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PRODUCTIZING CARBON FOOTPRINT AND HANDPRINT FOR WOOD CONSTRUCTION

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ABSTRACT

Productizing Carbon Footprint and Handprint for Wood Construction

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The construction industry is recognized as one of the leading industries contributing significantly to carbon footprint creation. While the footprint concept is utilized for negative environmental impacts, handprint is a new topic, which refers to positive environmental impacts that businesses can gain and communicate by offering goods and services that reduce customers' footprints. This thesis aims to study methods that promote low-carbon construction with a small carbon footprint but a large carbon handprint. For that goal, wooden construction was chosen as a highly promising solution for creating carbon handprints and reducing the carbon footprints of construction.

The study combines a literature review and qualitative analysis of empirical data collected from two companies and one specialist. This study first reviewed the literature to identify the critical elements of carbon handprint and footprint in general and wooden construction. Then data is gathered through semi-structured interviews to study the potential of wooden buildings in decreasing the construction carbon footprint and increasing construction handprint. This study applies the Gioia method for data analyses.

Findings show that the construction industry has a lot of carbon footprint elements, such as materials, energy, transportation, and supply chain. Results show that wood products are beneficial to the environment, businesses and customers. Also, the critical role of centralized product data and the systematization of sales items in reducing carbon emissions in wooden construction is demonstrated. We conclude that carbon footprint and handprint could be productized, decrease carbon footprint and increase carbon handprint via replacing footprint sources with sustainable materials, energy, construction processes, transportation, and supply chains in the construction industry.

Keywords: Carbon footprint, carbon handprint, product structure, productization, product data, wood construction

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LIST OF ABBREVIATIONS

BIM	Building Information Modeling
BSI	British Standards Institute
CE	Carbon Emissions
CF	Carbon Footprint
CO2	Carbon Dioxide
EWPs	Engineered Wood Product Sub-Sector
GE	Gas Emissions
GHG	Greenhouse Gas
ISO	International Organization for Standardization
PD	Product Data
PDM	Product Data Management
PS	Product Structure
SHINE	Sustainability and Health Initiative for Net Positive Enterprise
WBCSD	World Business Council for Sustainable Development
WRI	World Resources Institute

1 INTRODUCTION

1.1 Background

Construction is one of the industries with the highest carbon footprint (Sizirici et al. 2021). The term carbon footprint refers to the total amount of carbon dioxide (CO2) emissions caused directly or indirectly by activity or generated over the life stages of a product (Wiedmann and Minx 2008). In 2009, the total CO2 emissions from the construction industry were 5.7 billion tons, accounting for 23% of global economic activity emissions (Huang et al. 2018). It emphasizes the necessity of enterprises and customers in the construction sector to implement approaches to reduce carbon footprint during the construction process.

Many recent studies have proposed alternative approaches to reducing carbon footprint in energy consumption (Sizirici et al. 2021; Wang et al. 2021; Jiang et al. 2022), using sustainable materials (Sudarsan et al. 2022), sustainable transportation (Luo et al. 2021), and modular-based construction (Kamali and Hewage 2017; Jang et al. 2022) in both production processes and operational phases of construction and supply chain (Karlsson et al. 2021; Li et al. 2021; Nematchoua et al. 2022). Recently, many studies have investigated replacing non-renewable materials of a building product with sustainable alternatives like wood. According to Viholainen et al. (2021), sustainable qualities of wooden materials address economic, social, and environmental concerns. There is an excellent agreement that wooden materials, due to their carbon storage properties, play a crucial role in greenhouse gas emissions (Petersen and Solberg 2005; Lippke et al. 2011). Lakkala and Pihlajaniemi (2021) underline the high degree of positive user impression of wooden materials and the higher level of modularity of the wood as a renewable building material. Another research looked at the Finnish perspective of wooden construction, finding that it is now seen as a trendy and stylish material due to its naturalness, warmth, and healthiness (Lakkala et al. 2020).

The ideas presented show the potential to reduce the direct and indirect carbon footprint of construction products and operations (Cabeza et al. 2013; Huang et al. 2018). Carbon emissions can be separated into direct and indirect emissions (Sandanayake et al. 2016). Direct carbon emissions (or footprint) are those produced on-site during construction, whereas indirect carbon emissions (or footprint) are produced by off-site operations such as manufacturing and transportation in the construction industry (Marzouk et al. 2017). The whole life cycle of a building is considered in a carbon footprint analysis. It covers the manufacturing and shipping of items needed in construction projects and the worksite, building use and repair, demolition, and recycling (Kuittinen 2019).

Typically, evaluating environmental effects has focused on assessing and modelling the negative effects that goods, services, and businesses have on the environment. McDonough (2002) has proposed a reverse approach to assessing environmental impacts, which focuses on finding new business prospects by generating positive benefits. While the footprint concept is utilized for negative environmental impacts, handprint is a new topic, which refers to positive environmental impacts that businesses can gain and communicate by offering goods and services that reduce consumers' footprints (Pajula et al. 2021).The handprint approach is appropriate for businesses that want to measure and communicate the environmental advantages of their products and services to their customers (Grönman et al. 2019). Dyllick and Rost (2017) discuss genuinely sustainable business, in which a business shifts its perspective from a company to a product level. This approach focuses on improving products' positive impacts (handprint) rather than limiting their negative imprints (Dyllick and Rost 2017).

In the construction industry context, despite this interest, the concept of handprint is not yet known, and limited research has been conducted to the best of our knowledge. According to Kuittinen (2019), The term carbon handprint refers to the environmental benefits that would not have been possible if a construction project did not exist. Extra renewable energy created during the life cycle of the structure and the benefits received from the reuse and recycling of construction items are examples of carbon handprint (Kuittinen 2019).

Making construction systemized via productization is one possible method for sustainable construction, decreasing carbon footprint, and increasing efficiency. Productization creates a standardized and repeatable offering that is easier to buy, sell, and market by assembling an appropriate collection of tangible or intangible aspects (Harkonen et al. 2015). Productization is consistent with sustainable product development, which assists in managing natural resources and reduces carbon emissions (Leppänen et al. 2020). Productization is divided into technical and commercial, or capacity-to-produce (inbound) and capacity-to-sell (outbound) activities. Inbound activities aim to synchronize and organize the providing delivery process, whereas outbound productization seeks to increase product value to consumers and provide a broader product family to meet needs (Simula et al. 2008). Product structure (PS) is one method of productization, which refers to the systematization of product descriptions. (Mansoori et al. 2022). PS connects the development and distribution of new products (Simula et al. 2008; Harkonen et al. 2015), and PS enables the timely and reliable exchange of information between technical and commercial sides in an incorporated and well-designed way (Mansoori et al. 2022)

1.2 Objectives and thesis structure

Against the background above, this research looks into solutions promoting low-carbon construction with a small carbon footprint but a large carbon handprint. Since the concept of carbon handprint is relatively new and is not known in the construction industry, in this study, we will analyze the carbon footprint of a particular building product and then study the potential handprint of producing the product. To this end, the study follows Grönman et al. (2019) *approach as the Carbon handprint (product X) equals the Carbon footprint of Baseline practice minus the Carbon footprint of Modified practice* (Grönman et al. 2019, p. 1061)

Productization of building products is an approach we follow in this study that minimizes their carbon footprint to generate products that have a positive impact on the environment or have a higher carbon handprint. Considering the direct carbon footprint produced on-site during construction, or upstream emissions of a product (Luo et al. 2019), could be linked to the technical side of product structure, as it refers to the ability to produce in an earlier stage of building production. On the other hand, indirect footprint, or downstream emissions of a product (Luo et al. 2019), could be related to the business component of product structure, making the product more marketable and easier to sell. Accordingly, it could be assumed that a higher level of productization will decrease the level of carbon footprint. On the other hand, it will increase the carbon handprint. Carbon storage and sinks in buildings, added renewable energy generated during the building's life cycle, and the benefits received from the reuse and recycling of construction goods are all approaches that will increase the level of carbon handprint throughout the building's life cycle (Kuittinen 2019). According to Kuittinen (2019), carbon handprint can be determined in the whole lifecycle stages of a building regarding material, energy, transportation and construction. The scope of this study is limited to wooden construction to see how carbon-neutral materials and processes can facilitate the increase in construction handprint. The research questions (RQ) for the study are set as follows:

- RQ1: What are the critical elements of carbon handprint and footprint in construction?
- RQ2: What are the benefits of wooden buildings in decreasing construction carbon footprint and increasing the handprint?
- RQ3: How can carbon footprint and handprint be described in wood construction?

The first research question will be answered through a literature review about critical elements of carbon handprint and footprint in construction (chapter 2(. A synthesis of findings from the literature review will be utilized as the foundation for empirical data collecting from case organizations to determine what elements they perceive as crucial in practice to elevate handprint in construction (chapter 3). Then the elements of productizing building products with higher carbon handprint will be examined. Then the product structure of footprint and handprint in the wood construction is discussed in detail (chapter 4). In the discussion and conclusion part (chapter 5), the potential solutions will be proposed, answering the RQ3.

