH_4 (NH_4-N) and 78% of nitrite and nitrate-N (NO_2+NO_3-N) [13].

3 Results and discussion

Based on water handprint assessment, water scarcity handprint is 94 m^3 world eq. / year, which corresponds to 34% of the annual water demand of the baseline. The water quality handprint in terms of eutrophication showed to be 460 kg PO_4^{3-} eq. / year, meaning a 63% reduction in the eutrophication potential compared to the baseline solution. Both water scarcity and water quality handprints are presented in Figure 4.

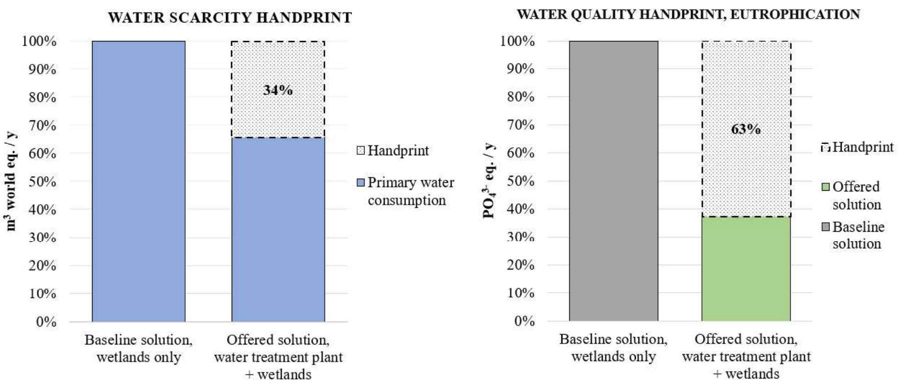

Fig. 4. Water scarcity handprint and water quality handprint as a eutrophication per year in the case study.

The results of the case study show that water purification technology can reduce both water consumption and eutrophication potential compared to the baseline solution. Consequently, the provider of water purification technology may communicate both water scarcity handprint and water quality handprint for its water purification technology when used by the specific mining company in the specific year. The results show that water handprint is a useful and a practicable method for quantifying changes in water use and quality when a new solution is introduced in market or when comparing existing solutions.

With handprints organizations and companies are able to show environmental benefits of their products, technologies, and services, as well as scientifically show their environmental responsibility. Handprint assessment also provides information on improvement potential throughout the life cycle of an offering, thus supporting product development and decision making. For companies, the handprint is not only an effective marketing and communication tool, but also gives valuable information for customers in decision-making.

4 Conclusions

Transition towards more sustainable production and consumption requires actions, which bring about positive changes throughout the value chain of offerings. The approach to assess environmental handprints provides a systematic, scientific-based approach to assess beneficial environmental impacts of products, services, organizations, and projects. It allows consideration of several impact categories including climate change, air quality and utilization of nutrients, water and resources thus providing a multi-purpose indicator for many applications.

As footprints measure principally the negative life cycle impacts of products and services, environmental handprint approach provides a way to assess and communicate positive environmental impacts hence offering a necessary extension for life cycle studies.

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Publication IV

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Carbon handprint approach for cities and regions: a framework to reveal and assess potential of cities in climate change mitigation

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Article

Carbon Handprint Approach for Cities and Regions: A Framework to Reveal and Assess the Potential of Cities in Climate Change Mitigation

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Abstract: Cities play a pivotal role in climate change mitigation; however, the methodology to quantify actual emission reduction potential of climate interventions implemented by cities and regions has been lacking. The aim of this study is to create a framework to assess positive climate impacts of cities and regions by modifying the life-cycle assessment (LCA)-based carbon handprint framework. Additionally, a step-by-step guidance to perform calculations is presented. A case study of the Finnish city of Espoo is used to further develop and test the regional handprint approach both qualitatively and quantitatively. According to our research, a city′s carbon handprint can be determined through the three main mechanism categories of ownership, operating environment and projects. In the case of Espoo, the carbon handprint of building public electric vehicle charging stations on city-owned land from the mechanism category of ownership showed to be up to 110 tCO_2eq/a for 18 charging stations. However, the overall handprint of a city consists of several actions, to be calculated separately. The regional carbon handprint approach provides a useful instrument to reliable quantify and communicate the innovative climate actions implemented by a city and it can be used in cities′ climate work as well as in marketing and branding purposes. Handprint turns the focus on possibilities for increasing a city vitality. As a provider of climate solutions, a city can attract new taxpayers and by focusing efforts to a certain sector, a city can help companies to reach synergies in fields essential from the climate point of view.

Keywords: footprint; handprint; carbon footprint; carbon handprint; greenhouse gas emissions; climate change; life-cycle assessment

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1. Introduction

Urban areas play a significant role in global climate change mitigation and the implementation of low carbon solutions. Due to the current trend towards ever greater urbanisation, more than half the world′s population live in cities, and this share is constantly increasing [1]. Urbanisation is also a major contributor to global climate change. In 2020, cities were responsible for two thirds of global energy consumption and over 70% of greenhouse gas (GHG) emissions [2]. Various actions to cut urban emissions and achieve carbon neutrality have already been implemented. These are based on city-level GHG inventories and voluntary frameworks and share a focus on reducing GHG emissions from the key sectors of energy and transportation [3].