2 LITERATURE REVIEW

2.1 Carbon emissions

2.1.1 Carbon footprint

Global warming is a fact, and one of the most difficult issues of modern living has been dealing with global warming and its environmental repercussions. In fact, the majority of recent sustainable initiatives are inextricably linked to the goal of lowering our overall carbon footprint (Fenner et al. 2018).Gao et al. (2014, p. 237) Define that "the carbon footprint originates from the concept of ecological footprint, which is a measure of human demand on the Earth's ecosystems". The term carbon footprint refers to the total amount of carbon dioxide (CO2) emissions caused directly or indirectly by an activity or generated over the life stages of a product (Wiedmann and Minx 2008). This includes activities of individuals, populations, governments, companies, organizations, processes. Industry sectors etc. Products include goods and services (Wiedmann and Minx 2008). Chainho and Matos (2012) define carbon footprint as a measure of how much CO2 is released into the environment over the duration of a product's or activity's life cycle. It's usually determined by looking at the direct and indirect emissions of resources used in certain activities. Carbon footprint (CF) is generally adopted as an indicator to quantify carbon dioxide (CO2) emissions (CE) or greenhouse gases (GHG) emissions (GE) in terms of CO2equivalents (CO2-eq) (Chen et al. 2021).

To create carbon emissions accounting results comparable, governments and international organizations such as the International Organization for Standardization (ISO), the World Resources Institute (WRI), the World Business Council for Sustainable Development (WBCSD), and the British Standards Institution (BSI) have introduced various types of carbon footprint assessment standards, primarily for organizations and products, through a large number of research studies (Gao et al. 2014). After years of work, a greater understanding of carbon footprint assessment standards such as ISO14064, GHG Protocol, and PAS2050 has established. The adoption of these standards contributed significantly to the reduction of world carbon emissions (Gao et al. 2014). Nevertheless, several issues remain in the implementation of these regulations, like the lack of uniformity in carbon emissions accounting techniques, as well as the fact that many carbon emissions are unknown.

Increased population and urbanization have increased in construction projects, and more construction projects will lead to an increase in carbon footprint (Kisku et al. 2017). The construction sector is one of industries with the highest carbon footprint (Sizirici et al. 2021). In 2009, the total CO2 emissions from the construction industry have been 5.7 billion tons, accounting for 23% of world economic activity emissions (Huang et al. 2018). Buildings contribute 33 percent of global greenhouse gas (GHG) emissions and 40 percent of global energy consumption due to the use of equipment, the manufacture of building materials, and transportation in both developed and developing countries (Sizirici et al. 2021). It emphasizes the necessity of enterprises and customers in the construction sector implementing approaches to reduce carbon footprint during the construction process.

Many recent studies have proposed alternative approaches to reduce carbon footprint in energy consumption (Sizirici et al. 2021; Wang et al. 2021; Jiang et al. 2022), using sustainable materials (Sudarsan et al. 2022), sustainable transportation (Luo et al. 2021), and carbon emissions assessment (Jang et al. 2022) in both production processes and operational phases of construction and supply chain (Karlsson et al. 2021; Li et al. 2021; Nematchoua et al. 2022). According to Kuittinen (2019), carbon footprint could be measured within a building's whole lifecycle including material, energy, transportation and construction areas, as illustrated in Figure 1 (Kuittinen 2019).

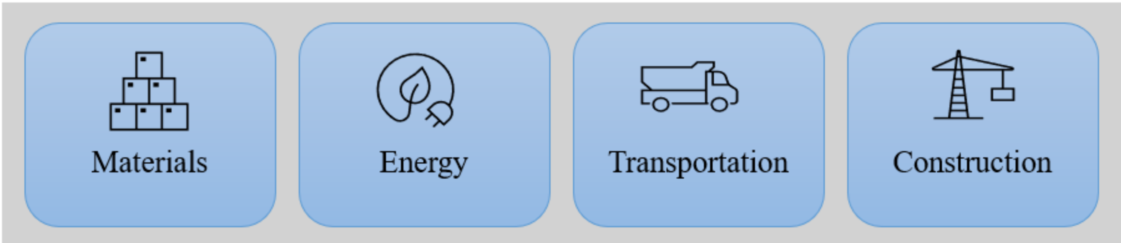

Figure 1. Potential areas for a building product footprint (adopted from Kuittinen 2019., page 15)

The ideas presented shown potential to reduce the direct and indirect carbon footprint of construction production and operations (Cabeza et al. 2013; Huang et al. 2018). Based on the emission source, carbon emissions can be separated into direct and indirect emissions (Sandanayake et al. 2016). Direct carbon emissions (or footprint) are those produced on-site during construction, whereas indirect carbon emissions (or footprint) are those produced by off-site operations such as manufacturing and transportation in the construction industry (Marzouk et al. 2017). The whole life cycle of a building is considered in a carbon footprint analysis. It covers the manufacturing and shipping of items needed in construction projects, as well as the worksite, building use and repair, demolition, and recycling (Kuittinen 2019).

2.1.2 Carbon handprint

Typically, evaluating environmental effects has focused on assessing and modelling the negative effects that goods, services, and businesses have on the environment. McDonough (2002) have proposed a reverse approach to assessing environmental impacts, which focuses on finding new business prospects through generating positive benefits. Meanwhile footprint concept is utilized to negative environmental impacts, handprint that is new topic refers to positive environmental impacts that businesses can gain and communicate by offering goods and services that reduce consumers' footprints (Pajula et al. 2021).The handprint approach is appropriate for businesses that want to measure and communicate the environmental advantages of their products and services to their customers (Grönman et al. 2019). The handprint method forces businesses to expand their sustainability practices. It encourages them to adapt their product to each customer's demands and tastes, as well as to modify it to the real-world working environment in terms of CO2 emissions (Grönman et al. 2019). Dyllick and Rost (2017) discuss about truly sustainable business, in which a business shifts its perspective from a company to a product level. This approach focuses on improving the positive impacts (handprint) of products rather than limiting their negative imprints (Dyllick and Rost 2017).

UNESCO first introduced the handprint concept in 2007, when it was identified as a measure of Education for Sustainable Development activity aimed at reducing the human footprint (CEE 2014)In recent years scholars and articles (Biemer et al. 2013; Norris 2015) have stressed the importance of taking a sustainable approach to handprinting. Since Carbon handprint as a term is quite new and has many definition in literature for example (Pajula et al. 2021) explain that the handprint method is based on the idea that minimizing one's own footprint is not a handprint. Instead, a handprint is obtained by optimizing the productivity of others – by decreasing their footprint. A basic and clear idea by (Pajula et al. 2021, p. 11) define carbon handprint "A carbon handprint is the reduction of the carbon footprint of others". Similarly, the reduction of a customer's carbon footprint is equivalent to the carbon handprint. Every product that has the ability to reduce carbon emissions has a carbon handprint (Grönman et al. 2019). According to Grönman et al. (2019) there are two ways to generate a carbon handprint. Solution A refers to reduced emission of handprint good or service during its lifecycle. Solution B refer to reduced consumer emissions as a result of using a handprint solution, as presented in Figure 2.

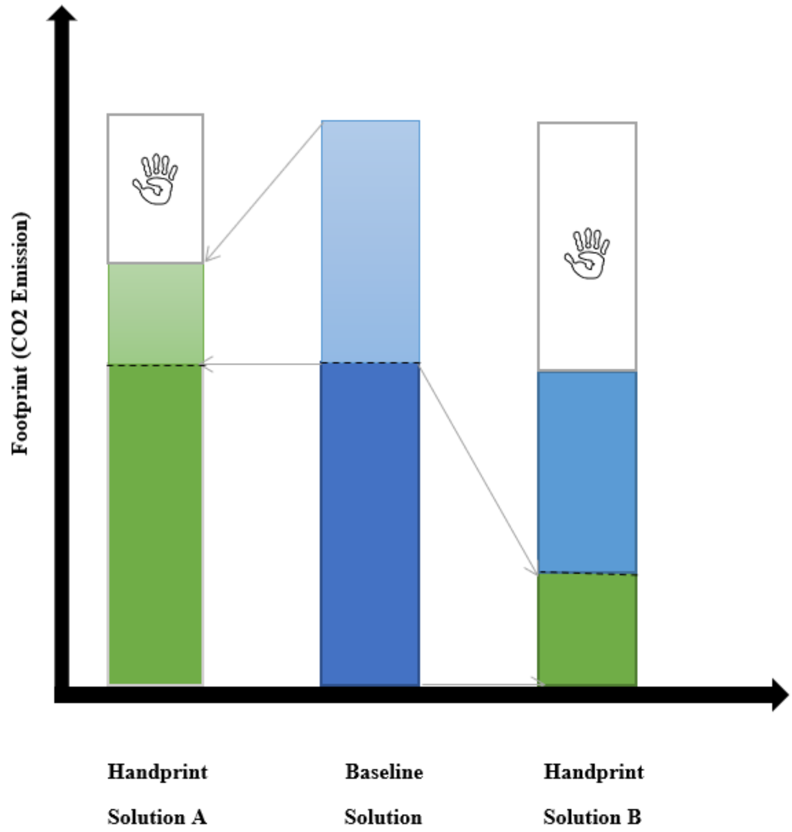

Figure 2. Two ways to create carbon handprint (adapted from Grönman et al. 2019, page 1063)

The carbon handprint approach has multiple aims in various sector but Pajula et al. (2021, p. 15) describe that "the goal of handprint is to assess the positive impacts that would be achieved when an offered product or service is used by a known or potential user." Another goal of carbon handprint a product is that determine how much carbon the product already has eliminated, either through the use of emissions-negative energy in processing or by being a product manufactured without the use of CO2 (Daneshvar et al. 2022). One of the most important carbon handprint tasks in organizations could be that the handprint offers details for strategic decision-making and internal operations by displaying the environmental capabilities of various product types and how effects along the value chain could change in different markets (Vatanen et al. 2021).

In context of construction industry, despite this interest, the concept of handprint is not yet known, and limited research have been conducted to the best of our knowledge. According to Kuittinen (2019), The term carbon handprint refers to the environmental benefits that would not have been possible, if a construction project did not exist. Extra renewable energy created during the life cycle of the structure, as well as the benefits received from the reuse and recycling of construction items, are examples of carbon handprint (Kuittinen 2019).

The hand approach is developing, and scholars have recently proposed another new term called SHINE handprint, which differs from carbon hand print (Norris et al. 2021). The SHINE (Sustainability and Health Initiative for NetPositive Enterprise) project will enhance the scientific foundation for beneficial environmental, social, and economic transformations known called handprints (Norris et al. 2021).The carbon handprint concentrates on one type of impact, namely climate change while all LCA-relevant effect categories are covered by the SHINE handprint concept. The carbon handprint assigns handprints to products but SHINE handprint believe that it is actors that change the outcome of handprints not products (Norris et al. 2021).

2.2 Wood products in construction

Wooden products are attractive for various reasons, including social, financial, and environmental reasons (Wegner et al. 2010). Compared to non-wood alternatives, wood products have numerous environmental benefits. Non-wood alternative construction materials such as concrete, steel, and plastics need higher fossil fuel to produce than wood products (Bergman et al. 2014). In order to develop effective ways to replace fossil fuels and non-biomass resources, expanding the use of wood in building has been considered as a key possibility (Eriksson et al. 2012).

Wood-based products help to mitigate climate change through two different mechanisms: carbon substitution and storage (Hurmekoski 2017). First, replacing wood with steel, concrete, and other energy-intensive products reduce fossil fuel usage and, as a result, carbon footprints. Second, trees absorb CO2 from the environment through photosynthesis and store it in wood-based products for the length of the product's life cycle (Hurmekoski 2017). Figure 3 illustrates how trees sequester CO2 through Photosynthesis.

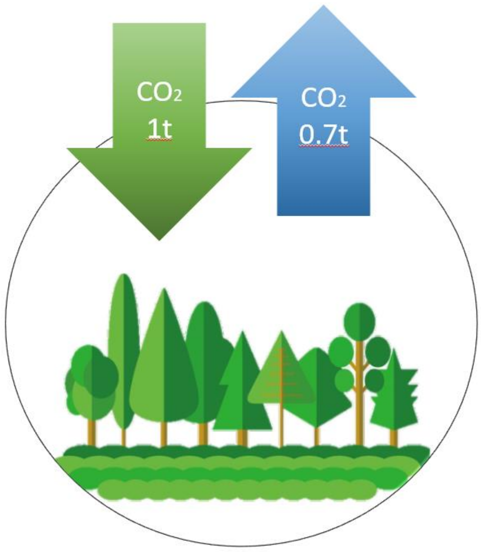

Figure 3. Illustration of how trees sequester CO2 through Photosynthesis (adopted from Hurmekoski 2017, page 7)

According to (Viholainen et al. 2021), sustainable qualities of wooden materials address economic, social, and environmental concerns. There is a great agreement on that wooden materials due to its carbon storage properties plays a key role in greenhouse gas emissions (Petersen and Solberg 2005; Lippke et al. 2011). Lakkala and Pihlajaniemi (2021) underline the high degree of positive user impression of wooden materials, as well as the higher level of modularity of the wood as a renewable building material. In another research, they looked at the Finnish perspective of wooden construction, finding that it is now seen as a trendy and stylish material due to its naturalness, warmth, and healthiness (Lakkala et al. 2020).

According to Ritter, Skog and Bergman (2011) wood product and construction process research and development lags behind that of other materials. To continue to expand wood as a sustainable construction resource, both scientific advancement in the fields of life cycle analysis and the technological development for enhanced and extended wood utilization are required.

Any type of building in which the load-bearing structural frame is built of wood-based items is known as wood construction. Typically, wood has been utilized primarily in single-family homes (Hurmekoski 2016). With the advent of EWPs (Engineered Wood Product Sub-Sector), however, wood has become more widely used in large-scale construction, such as bridges, industrial halls, schools, sport facilities, and multi - story residential buildings (Buehlmann and Schuler 2013; Hurmekoski 2016). Due to the numerous advantages it provides, including as design possibilities, fresher indoor air, longer structure lifecycles, higher sustainability, reduced carbon footprint, more energy efficiency, and reduction in costs, wood construction is a rising industry particularly in Finland (Piispanen et al. 2022).

2.3 Product management

2.3.1 Product structure

The product structure depicts the product's elements, characteristics, and interconnections between them (Crnkovic et al. 2003). The product structure is defined as a hierarchical representation of product's components and assembly relation between them (Pinquié et al. 2015; Belkadi et al. 2016; Heimes et al. 2020). The product structure can help stakeholders gain a general grasp of a company's products and services. It assists managers in various areas of the company, such as managing different products and product data management (Kropsu-Vehkaperä 2012). Also product structure contains activities like as organizing functional parts, translating them to physical parts, and designing interfaces between components and technical objects (Chu et al. 2009). Components, elements, installations, and documents make up the product structure, which varies depending on the type of product (Mustonen 2020)

Tolonen et al, (2014) propose a two-sided product structure model in the context of productization: the commercial and technical product structure. Figure 4 shows hierarchical structure of product elements, separated in technical and commercial sides. (Mansoori et al. 2022). Commercial product structure is generally concerned with selling items and customers, whereas technical product structure is concerned with technical issues such as assembly and sub assembly (Tolonen et al. 2014; Harkonen et al. 2017; Adusei et al. 2021). A product structure has replaceable and customizable components that allow the product to be tailored for a specific customer configuration (Mustonen 2020).

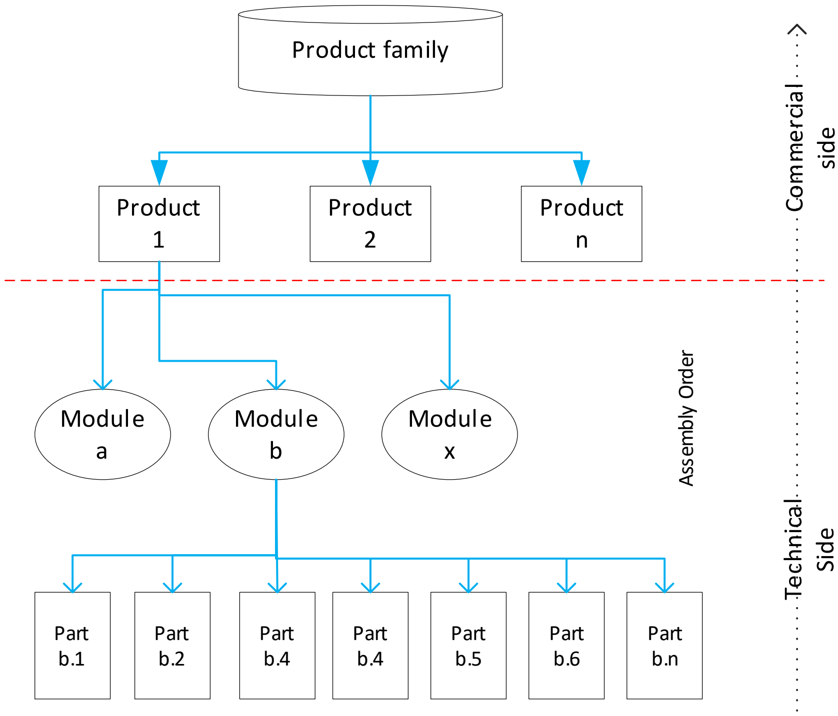

Figure 4. PS of hierarchical product elements (adopted from Mansoori et al., 2022)