A community-level GHG inventory, that is, a carbon footprint calculation, is the main tool used to support the carbon neutrality of cities and communities [4]. A city′s carbon footprint assessment gives an understanding of emission sources and quantities [5]. Thus, transparent and consistent inventories form the basis of cities′ climate action plans. Several international voluntary frameworks for calculating cities′ carbon footprints have been developed, such as the GHG Protocol for Cities [5] and PAS 2070 [6]. City-level carbon emission inventories based on different frameworks have been shown to be useful in lowering local emissions and increasing the effectiveness of local climate work [7]. Additionally, different city emission accounting systems, such as territorial-, production-, and consumption-based calculations, have been developed to deepen awareness of climate change mitigation in cities [8]. Cities′ climate plans may also be linked to a national regulatory process, as in Sweden, Italy and France [9]. Additionally, cities may have made national (e.g., carbon neutrality communities in Finland (Hinku) [10]) and international (e.g., Covenant of Mayors (CoM) [11], C40 Cities Climate Leadership Group [12]) commitments to climate actions aimed at achieving carbon neutrality. However, it has been recognised that cities struggle to achieve carbon neutrality when regional targets are more ambitious than national ones [13]. In contrast, cities are better enabled to achieve carbon neutrality targets through commitment on the local level, a shared understanding between the city, its citizens and stakeholders in the vision and goals of climate action, and a high level of local activities [4].

Alongside footprint approaches, which mainly measure environmental burden, 'handprint' thinking has recently emerged, which assesses the positive environmental impacts of actions [14]. Norris et al. [15] introduced a framework to quantify the positive environmental, economic and social changes caused by an actor when compared to a business-as-usual situation. Biemer [16] highlighted the importance of concentrating on the positive point of view when promoting sustainability. The carbon handprint framework proposed by Grönman et al. [14] and Pajula et al. [17] provides an approach to quantify and communicate the positive climate impacts that solutions can achieve compared to a baseline practice. The fundamental characteristic of the carbon handprint approach is that the handprint can be achieved by improving the performance of other actors and reducing their carbon footprint. As centres of education, research, economic activities, innovation and new technologies [18], cities influence private and public actors as well as other cities and regions [19]. Thus, a city′s potential to implement climate change mitigation actions is broader than simply reducing its own carbon footprint. For example, Mohareb et al. [20] considered cities′ role in mitigating life-cycle GHG emissions from the food system in the United States through selected measures. The authors concluded that the actions implemented by cities, such as waste management practices or reduction of post-distribution food waste, have the potential to reduce total food sector emissions when compared with the baseline situation. Such findings suggest that cities have the potential to positively influence emissions on a large scale.

Community-level GHG inventory frameworks focus on the identification of emission sources and quantities [5]. However, cities lack a more systematic understanding of how to estimate and quantify the emission reduction potential of different climate interventions [21]. Recent research has also underlined the effectiveness of using life-cycle assessment (LCA) methodology to bring about GHG emission reductions locally and globally, as it accounts for emissions at a systemic level [22]. Furthermore, there have been calls for reliable information to support decision-making for future actions to ensure the effectiveness, continuity and development of climate work [23]. Besides sustainability and climate aspects, cities need to ensure their viability and livability in the face of changeable conditions. Adopting a pioneering role in climate actions may also promote the vitality and prosperity of a city.

To date, the assessment and quantification of positive climate impacts and avoided emissions has concentrated on product level, such as in the framework for estimating and reporting the comparative emissions impacts of products by the World Resources Institute (WRI) [24] and Kawasaki Mechanism Certification System [25]. The carbon handprint framework is applicable at product, service and project levels, as well as that of organisations, through a product or service portfolio [26]. However, a regional-level carbon handprint assessment has been lacking even though cities and regions also need tools to define, quantify and communicate the positive impacts of climate actions. In this paper, we present a novel approach to recognise and quantify the innovative climate actions implemented by a city or region. Our study responds to the need for a systematic, LCA-based framework to evaluate and quantify emission reduction potential of climate actions done by cities and regions also when aimed at carbon footprint reductions of other actors than city itself. The proposed approach is based on the carbon handprint framework [26], which provides guidelines to assess positive climate impacts.

2. Materials and Methods

This section briefly describes the methodological development of the regional carbon handprint approach and then introduces the case study. The framework for assessing the carbon handprint for cities and regions is presented in Section 3, 'Results', as is the outcome of the case study.

2.1. Methodology Development

This study applies the LCA-based carbon handprint approach introduced by Grönman et al. [14] and Pajula et al. [17]. The carbon handprint refers to the positive climate impacts that a product or service may yield when compared with a business-as-usual solution. Thus, the carbon handprint equates to the reduction in the carbon footprint of a product or service user. The carbon handprint approach has been modified recently to cover other elements besides products and services, such as projects and organisations through their product portfolios as well as other environmental categories beyond climate change [27]. In Lakanen et al., the carbon handprint was applied in the context of air quality [28].