The product structure is not studied much in the context of the construction industry and only a few studies on product structure in construction have been conducted (Mansoori et al. 2022). Tasks such as arranging functional elements, mapping them to physical components, and defining interfaces among both components and technical objects are all part of the overall product structure (Chu et al. 2009). In a construction company, the value of technical objects that facilitate information exchange can be considered during the construction process (Mansoori et al. 2022). Also, modelling technical and commercial solutions is appropriate for construction projects (Harkonen et al. 2018). Technical issues such as design and building can be included on the technical side, while commercial issues such as advertising and sales can be included on the commercial side

2.3.2 Productization

Productization is the method of recognizing a requirement, identifying and merging appropriate tangible and intangible parts into a product-like specified set of deliverables that is standardized, repeatable, and understandable (Harkonen et al. 2015). When discussing productization, the terms standardization, systematization, productization, industrialization, and commercialization are frequently used interchangeably (Mansoori et al. 2022). Productization is a useful idea for enabling interaction between marketers and designers during the product development process (Hänninen et al. 2012). Productization is defined as a way for companies to reach and understand their customers' problems and develop creative solutions (Hänninen et al. 2012). Productization is defined from the standpoint of the product portfolio as "defining a company's products to gain a consistent understanding of what the company's product portfolio consists of" (Mustonen 2020, p. 11).

Productization also refers to goods and service management, as well as commercial and technical product portfolios (Harkonen et al. 2018). From a commercial standpoint, it focuses on the customer and has been recognized through marketing, sales, and product management (Tolonen et al. 2014). Usually, the most important factor in commercial aspects is price (Quelch and Jocz 2008). The pricing of a product is the sole ingredient in the marketing mix that generates income, whereas the rest of the elements are costs. Price can refer to the amount of money charged for a product, but it can also refer to the sum of all the values that buyers are willing to forego in exchange for the benefits of owning or utilizing the product (Kotler and Armstrong 2006).

On the other hand technical perspective is recognized with product and service development, technology, checking, buying, transportation and distributions (Tolonen et al. 2014). Technical Productization focuses on defining, clarifying, and making the deliverable offering tangible based on the product structure concept (Harkonen et al. 2017). The role of the bill of materials (BOM) is well recognized in terms of technical product structure, but it can differ between goods or market sectors (Harkonen, Mustonen, and Hannila 2019). Härkönen et al. (2019) describe the product must be viewed as both a technical and a commercial item because it combines the product's sales and cost structure perspectives. Traditional understanding of the structure of technical products is insufficient (Harkonen, Mustonen, and Haapasalo 2019).

According to the literature, a product can take several forms, including hardware, software, and services. It also needs to be defined in terms of commercial and technical aspects (Kropsu-Vehkaperä 2012). In the construction industry, the definition of a product is not clear (Harkonen et al. 2018; Mansoori et al. 2022) In the construction industry, a product is typically described as the physical structure itself (hardware) or the building materials, which are primarily viewed as products that can be sold (Harkonen et al. 2018; Mansoori et al. 2022).

Productization is effective in the manufacturing sector, and it is now gaining traction in the construction industry (Boton et al. 2018; Harkonen et al. 2018). Productization in the construction industry is a relatively new concept, and only a few studies have been conducted on it (Mansoori et al. 2022). The authors describe that productization has the potential to help with the standardization of the construction offering and the improved performance of the efficiency of construction activities through the Product structure. This could allow for the systematic and consistent integration and sharing of reliable information from all construction phases (Mansoori et al. 2022).

Right now it is clear that productization methods are unfamiliar in the construction industry (Lassila, 2021). Construction activities are complex and many times they are unrelated. for example In the construction industry, order-delivery-invoicing practices based on progress payments do not support the definition of a product (Ahmadisheykhsarmast and Sonmez 2020; Grenzfurtner and Gronalt 2021). As a result, defining productization in the construction industry is rather complicated.

2.3.3 Product data management

Today's business environment is heavily reliant on data systems. Efficient data management practices have become one of the most important aspects of business efficiency in engineering and manufacturing firms (Kropsu-Vehkapera et al. 2009). Product data are referred to as information about a product in generally (Saaksvuori and Immonen 2004) Product data management (PDM) is the process of linking and controlling activities, applications, and all sorts of data that identify products across various systems and media (Saaksvuori and Immonen 2004; Stark 2005). The PDM network links PD (Product Data)-related product and process management, offering a framework for users to manage and share information, as well as a user interface (Rueckel et al. 2005; Kropsu-Vehkapera et al. 2009). Product data management can help to improve the design and manufacturing processes in a company when data is properly shared, and the use and visualization tools of PDM can boost organizational efficiency (Chan and Yu 2007).

The primary goal of implementing PDM is to assist businesses in electronically managing their operations and enhance efficiency and effectiveness. The primary function of PDM systems is to control all essential data for the design, maintenance, and disposal of goods and services. When a company is able to manage data management, it can gain control of its product (Stark 2005; Kropsu-Vehkapera et al. 2009).

In comparison to other industries, the construction industry pays minimal attention to product data management (Halttula 2020). With numerous small, medium, and large enterprises, the construction industry is fragmented, and the design, pre-production, and construction phases are typically maintained distinct (Borrmann et al. 2009). In the construction sector, the concepts product data, product data management, and product lifecycle management are unknown (Halttula 2020; Lassila 2021). To take use of the advantages of building information models, a project's product data must be described. BIM (Building Information Modeling) creates a unified platform for all information identifying a building's shared components and functions (Lassila 2021; Mansoori et al. 2022).

2.4 Literature synthesis

Table 1 presents the review literature synthesis regarding the essential aspects of carbon footprint and handprint, as well as product structure and productization concepts in general and construction contexts.

Table 1. Synthesis of the literature

Topic		**Main concept**	**Main reference**
Carbon footprint	Definition	• Carbon footprint refers to the total amount of carbon dioxide emission released directly or indirectly due to resources used in activity by the population, government, companies, etc.	(Gao et al. 2014); (Wiedmann and Minx 2008);(Chainho and Matos 2012)
	Types	• Direct and indirect based on emission source	(Chen et al. 2021)
	In construction	• The construction sector is one of the industries with the highest level of carbon footprint	(Sizirici et al. 2021); (Huang et al. 2018).
	Types in construction	• During in-site construction (direct) & within off-site operations (indirect)	(Chen et al. 2021).
	Sources in construction	• Energy consumption, • Materials used, • Production processes, • Operational processes, • Transportation, • Supply chain	(Jiang et al. 2022); (Sizirici et al. 2021); (Wang et al. 2021) (Sudarsan et al. 2022); (Marzouk et al. 2017); (Luo et al. 2021); (Kuittinen 2019)

Topic		Main concept	Main reference
Carbon handprint	Definition	• Carbon handprint refers to positive environmental impacts that businesses can gain and communicate by offering products and services that reduce consumers' footprints. The goal of handprinting is to evaluate the positive impacts obtained if a potential user uses an offered product or service.	(Grönman et al. 2019); (Kuittinen 2019)
	Carbon handprint in construction	• Carbon handprint refers to positive climate impact and the environmental benefits that would not have been possible if a construction project did not exist.	(Kuittinen 2019); (Grönman et al. 2019)
	Sources of carbon handprint in construction	• Emission is avoided through the reuse of building parts, • Carbon capturing with new type of materials • Recycling of materials, replacing with new methods, new and smart material • Renewable energy is created during the life cycle of a building	(Kuittinen 2019); (Hurmekoski 2017)
Wood products	Advantage of use of wood material	• Sustainable qualities of wooden materials address economic, social, and environmental concerns. • Wood-based products help to mitigate climate change through two different mechanisms: carbon substitution and storage	(Viholainen et al. 2021); (Hurmekoski 2017)
Product structure & productization	Product structure	• The product structure is defined as a hierarchical representation of the product's components and assembly relation between them; product structure contains the detail about technical components (how to build) and commercial procedures (how to sell) of a product.	(Heimes et al. 2020); (Pinquié et al. 2015); (Belkadi et al. 2016); (härkönen et al., 2019); (Tolonen et al. 2014)
	Product structure in construction	• Modelling technical and commercial solutions is also appropriate in a construction project. • Technical issues such as design and building can be included on the technical side, while commercial issues such as advertising and sales can be included on the commercial side	(Harkonen et al. 2018); (Harkonen et al. 2015); (Mansoori et al. 2022)
	Productization	• Productization is the method of recognizing a requirement and merging appropriate tangible and intangible parts into a product or service that is standardized, repeatable, and understandable. • Productization also refers to goods and service management and commercial and technical product portfolios.	(Harkonen et al. 2018); (Harkonen et al. 2015); (Mansoori et al. 2022)
	Productization in construction	• Productization practices are not familiar in the building industry. • Productization has the potential to help with the standardization of the construction offering and the improved performance of the efficiency of construction activities	(Harkonen et al. 2018); (Harkonen et al. 2015); (Mansoori et al. 2022)
	Product data management	• Product data are referred to as information broadly related to a product. • Product data management is the process of linking and controlling activities, applications, and all sorts of data that identify products across various systems and media	(Kropsu-Vehkapera et al. 2009); (Saaksvuori and Immonen 2004); (Stark 2005)

Topic		Main concept	Main reference
	Product data management in construction	• The concepts of product data, product data management, and product lifecycle management are unknown in the construction sector. • The product data for a project must be described to take advantage of building information models.	(Halttula 2020); (Lassila 2021)

The first research question of this study, what are the critical elements of carbon handprint and footprint in construction, could be answered based on the synthesis. Carbon footprint refers to the total amount of carbon emission released by resource consumers. The emission could be direct or indirect, depending on the emission source. In the construction context, direct and indirect emissions refer to those released in-site construction and off-site operations. Construction's carbon footprint may be caused by energy consumption and materials used in production and operational processes and supply chain and transportation. It is achievable in construction projects to create a positive environmental impact (carbon handprint) when a building product is produced and used by a specific user. To this end, reuse of building parts, recycling of materials, and renewable energy created during the life cycle of a building are some of the potential practices to avoid carbon emission and increase the level of the product handprint.

3 EMPIRICAL STUDY

3.1 Overview of the research methods

In this study, an inductive research approach is used to attain the research aims and answer questions. In the inductive approach, the process begins with observation of the topic under investigation in order to get a deeper understanding of it and establish generalizations from it (Wilson 2014). This research uses a qualitative reasoning approach as a research strategy. Qualitative research and inductive studies are frequently related and have much in common since both provide insight that allows for the development of theoretical frameworks (Wilson 2014). Multiple case study serves as a framework for gathering and analyzing data. The data is collected via semi-structured interviews (Rocco 2003; Mason 2004) with the representatives of case organizations to narrow inquiries. The interview questionnaire (Appendix 1) is formulated based on the knowledge gathered from the literature findings (Mason 2004).

Main phases of the research processes are presented in Figure 5. As can be seen, the first phase corresponds to conducting literature review. The finding from literature review in section 2 is provided a theoretical framework that consist of the critical elements of carbon handprint and footprint in construction. The knowledge gathered in the first phase, is used to answer the RQ1 as well as used as a bases to develop a questionnaire to be used for data collection.

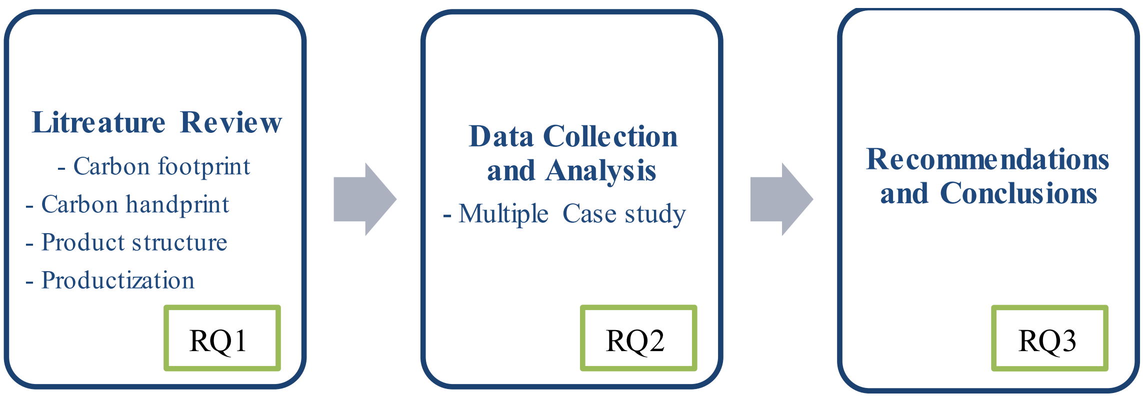

Figure 5. The research process

A qualitative case study is undertaken in the second phase to learn about the benefits of wooden buildings in terms of reducing construction footprint and increasing construction handprint. To this end, case companies are selected for data collection.

This study applies the Gioia et al., (2013) method for data analyses. It is used to analyze the gathered data. This approach categorizes and analyses the acquired data at three levels of abstraction: first-order ideas, second-order themes, and aggregate dimensions. Early ideas produced from data and classified based on similarities are referred to as "first-order concepts."

Then "second-order themes" are produced by combining comparable categories, and "aggregate dimensions" are built by integrating the second-order themes at a higher level of abstraction (Gioia et al. 2013). Figure 6 illustrates three sequential steps of the Gioia approach and shows the data structure, explaining how the collected data is analyzed in this study. The concepts came out as aggregate dimension that is used to answer the RQ3 to propose a solution to productizing building product with a higher carbon handprint.

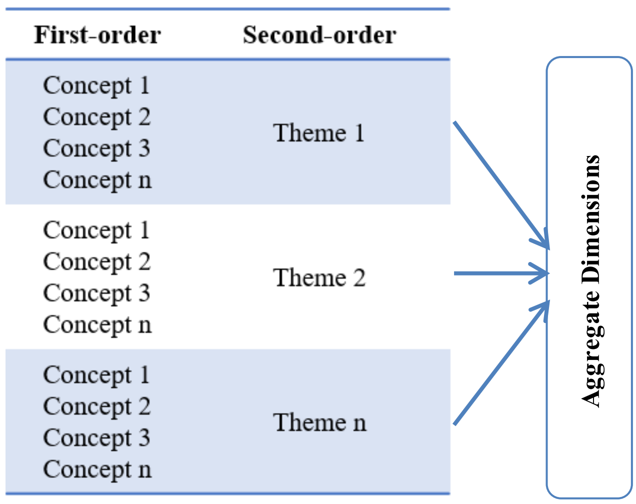

Figure 6. The structure of data analysis

The interview questions included twenty-one questions selected based on the literature review. The questions are presented in Appendix 1. Data collected from both the industrial and scientific sides. On the industrial side, two interviews (Cases A and B) have been conducted with case companies that have low or neutral carbon footprint practices and products. An interview (Case C) was also conducted with a researcher to collect his views on the subject of study as complementary data to the industry side. All of the interviews were conducted in English and using the same semi-structured format. Data collected from 3 interviews are presented in the text as A, B and C. The list of interviewees' specializations in terms of their current role in the case company is presented in Table 2.

Table 2. Roles of the interviewees in the case companies

Interviewees	Role in the company
Case A	Chief Executive Officer (CEO)
Case B	Chief Development Officer (CDO)
	Development Assistant
Case C	Professor of architecture

Interviews were conducted online and were recorded and transcribed to allow detailed analyses. Then data is analyzed using Gioia method (Gioia et al. 2013). The data analysis process is described in detail in section 3.3.

3.2 Introduction to cases

3.2.1 Case A

The first company (Case A) is a Finnish construction company. They produce products related to construction such as ventilation, roof hoods, and different kind of air diffusers. The company was started in 2007. The company's headquarters are in Helsinki, and all products are manufactured in Finland. Furthermore, the company has nearly 14 resellers in other countries. In 2021 the company's net sales were 14 million euros, and the company has 65 employees. In 2020 company was among the first companies to achieve carbon neutrality in the construction and ventilation industry.

3.2.2 Case B

The second company (Case B) is a Finnish construction company. They manufacture wood products related to the construction industry, like prefabricated wood components and finished building products. The company was established in 2001. The company headquarter is in Northern Finland, and all products manufacturing is in Finland. The majority of the company's products are sold in Finland, and some are delivered to Estonia. In 2021 the company's net sales were 29 million euros, and the company had 165 employees. Now that the company is expanding, they are hoping to find new markets and business opportunities as early as possible.

3.2.3 Case C

The third interview (Case C) was conducted with an architecture and construction industry specialist. He has a strong background and solid research background in the wooden construction industry.

3.3 Data analysis

Semi-structured interviews with carbon-neutral and wooden building professionals were used to collect primary data. Each interview lasts roughly 1.5 hours. Interviewees were provided the interview guide ahead of time so that they may prepare for the discussion. The interviews were recorded and transcribed to allow for in-depth analysis.

The data analysis process began with an evaluation of the interview transcripts in order to capture early ideas expressed, which were then categorized based on similarities and labeled as "first-order concepts." Then "second-order themes" are produced by combining comparable categories. In this stage, 22 themes were extracted, which were integrated to build a foundation for the next level of abstraction from gathered data. Accordingly, 5 "aggregate dimensions" are found from linkages among the second-order themes in the previous stage to construct broader classes that bring relevant concepts together. A summary of the findings is illustrated in Table 3. The determined aggregate dimensions are utilized to organize the presentation of the findings.