Figure 1 presents the development stages of the regional carbon handprint approach. The starting point for the approach is the existing ISO standards for LCA [29,30] and carbon footprinting [31]. Moreover, the basis for carbon handprint thinking is derived from the work carried out by LUT University and the research institution VTT.

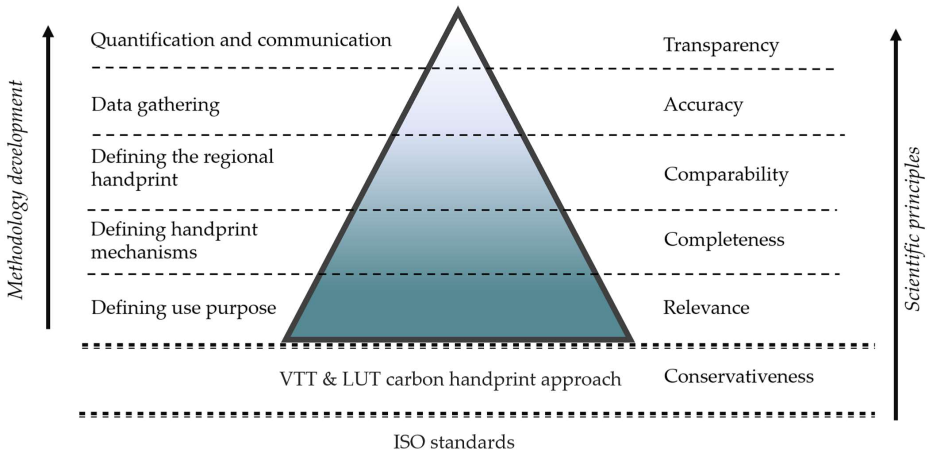

Figure 1. The process of methodology development.

The methodology development for the carbon handprint of cities and regions followed the scientific principles of relevance, completeness, comparability, accuracy and transparency. Firstly, the purpose of the regional-level carbon handprint was defined with regard to relevancy. The need and use purpose of this approach were clarified according to recent literature as well as discussions with several city, regional council and voluntary sector representatives. Consequently, the use purpose of the city carbon handprint framework was built upon three main points:

1. Bringing the focus onto opportunities for a city to be a beneficial actor in climate-related issues. The opportunities cities have to mitigate climate change are not limited to reducing city GHG emissions or achieving carbon neutrality, but comprehend reducing GHG emissions more widely. In addition to reducing emissions, innovative actions with wide-reaching impacts serve as examples to others and help to reinforce a city′s continued viability.

2. Unveiling the significant potential of cities to act as solution providers for actors such as citizens and organisations both within and outside the city′s boundaries. Cities are important platforms for innovation and novel solutions. In cities, the cooperation between different actors, such as the city, educational institutions, companies and research facilities, provides a setting for developing innovations that benefit different stakeholders both within and outside the city.

3. Assisting a city to increase its handprint systematically so that benefits for the city can be maximised. One of the main aims of determining a city′s carbon handprint is to increase its handprint, year by year, which can only be achieved by systematic planning and establishing clear development targets in specific sectors which are important in the city.

In the second step of the methodology development process, the handprint mechanism categories for cities were identified following the principle of completeness. Versatile mechanisms were identified to guarantee that the complete set of contributors that reduce the footprint of others, and thus create the handprint in the regional setting, is considered. The third step involved ensuring that the regional handprint was defined in such a way that it could be compared with existing handprint frameworks and ISO standards. For the fourth step, the novel carbon handprint approach for cities and regions was applied to the case study, which began by gathering data in cooperation with the city of Espoo. The accuracy of the data used is vital to acquire reliable and useful results from the handprint assessment. Finally, the results of the case study were summarised and communicated transparently. This paper presents an exemplary calculation from the Espoo case and qualitatively describes other actions carried out in Espoo which may contribute to its carbon handprint.

Based on the methodology development, a systematic four-stage framework adapted from previous carbon handprint work [26] was compiled to define and guide regional carbon handprint assessments.

2.2. Case Study: The Carbon Handprint of the City of Espoo

To demonstrate the carbon handprint approach for cities, a case study of the city of Espoo, Finland, was conducted. Espoo is located in Southern Finland, in the region of Uusimaa, and is the second-largest Finnish city by population, with approximately 300,000 residents and a population density of 950/km^2 [32]. Espoo is a hub for many major international technology companies and home to the Aalto University and Technical Research Center of Finland. The city of Espoo joined the CoM in 2010. In the same year, the city set a goal of reducing its GHG emissions by 28% from the 1990 level by the year 2020. Having reached this goal in 2016, the city set a further goal of reaching carbon neutrality by 2030, defined as an 80% reduction in emissions compared with the 1990 level. Espoo is also engaged in Sustainable Energy and Climate Action Plan (SECAP) submission, which consists of several measures aimed at GHG reductions in different sectors. To date, Espoo has, for example, executed emission-free and carbon-neutral district heating projects, increased the utilisation of renewable energy sources in city-owned buildings and advanced smart-home solutions within the city. Many of the actions have been carried out in collaboration with public and private organisations [33].