Table 3. Summary of collected data

First-Order Concepts	Second-Order Themes	Aggregate Dimensions
• The construction's carbon footprint elements could be categorized into the material, energy, transportation, and supply chain elements. • Materials like plastic, concrete, steel etc. Produce a carbon footprint. • Traditional energy sources like fossil fuels produce a high level of carbon footprint. • Transportation element refers to CO2 emission due to movements required in the process of production. • Supply chain elements consist of the carbon footprint produced in supplying the resources and the level of the greenness of the supplier itself.	Material Energy Transportation Supply chain	Carbon footprint elements
• By using durable materials, the products do not need to be replaced as frequently • Wooden material is a proven option for decreasing the carbon footprint • Composite materials can be used to replace various plastics. • Replace fossil fuels with solar or wind power • Replace the traditional insulate process with a new method • Using suppliers who are close to their factory to reduce carbon emissions during the transportation process • Produce smart products such as smart ventilators to reduce carbon emission	Replacing the method of production, energy source, and material	Replacing carbon footprint elements
• Wood has an inherently positive impact on the environment, and those wood products have a low carbon footprint • Wood is a renewable resource, and its reuse positively affects the environment • Wood absorbs CO2 from the environment; carbon is contained within the wood, so wood construction is considered a potential method to reduce emissions. • Access to wood is easy and cheap in Finland compared to many other countries, and a shift toward massive wooden structures could positively impact reducing carbon emissions. • Wooden materials are beautiful and natural, and they give consumers a good feeling • As a carbon-neutral business or being in a way to become carbon-neutral improves the company's image and brings some competitive advantage. • Sales elements in wooden construction are mainly module-based and efficiently produced through assembly and sub-assembly processes.	Inherently increase handprint by absorbing CO2 from the environment. Wood is a renewable resource Competitive advantage Efficient modular based production In Finland, the wood material is easily accessible and is low in price. Customers like it because it is attractive and natural.	Benefits of wooden buildings for the environment, business, and customers

First-Order Concepts	Second-Order Themes	Aggregate Dimensions
• Key customers vary, including private customers, construction companies, designers, construction project managers, consultant companies, and real estate institutions. • Using durable materials that produce a low carbon footprint and are at a low price • Extending the lifetime of products and making them reusable • Advertising the carbon-neutral objectives and method via social media, for instance, that company uses to build the product. • Providing customers with the product's carbon footprint calculations to let them know the effect of using the product • Government regulation could encourage customers to use products with a lower carbon footprint; the government could assign economic incentives to people who use low-carbon products.	A diverse group of customers value carbon-neutral products for different purposes. Durable, carbon-neutral and low in cost material Extending the lifetime of product durability Calculate accurate carbon emission Well established public regulations	Actions to influence the value of customers
• The importance of structured product information and materials flow in a standardized and replicable method is perceived but is not used systematically. • Products/sale items in wooden construction are mainly module-based and produced through assembly, sub-assembly, insulation, and coloring. • Product data management is perceived that reliable data and information are essential to gain through tools. • Many reworks and waste might happen if we do not have a central information repository. • A reliable flow of data is essential for calculating carbon emissions. • Prefabrication models in the construction industry could help reduce carbon emissions, and BIM can manage data properly in a company.	Product structure and productization are unknown Reliable data and information Accurate data for calculating the carbon footprint Use of prefabrication modules to reduce emission Use of BIM to manage data	Key role of centralized product data systematization of sales elements offering

3.4 Findings

3.4.1 Carbon footprint elements

Interviews from A, B, and C showed plenty of carbon footprint elements in the construction industry. Material, energy, supply chain, and transportation have a carbon footprint. Using materials like plastic, concrete, steel, etc., produces a considerable carbon footprint. The interviewees agree on the high level of the carbon footprint caused by using traditional energy sources like fossil fuels. Fossil fuels and electricity are seen as the most common source of energy used in construction, producing a considerable carbon footprint.

"There are plenty of carbon footprints elements in construction industry (Case B)

The next element discussed by interviewees was transportation, which refers to any movement activities in building processes. Supply chain, as the last identified, footprint element in construction includes both the way that resources are supplied for building and the level of the greenness of suppliers themselves.

3.4.2 Replacing carbon footprint element

Many of the identified footprint elements in construction could be revised or replaced with a lower carbon footprint or carbon-free materials or processes, according to A, B, and C. For example, A and B suggest that some composite materials can be used to replace various plastics. A, B, and C propose that companies can replace solar power or wind energy with fossil fuels to reduce their carbon footprint in the energy issue. Company A is also offering various building technology products for electrification of lighting and ventilation, with the possibility of having a negative carbon footprint (handprint). For example, producing a smart product such as an intelligent ventilator reduce carbon emission. Company B has a high carbon footprint in the insulation process. When they insulate their product against wind or water, the material they are using has a high carbon footprint. They can replace this process with a new method and material, but it is very costly. Company B suggests using supplier's who are close to their factory to reduce carbon emissions during the transportation process. C believes that products do not need to be replaced as frequently by durable materials, thereby increasing product lifetime. C suggests that building less, in general, is the most effective way to reduce carbon emissions.

"Solar energy could replace fossil fuels" (*Case B)*

3.4.3 Benefits of wooden buildings for the environment, business, and customers

Discussions regarding the benefits of wooden buildings as low carbon footprint material and practices fall into three categories: benefits for the environment, benefits for the business, and benefits for the customer.

The benefits of wooden buildings for the environment are considerably highlighted. B and C have similar views on wood products, highlighting that wood has an inherent positive impact on the environment and that wood products have a minimal carbon footprint. Carbon is kept in wood because wood absorbs CO2 from the environment, according to C. As a result, wood construction is being considered more than a emission-reducing construction approach, rather as a carbon handprint promoter. B and C also believe that a lack of knowledge about handprints is a big challenge in the construction industry. Company B noted that while carbon emissions in construction have not been studied well, they believe that wood is more environmentally beneficial comparing other materials in use. According to B and C, wood is a renewable resource whose use can benefit the environment.

"Trees absorb CO2 from environment it is reason why wood construction is seen as a potential construction method to reduce the emissions, (Case C)

The benefits of wooden buildings go beyond environmental concerns and their positive impact back to the construction businesses; those are following to be carbon-neutral. According to the interview with A and B, having a lower carbon footprint or trying to be carbon-free can boost a company's image and provide them with a competitive advantage. A and B believe that it increases the company's sales because clients currently choose environmentally friendly products. It also has a positive effect on hiring a company, according to A, because people like to work for companies that use environmentally friendly products and respect the sustainability objectives. According to B, wooden materials facilitate modular-based production, which is in line with improvements in the efficiency of wooden construction processes.

When company is carbon neutral it brings competitive advantages for company", (Case A)

For customers, the wooden buildings are attractive commercially and culturally in Finland. According to data, the price of wood material is lower than other alternatives for building, as high-quality sources of wood exist and are easily accessible, according to A and C. Furthermore, customers value wooden buildings because the wood gives a feeling of natural beauty and tradition to Finnish people.

"In Finland wood materials are easy access and low price" (Case C)

3.4.4 Actions to influence the value for customers

To facilitate discussion about actions that could be undertaken to influence the value for customers regarding low carbon footprint products, the interviewees were asked to first identify their key consumers. Customers for A and B are diverse. Designers, project managers, private customers, construction companies, consulting firms, and real estate institutions are all key customers.

A, B, and C all agree that businesses can influence customers by providing durable, carbon-neutral, low-cost materials. Another suggestion made by B and C is to extend the life of products and make them reusable. C strongly believes that the durability of a product plays a vital role in influencing customers. It has also mentioned that advertisement and social media play a key role in introducing carbon neutral products and encouraging the customers to use those products.

Company A feels that in addition to manufacturing a product with a lower carbon footprint, providing customers with carbon emission calculations will have a positive impact on their customers. Case A, for example, creates a smart ventilator that uses less energy than typical ventilation systems. Customers can see how much carbon is produced by the product. But it is also mentioned that the calculation of carbon footprint is quite challenging and complicated process, as there is not yet standard guideline to calculate it, according to A, B, and C

Another interesting concept that emerged is the important role of government in encouraging the customers to use the products with low carbon emissions. B and C believe that government regulation could encourage customers, for example, by assigning financial incentives to encourage consumers to choose products with lower carbon footprints.

"Companies can influence their customers by producing durable materials" (Case B)

3.4.5 Key role of centralized product data systematization of sales elements offering

Even though the terminology was unfamiliar to some of them, all interviewees recognized the importance of having a structured way of presenting product information and materials in a standardized manner. They did not benefit from the full potential of applying product data management, product structure, and productization. They all believe that a lot of rework and waste might happen if they do not have this centralized information repository. Company B does not have central information to know how much carbon emission they have in their process. They believe that having central information will make it easier to calculate carbon emissions. They have recently used BIM in their factory for planning and control systems.

Access to reliable information through IT systems, according to B, facilitates module-based production. BIM is a well-known data management approach in construction that can be used. According to C, prefabrication modules in the construction industry could help reduce carbon emissions, and BIM can manage data accurately in the company. B indicates that their product's material is supplied, and then the critical processes of assembly, sub-assemblies, insulation, and coloring are performed before the product is commercially ready. They believe there is an excellent opportunity to apply product structure and productization concepts in their businesses, but it will require considerable expenditure and effort. According to B, applying those concepts will be unquestionable in the future.

According to A and C, information should be accurate so that customers can rely on it. If information is not accurate, it can lead to an out-of-control situation. A, B, and C are sure that reliable data is essential for calculating carbon emissions. This data can be used to compare the carbon emissions of new products with previous products.

"*Reliable information is important in the construction process and avoids of a lot of rework and waste*" (*Case A)*

3.5 Summary of the findings

This section represents the findings in line with the synthesis of the literature (Table 1) to complement the essential aspects of carbon footprint and handprint, as well as productization and product structure concepts.

3.5.1 Carbon footprint

In construction companies studied, the carbon footprint creation depends on the material used to build the final product, the energy used, and the transportation and supply method. It was discussed that there are materials in use for which carbon footprint is created already during their production processes. The energy source used in construction mainly creates a high level of carbon footprints. It was also mentioned that carbon footprint creation highly depends on the transportation of supplied materials and final products. These elements that are actively in use concurrently in construction could be replaced with those with lower carbon footprint emissions. Materials like plastic and steel, for example, are suggested to be replaced with wood and geopolymer and those which are more durable and reusable. These elements were considered sources of direct carbon footprint emissions. Regarding transportation and supply chain, as sources of indirect carbon footprint emissions, the case organizations mentioned that they have less control over them because they do not have access to the level of carbon emission created by suppliers to choose one who creates less emission. However, they can choose those in closer locations to avoid emissions caused by long-distance transportation. The case companies suffer from the highly limited knowledge and instruction or guideline for calculating the carbon footprint of their activities.

3.5.2 Carbon handprint

The concept of carbon handprint was relatively new for studies cases. However, after giving them a simple definition and clarifying the phenomenon's objective, they could track how to increase the level of carbon handprint in construction. Wooden construction has been identified as an upcoming option for increasing carbon handprint. The underlying reasons are found in the wood substance itself and its modularity potential.

Wood is an excellent option because it creates a considerable amount of carbon handprint during its production process (as trees absorb the carbon emission in the air and naturally reduce it). Wood is the material that customers value because it is natural, beautiful and healthy. Surprisingly, wood is usually lower in cost compared with other alternative materials like concrete and steel. In addition, wood transportation is a low carbon footprint since it could be supplied from very close to construction locations, hindering transportation footprint creation. The findings from the case studies indicate that sales elements in wooden construction are mainly module-based, which shows a high level of the wooden products productization. This aspect is presented in section 3.5.3 in detail.

Customer value and the company's image are other essential aspects of wooden construction as a product that creates carbon handprint. Findings show that the carbon capturing, natural beauty, healthiness, reusability and durability of wooden materials positively influence the customers to choose wooden construction. Meanwhile, the businesses whose products and processes are in line with sustainability objectives have an excellent image for the consumer and the society and bring considerable competitive advantages for the business. So, as can be seen, the benefits of carbon handprint products go to the environment, businesses and product consumers.

3.5.3 Product structure and productization

The findings emphasized the importance of centralized and structured product data in facilitating the systematization of sales items offered, even though product structure and productization concepts were not conceived in the studied companies. Wooden construction shows a high level of potential to systemize the sales elements since wooden modular-based products are building blocks of wooden construction, through which the products are produced through assembly and subassembly processes. The findings indicate that a reliable flow of product data reduces many potential reworks and waste, which results in direct and indirect carbon footprint emissions. The case organizations see the value of standardization to avoid waste of resources and more efficient production via building information management.

3.5.4 Comparison of literature and empirical findings

The key statements from the literature review and empirical studies analysis are collected to Table 4 & Table 5. Tick symbol in the empirical study column and references in the literature review column indicate that that section of the study supports the statement in the same row. Tables 4 and 5 show that most of the key statements are supported by both the literature review and the empirical study of the thesis.

Table 4. Findings related to carbon footprint and carbon handprint

NO	Findings	literature Review	Empirical Study
1	The carbon footprint in construction is created by the materials used to build the final product, the energy used, and the transportation and supply method.	(Jiang et al. 2022); (Sizirici et al. 2021); (Wang et al. 2021) (Sudarsan et al. 2022); (Marzouk et al. 2017); (Luo et al. 2021)	✔
2	Material and energy replacement to reduce carbon emissions and create Handprint	(Kuittinen 2019)	✔
3	Carbon emissions in the construction industry are classified as direct and indirect.	(Chen et al. 2021)	-
4	Use of wood material and geopolymer to create carbon handprint	(Viholainen et al. 2021); (Hurmekoski 2017)	✔
5	Suffer from the highly limited knowledge and instruction or guideline for calculating the carbon footprint	-	✔
6	Carbon Handprint Definition is unclear in building industry	(Kuittinen 2019)	✔
7	Customer value and the company's image are other essential aspects of wooden construction as a product that creates carbon handprint	-	✔
8	Benefits of carbon handprint products such as wood material go to the environment, businesses and product consumers.	(Wegner et al. 2010)	✔

Table 5. Findings related to Product structure and productization

NO	Findings	literature Review	Empirical Study
1	Product structure and productization definition is unclear in building industry.	(Mansoori et al. 2022)	✔
2	In the construction sector, a product is mainly defined as a physical item.	(Mansoori et al. 2022)	✔
3	The value of centralized, structured product data in improving the systematization of sales items	(Harkonen et al. 2018)	✔
4	Reliable flow of product data reduces many potential reworks and waste	-	✔
5	More efficient production via building information management.	(Mansoori et al. 2022)	✔
6	Modelling technical and commercial solutions is also appropriate in a construction project	(Harkonen et al. 2018); (Harkonen et al. 2015); (Mansoori et al. 2022)	-

4 PRODUCT STRUCTURE OF CARBON FOOTPRINT AND HANDPRINT IN THE WOOD CONSTRUCTION

In literature, product structure is defined as a hierarchical depiction of a product's *parts* and *modules/assembly* in which these elements are assembled to form a final product. Product structure details a product's technical components (how to build) and commercial procedures (how to sell). The findings from the literature show the crucial role of product structure in helping the standardization of the construction offering and the improved performance the efficiency of construction activities. The product structure elements have the potential to enable the productization and offering of carbon footprint and handprint to the customers.

Regarding the sources of carbon footprint, the literature review shows that *material*, *energy*, *transportation* and *supply chain* are the primary sources of carbon footprint in construction. This study demonstrates which elements of product structure (part, module, order) are sources of carbon footprint and which are potential for carbon handprint (material, energy, transportation and supply chain). Wooden construction shows high potential in productization and offering of carbon footprint and handprint to the customers. The empirical data gathered from the wooden construction shows how sources of carbon footprint and potential sources of carbon handprint could be considered in different elements of product structure (part, module, order), summarized below.

In the parts level (parts used to build final product), all sources of carbon footprint can be seen (material, energy, transportation and supply chain). Materials like plastic, concrete, steel, etc., currently produce a carbon footprint. Traditional energy sources like fossil fuels produce a high level of carbon footprint. Long distances between where the part is produced and where it is used may necessitate the usage of non-green energy. There is limited knowledge about which supplier is doing low carbon activities.

Concerning potential sources of carbon handprint in parts of product structure, the most important one is using wood as the primary source of building final products. As mentioned earlier, replacing concurrently used materials with wood, which creates carbon handprint, is the most significant source of carbon handprint. Greenhouse gas emissions could be avoided by using renewable energies. Supplying materials from carbon-neutral suppliers located close to the production site are potential sources of lower carbon emissions and carbon handprint creation.

Wooden construction is mainly module-based, making it a low carbon footprint production. However, in the module and assembly level of product structure, there are still sources of carbon footprint. The primary sources identified in empirical data are caused by energy use and method of production. Traditional procedures of part insulation, for example, release carbon due to the materials and energy utilized in the process, as well as the assembly process itself. Furthermore, the energy used in the production and assembly processes is rarely renewable.

Concerning potential sources of carbon handprint at the module and assembly level of product structure, data says that the assembly process could be streamlined to become energy efficient and replace the fossil fuels with solar or wind power in production. In addition to energy, in the assembly and production processes, there are some solutions to reduce carbon emissions and create a carbon handprint. For example, there are new methods of insulation that are carbon-neutral but are costly compared with traditional processes. However, it could still be considered a carbon handprint source at the module and assembly level.