The case study was conducted primarily as a literature review to identify potential carbon handprint-producing activities associated with the city. Discussions with city representatives were also held to gather data. No exhaustive list of handprint contributors was composed, but relevant examples were identified and applied to the city carbon handprint framework. Although the total carbon handprint of a city is the sum of the effects of many activities, as an instance the handprint of a single activity was calculated.

3. Results and Discussion

The carbon handprint of a city or region is a means to recognise the climate leadership initiatives of a city and thereby maximise their positive impact, both in and outside the city. In addition to communicating the current climate actions taken by a city, the carbon handprint framework provides a tool to develop future climate actions.

3.1. The Framework for Assessing the Carbon Handprint of Cities and Regions

Figure 2 presents the framework for defining and assessing the carbon handprint of cities and regions. The framework consists of four stages, each including multiple steps, and thus provides detailed guidance for conducting regional-level carbon handprint assessments. In the following sections, every step of the first stage is explained. Instructions for stages 2–4 are available for review in the carbon handprint guide [26].

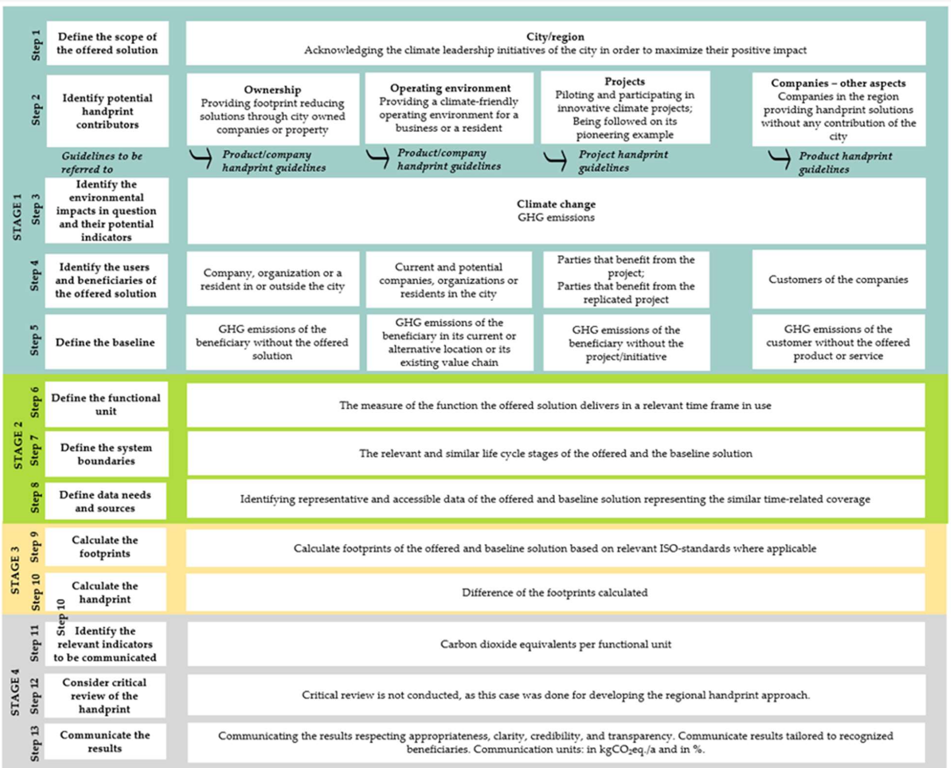

Figure 2. The framework for assessing the carbon handprint of cities and regions.

The framework consists of four main stages: Stage 1. Handprint requirements; Stage 2. Additional LCA requirements; Stage 3. Quantification; and Stage 4. Communication. The first stage, handprint requirements, is specific to handprint assessments and the foundation of further quantification. The first step is to define the scope of the study, which in the case of regional carbon handprints refers to the city or region under review. In the next step, the actions which may generate or contribute to a handprint are identified and classified into mechanism categories. In our study, three main mechanism categories were identified:

1. **Ownership** refers to the GHG-reduction actions that can be implemented through city-owned property or companies. For example, city-owned companies may provide products or services that reduce the carbon footprints of their customers or a city may provide real estate or land for climate-friendly initiatives.
2. **Operating environment** refers to whether a city or a region offers a climate-friendly operating environment for a company or resident. For instance, through urban planning and construction, traffic, energy, waste management, implementation of a circular economy and public procurement processes, cities and regions may provide an operating environment that enables reductions in the carbon footprints of other actors.
3. **Projects** refers to the innovative climate projects or other initiatives in which the city plays an important role. A city can achieve direct benefits by participating in projects that reduce the GHG emissions of beneficiaries or indirect benefits if some other actor follows its pioneering example and the climate-friendly initiate is replicated elsewhere.

In addition to the three main mechanism categories, handprint contributors can be classified as **companies—other aspects**; however, these contributors should be reported separately. This category includes companies providing carbon handprint solutions through products or services where a city or region has no connection to that company′s operations except offering them a location in which to function. However, for marketing and branding purposes, it might be advisable to communicate the carbon handprints of companies that operate in the area.

In the case of the mechanism categories of ownership and operating environment, the assessor is advised to refer to the product [26] or company handprint guidelines [34]. The mechanism category of projects follows the guidelines for project handprint assessment, which are elaborated upon by Vatanen et al. [34]. Additionally, in the context of companies—other aspects, the product handprint guidelines [26] should, again, be referred to.

The third step involves selecting the environmental impact categories and their indicators. Currently, the regional-level handprint only covers the impact category of climate change; thus, it is advised that GHG emissions and removals be included in the assessment.

Identifying the beneficiaries of the actions included in the carbon handprint assessment is crucial since the fundamental function of handprinting is to facilitate emission reductions by others. Step four is to identify the users or beneficiaries of the city′s climate actions identified in the previous steps. In the context of cities, beneficiaries may include the city′s current and potential residents, companies and organisations as well as actors outside the city borders. However, depending on the situation, several beneficiaries may be identified, or no beneficiaries may be precisely identified. Then, an examination can be conducted at the system level by considering the case from a wider point of view. For example, the carbon handprint assessment of climate change mitigation projects may require system-level examination when society as a whole is identified as a beneficiary.

The final step of Stage 1 concerns establishing baseline conditions, which creates a point of comparison in the handprint assessment. Choosing a baseline depends on the mechanism category, as presented in Figure 2. However, generally, in each case, a baseline represents the conditions as they would be without the relevant climate leadership initiative provided by the city. The baseline should be chosen based on the current practices and conditions that the beneficiary is facing. For more detailed instructions and additional information on the baseline determination procedure, the reader is advised to refer to the Carbon Handprint Guide v. 2.0 [26]. The guide also provides instructions for following Stages 2–4 of the handprint assessment.

3.2. Separating a Carbon Footprint from a Carbon Handprint

The carbon footprint of a city or region is an absolute measure of the total GHG emissions a city causes and removes [5]. In contrast, its carbon handprint defines and quantifies the emission reductions achieved in the carbon footprints of other actors due to the actions it performs.

The core of climate change mitigation activities in cities is the minimisation of the carbon emissions within a city, that is, the reduction of its carbon footprint. However, an even higher potential to reduce emissions exists in taking measures that affect the carbon footprint of others. Residents, other stakeholders and companies within and beyond a city might benefit from climate actions implemented by the city in terms of GHG reductions. For instance, by spreading good GHG-reduction practices, the impact of a city may reach even national and global levels. Hence, there is no upper limit when reducing the carbon footprint of others and, in contrast to its carbon footprint, a city′s carbon handprint should be extended to cover as many beneficiaries and areas as possible.

City-level assessments must consider separating the city as a geographical area from the city as an organisation. Generally, a city as an organisation is an executive organ of actions. Nevertheless, in a carbon footprint context, an emission inventory is performed according to activities occurring within the geographical boundaries of a city and reducing its carbon footprint requires the cutting of emissions or consumption within these predetermined boundaries. In contrast, in a carbon handprint assessment, geographical boundaries do not necessarily reflect the city′s boundaries because emission reductions may occur anywhere. Hence, geographical boundaries are defined for each case individually. However, handprint activities may also occur in the city and reduce the city′s carbon footprint. Importantly, the carbon handprint of a city cannot be subtracted from its carbon footprint. Figure 3 illustrates the relationship between the city as an organisation and the geographical boundaries of the footprint and handprint assessments of a city.

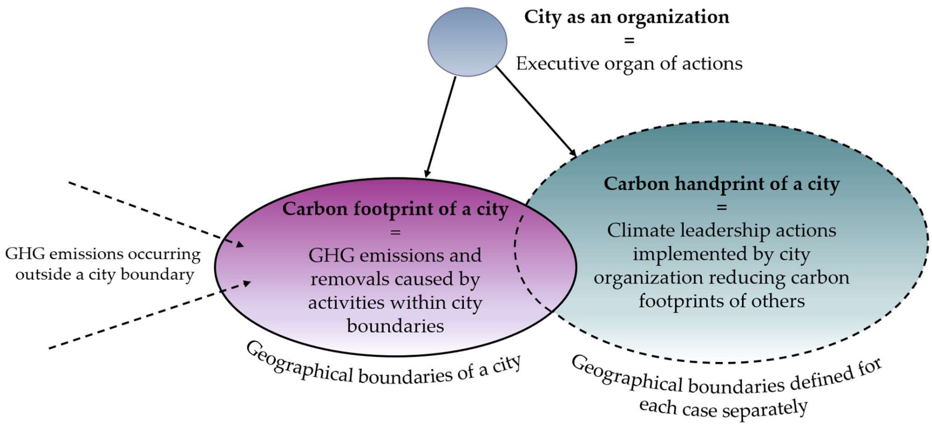

Figure 3. Relationship between the city as an organisation and the geographical boundaries of the footprint and handprint assessments.

3.3. The Results of the Espoo Case Study

In the case study, the carbon handprint contributors in the city of Espoo were divided according to the three main mechanism categories: ownership, operating environment and projects. Additionally, the actions that fall within the mechanism category of companies—other aspects were identified, but they should be reported separately. As the case study was conducted to support methodology development, no exhaustive list of handprint contributors was composed; rather, one example of each mechanism category was selected to be applied to the framework. Some additional examples of handprint contributors in Espoo are also mentioned in the text, but not in the framework.

Figure 4 illustrates three identified handprint contributors in the city of Espoo applied to the framework of the city′s carbon handprint. Only the first two stages are represented as they are the most central, as well as being unique to case assessments. Stages 3 and 4 follow the general framework represented in Figure 2.

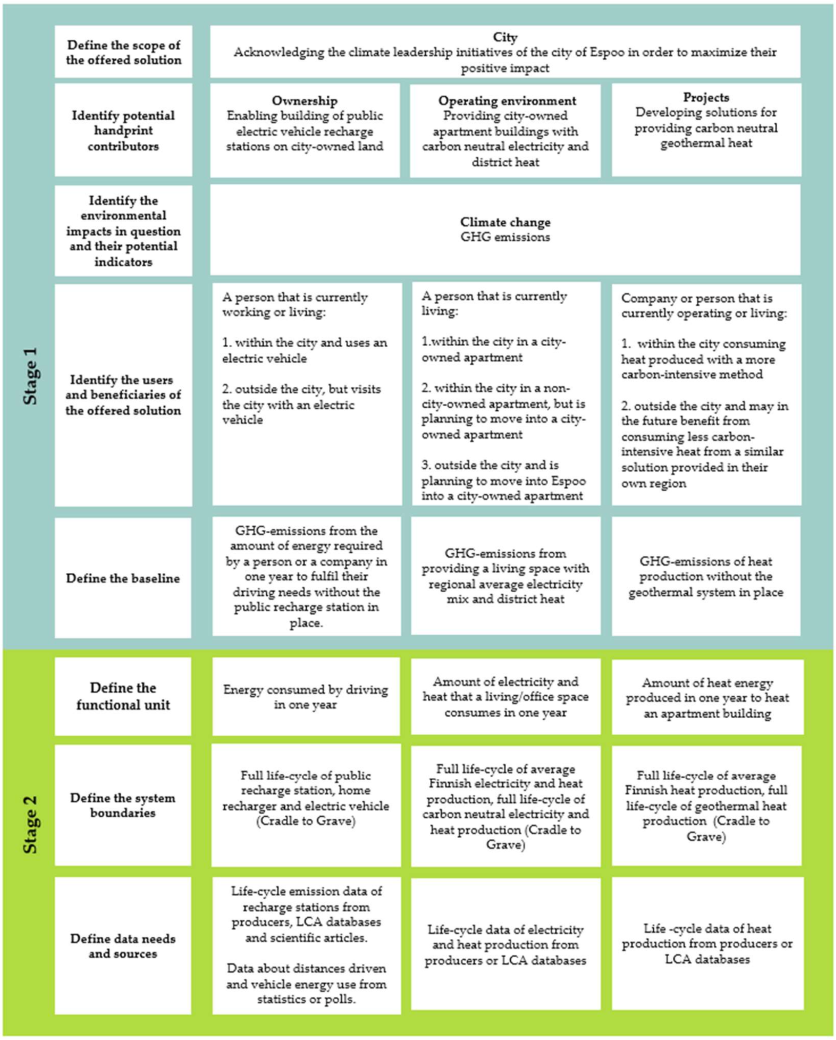

Figure 4. The framework for assessing the carbon handprint in the case of Espoo.

The mechanism category of ownership refers to city-owned companies or property through which the city can provide carbon footprint-reducing solutions to users. In the case of Espoo, a potential footprint-reducing activity related to city-owned property is enabling the placement of market-based electric vehicle (EV) charging stations on city-owned land. Although policies allowing the installation of charging stations on city-owned land or property do not directly reduce the carbon footprint of the city, the existence of an expanding charge station network may encourage the phasing out of fossil fuel vehicles, thus contributing to the city′s carbon handprint. Additionally, the availability of public EV chargers has the potential to create a carbon handprint when the charger uses renewable electricity instead of average grid mix [33].

The second handprint mechanism category is related to providing a climate-friendly operating environment for a business or resident. This category includes activities such as promoting carbon-neutral electricity production through solar electricity bidding, actions to increase the efficiency and diversity of transport and the provision of local ecosystems for green business [33]. The activity of providing city-owned apartment buildings with carbon neutral electricity and district heat is selected as an example in Figure 4.

The third mechanism category relates to the pioneering of novel footprint-reducing solutions. Espoo has been a pioneer in electrifying the public bus network. Currently, the city is participating in a geothermal energy project aiming at carbon neutrality. Successful projects may be replicated by other cities in the future and thus contribute to increasing Espoo′s carbon handprint [33].

The fourth and final mechanism category is related to the many ways in which non-city-owned companies can increase a city′s carbon handprint. Example activities within this category are the implementation of a virtual power plant within a shopping centre in the city and cleantech companies in the city providing footprint-reducing solutions to their customers [33]. However, the fourth mechanism category is excluded from Figure 4 as the city of Espoo has no immediate connection to these handprint activities. At the same time, they might increase the city′s attractiveness and viability.

The total carbon handprint of a city is the sum of the effects of many activities. To demonstrate the quantitative assessment, the carbon handprint of building public EV charge stations on city-owned land from the mechanism category of ownership was calculated. The hypothesis was that the availability of public EV chargers has the potential to create a carbon handprint if the charger uses renewable electricity. The handprint is created by the difference in carbon footprint when compared to charging the vehicle using an electricity mix containing energy produced with fossil fuels. In the calculation, the user of an offered solution is a person who already lives within the city and owns an EV.

EV charging at home with the national Finnish electricity mix is used as a baseline, whereas the offered solution includes the use of public charging stations in Espoo operating with electricity from wind power. The system boundaries of the solutions are presented in Figure 5. Calculations about the life cycle GHG emissions of an EV are not included in the assessment, as the life cycle is included in both solutions. The difference in the carbon footprints of the solutions is represented by the differences in life-cycle emissions between a home charger using mixed electricity and a public charger using renewable energy. The functional unit is the amount of energy consumed by driving an EV in one year.

The national Finnish average distance driven using a vehicle powered by a method of propulsion other than petrol or diesel was 15,062 km in 2018 [35]. The energy consumption of an EV is generally between 0.15 kWh/km and 0.30 kWh/km [36]. In the assessment, the average value 0.225 kWh/km is used. The GWP100 values for the Finnish electricity grid mix and electricity from wind power were derived from the GaBi LCA modelling software database [37]. The public chargers in Espoo are alternative current (AC) chargers. In its use stage, a public AC charger produces 9.62 gCO_2eq/kWh more emissions than a home charging device, due to greater use of material and energy during the material acquisition and manufacturing stages and to greater electricity loss in the use stage. The lifetime of both charger types is assumed to be eight years [38].

Maximum carbon footprint from the use of each charger type is produced when 100% of charging is carried out with a specific charger. For one EV vehicle, the carbon footprints for home charging and public charging are shown to be 671 kgCO_2eq/a and 62 kgCO_2eq/a, respectively. The maximum carbon handprint for a public charger can be calculated as the difference of the carbon footprints. Consequently, the maximum carbon handprint for a public charger is 609 kgCO_2eq/a for the one EV vehicle. In 2021, 18 new public charging stations were installed in Espoo [39]. As the European Union suggests that there should be, on average, one charging point per 10 cars [40], the potential to charge 180 EVs is created. In that case, maximum carbon footprints for home charging and public charging are 121 tCO_2eq/a and 11 tCO_2eq/a, respectively. The carbon handprint potential of installed public charging stations corresponds to up to 110 tCO_2eq/a, as visualised in Figure 6. This equals 91% emission reduction potential.

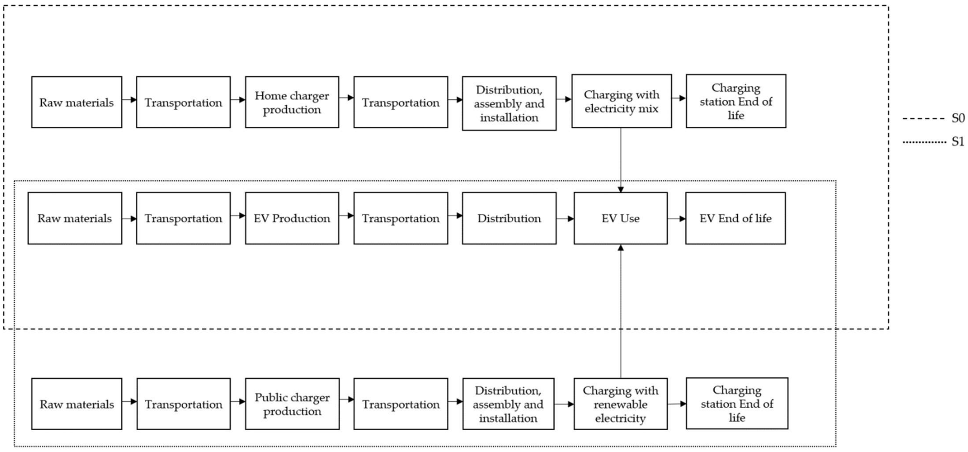

Figure 5. System boundaries of the baseline solution (S0) and the offered solution (S1).

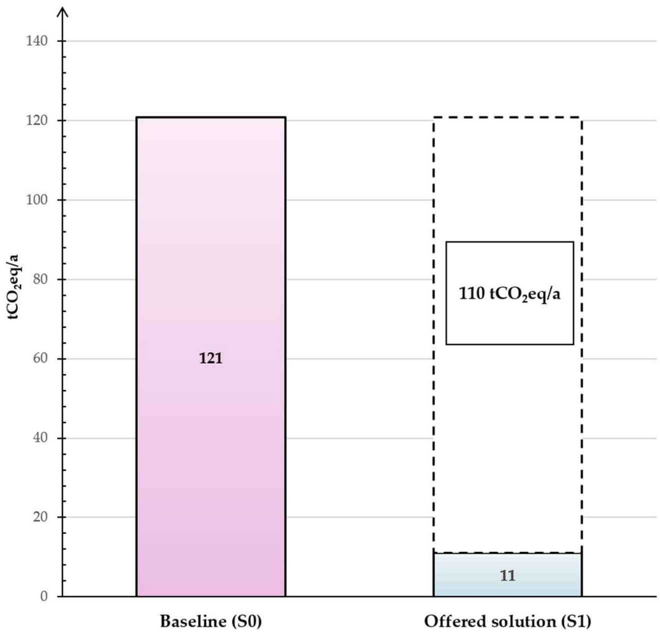

Figure 6. Carbon footprint and handprint of different solutions.

In reality, it is unlikely that 100% of EV charging is carried out in public charging stations. The more plausible scenario is one where the vehicle is charged both at home and at a public charging station during the year. In such a scenario, the handprint of EV charging in 18 new public charging stations will be between 0 and 110 tCO_2eq/a, where the numbers correspond to 0% and 100% of charging carried out at a public station, respectively.

3.4. Utility of the Carbon Handprint Approach for Cities

Whereas community-scale GHG inventories form the basis for understanding emission sources and reduction potential within a city's boundaries [5], the carbon handprint communicates the emission reduction potential which cities and regions may be able to achieve at global level.

Previous studies have indicated that cities′ potential to reduce the GHG emissions originating from the activities that take place within their boundaries are limited [13]. Additionally, community-level GHG accounting contains several uncertainties, which may further restrict climate change mitigation activities. For example, climate neutrality may be achieved more readily when convenient system boundaries are set in GHG inventory [41]. Thus, besides developing and harmonising present GHG accounting frameworks, the recognition and implementation of more widespread GHG-reduction activities are needed for cities to reach their full potential as mitigators of climate change. The regional carbon handprint approach presented in this paper provides a scientific and coherent framework by describing guidelines for assessing, as well as developing, large-scale mitigation activities in cities from a positive point of view. As the handprint framework provides an important extension to the existing climate work being done in cities, in the future, it would be interesting to consider integrating it into voluntary frameworks such as CoM commitments.

Besides providing an instrument to enhance climate change mitigation work, a carbon handprint can be used as a communication tool in cities′ marketing and branding. It provides a reliable indicator when communicating and promoting the actions a city is taking in the battle against climate change to attract new residents, businesses and initiatives to the area. With a systematic strategy, cities can maximise their handprint potential in the years to come. Additionally, especially given that recent research has underlined the need to transition from resource-dependent industrialisation to innovation-driven sustainable development in urban areas [42] and to avoid locking ourselves into high-emission pathways in the future [43], a systematic handprint strategy will promote and support cities′ development of novel, innovative solutions to combat climate change. For example, decisions concerning land use and infrastructure can significantly affect the future direction of emissions.

In the carbon handprint approach, identifying beneficiaries, users or clients is essential as the fundamental purpose of this approach is to reduce the carbon footprint of others. In the case of cities, a large number of diverse beneficiaries can be identified, such as residents, companies and other cities. One beneficiary group, companies, may gain considerable benefits from the climate actions implemented by cities. As companies strive for carbon neutrality and fewer emissions, cities can help to reduce their emissions, which may, in turn, reduce the need to compensate for emissions in companies. For example, cities may provide renewable fuels for companies, energy-efficient facilities or products that reduce the carbon footprint of the supply chain. Thus, the carbon handprint of cities also supports the work companies are doing to mitigate climate change as well as emission reductions on a larger scale.

Whereas community-level GHG accounting is based on the absolute emissions caused by a city, the carbon handprint concentrates on acknowledging and quantifying the emission-reduction potential of city-driven climate actions. In this paper, the carbon handprint approach for cities and regions was applied to the city of Espoo by identifying handprint contributors and calculating the carbon handprint for public EV charging stations built on city-owned land from the mechanism category of ownership. The results show that the city's climate leadership actions can be recognised and classified according to the guidelines, and the carbon handprint of different contributors can be quantified. However, future research is needed, particularly in terms of data gathering, quantification and communication. For instance, it should be studied whether it is feasible to compare cities′ handprints with each other.

4. Conclusions

This study modifies previous carbon handprint framework to be applicable in the scope of cities and regions. Presented framework provides guidelines to quantify and communicate GHG emission reduction potential of actions launched by a city, which also reduce carbon footprints of other actors. By following step-by-step guidelines, GHG-reductive climate activities of cities can be recognised, categorised and quantified, as shown in the case study of Espoo.

For wider adaptation of the carbon handprint framework of cities and regions, the following policy recommendations are given. The carbon handprint should be included in the climate work of cities to reliably show the life-time emission reduction potential of climate interventions. Cities and regions should develop the carbon handprint potential through long-term strategic planning to systematically increase the efficiency of their climate actions. The carbon handprint of cities and regions could be used as communication tool in cities′ marketing and branding to enhance the viability and attractiveness of a city or region. In future, the carbon handprint assessment could be integrated into international commitment frameworks such as CoM and C40 Cities.

The aim is that the carbon handprint framework for cities and regions would encourage cities and regions to develop and assess novel, innovative and widespread solutions in their climate work. As the main purpose of this study is to introduce and briefly test the novel framework for assessing regional-level carbon handprints, additional qualitative and quantitative case studies are suggested.

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