When the product is ready to be offered commercially, the same carbon emission sources discussed in part level of the product structure apply to transportation and supply of the product to market and customers. Supplying and transporting products by carbon-neutral suppliers located close to the production site are potential sources of lower carbon emissions and carbon handprint creation.

To summarize, the product structure of footprint consists of carbon-intensive materials and high energy levels needed in assembly processes, resulting in a product with high carbon emissions. Carbon neutral materials are utilized in the product structure of handprint, and renewable energy and modular-based manufacturing lower the carbon footprint production and end up with a product that creates carbon handprint while respecting the environment and consumer value. Figure 7 illustrates a potential approach to productizing carbon footprint and handprint for wood construction, showing direct and indirect carbon emissions conceived from a basic product structure sense.

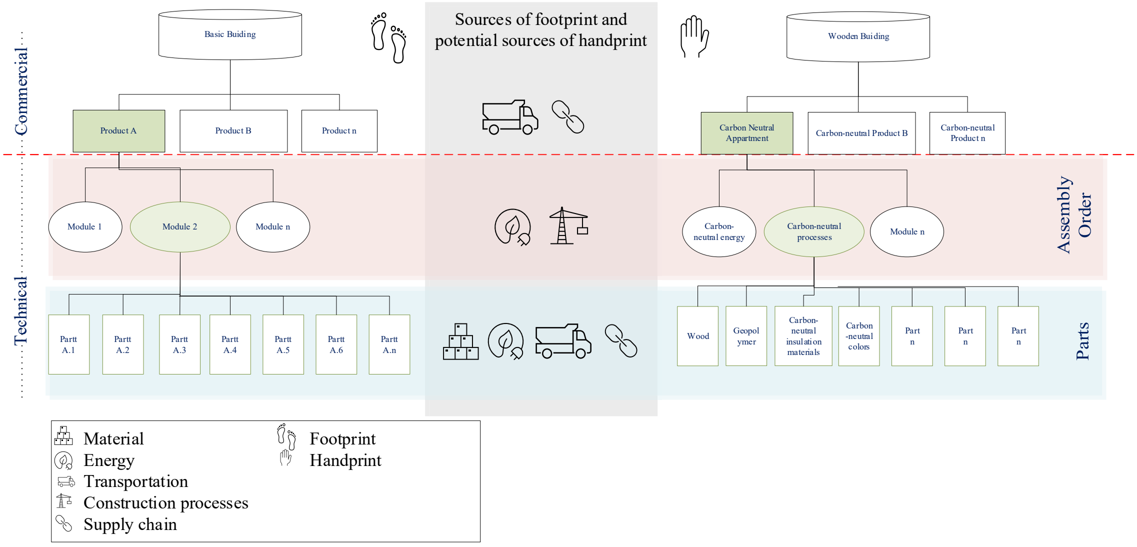

Figure 7. Productization of carbon footprint and handprint

As can be seen, the product structure of a basic building product on the left side is compared to a wooden building product structure on the right side, in which carbon footprint and handprint are productized as sale items. The technical side consists of the material used in producing different modules as building blocks of different building products. In this part, concurrently used materials like cement and steel could be replaced with carbon-neutral materials like wood, which can positively affect the environment and create a handprint. In the assembly order, various modules and sales items could be configured to be used in a final product, a carbon-neutral apartment, for example. The right side product structure provides the customers with clearly defined sales items with low carbon footprint and high carbon handprint. The components of the technical side of the product structure mainly consist of the direct carbon emissions caused by used materials and energy and methods of production, but there might also be indirect carbon emissions on the technical side. The commercial side of the product structure consists of carbon emissions like transformation, and the supply chain refers mainly to indirect carbon emissions. So, there might be overlaps between direct and indirect carbon emissions regarding the product structure.

5 DISCUSSION AND CONCLUSIONS

5.1 Key findings

5.1.1 Main contribution

There is a significant agreement that the sustainable attributes of wooden materials address economic, social, and environmental concerns and that their carbon storage properties play an essential role in greenhouse gas emissions. This research looks into methods that promote low-carbon construction with a small carbon footprint but a large carbon handprint. For that goal, wooden construction was chosen as a highly promising solution for creating carbon handprints and reducing the carbon footprints of construction. In this context, the information gathered about the potential of wooden construction, carbon footprint, and handprint aspects were used to discover how carbon footprint and handprint could be productized and offered to customers.

This study demonstrates which elements of product structure (part, assembly and order, final product) are sources of carbon footprint and which are potential for carbon handprint (material, energy, transportation and supply chain). Wooden construction shows high potential in productization and offering of carbon footprint and handprint to the customers. The empirical data gathered from the wooden construction shows how sources of carbon footprint and potential sources of carbon handprint could be considered in different elements of product structure.

As a result of this study, it was found that the customers value the wooden building from different perspectives, including wood's minimum carbon footprint creation and its positive effect on the environment (carbon handprint). From a productization point of view, it means that carbon footprint and carbon handprint have value, then could be considered sellable items and have potential if being productized in a structured way. This value is rooted in wooden buildings with minimal and sometimes positive effects on direct and indirect carbon emissions.

5.1.2 Theoretical contribution

Following the study's objectives, three research questions are answered, which are used to organize the content of the discussion section.

The first research question was about the critical elements of carbon handprint and footprint in construction. A review of the existing literature was needed to identify elements of the handprint in construction. Because the handprint concept is new to all industries, we took the perspective that the carbon handprint may increase by reducing carbon emission production. According to the findings of this study, there are numerous carbon footprint sources in construction, including energy consumption, materials utilized, production processes, operational procedures, transportation, and supply chain. Empirical data confirms the stated areas as carbon footprint sources in construction and suggests ways to minimize carbon footprint by replacing conventional procedures, materials, and energy sources with reusable and sustainable alternatives.

The second research question was: What are the benefits of wooden buildings in decreasing construction footprint and increasing construction handprint? A literature review and a case study answer this research question. According to a literature review, wood-based products reduce climate change by carbon substitution and storage (Hurmekoski 2017; Viholainen et al. 2021). The case study findings demonstrated that the benefits of wooden structures extend to businesses involved in wooden construction, customers who use the wooden building as a final product, and, last but not least, the environment. The findings provide additional empirical data to support (Wegner et al. 2010; Hurmekoski 2017; Viholainen et al. 2021) and expand our understanding that the benefits of wooden construction expand far beyond environmental benefits, a competitive advantage for businesses, and improved product saleability. The study's findings also confirm Kamali and Hewage (2017) findings that wooden materials have the potential to contribute to modular-based construction.

As mentioned earlier, the customers also benefit from the final product of wooden construction. The findings show that customers value carbon-neutral and durable products that can be recycled and reused. The customers perceive such products in line with a sustainable future and enjoy fabricated wooden buildings. The findings confirm previous findings (Lakkala et al. 2020) and highlight the great value of the wooden building for customers.

The study's third research question was about describing carbon footprint and handprint in wood construction. The finding related to the third research question shows the key role of centralized product data and the systematization of sales elements offered in wooden construction. The findings are in harmony with modular-based construction (Kamali and Hewage 2017), product structure and productization in construction (Harkonen et al. 2018; Mansoori et al. 2022). Even though product structure and productization concepts were not well known in studied cases, there was a significant agreement about how a structured and reliable product and production information minimized carbon emission, rework, and waste in production processes. Based on findings from the literature review and empirical data, the proposed product structure (Figure 7) provides a practical example of productizing the carbon footprint and handprint as sale items.

5.2 Implications

In conclusion, this study explained potential elements in construction that produce carbon footprint and potential methods to reduce carbon emission and even move towards creating carbon handprint. The evidence from this study shows that wooden construction could bring numerous advantages to the environment, businesses and customers that are all in line with sustainability objectives. This research underlines the high potential of wooden construction to be productized. It is evidenced that module-based production is a conventional construction method that allows easier achievement of a systematized sales item offering via a structured and consistent product structure.

We have obtained satisfactory results demonstrating how knowledge about footprint elements and their carbon emission level could enrich the product structure, helping to replace existing materials and processes with lower carbon footprint materials and processes. These findings suggest that the systematized and standardized flow of knowledge about carbon emission elements facilitates movement towards creating and productizing the carbon handprint.

This study has gone some way towards enhancing our understanding of wooden construction in productizing footprint elements, explicitly focusing on wooden construction. The present findings suggest several courses of action to decrease carbon footprint and increase the carbon handprint of products and processes of a building. A further important implication is analyzing the product's key customers and the many advantages of wooden buildings to influence the products' key customers and boost the products' saleability. This will result in a higher sale of products with a low carbon footprint. It indicates that as much as customers use such products, a higher carbon handprint is produced.

5.3 Limitations and future research

This thesis aimed to identify the elements of productizing building products with higher carbon handprint in wooden construction. However, alongside many inherent limitations of case study type of research, some particular to this research limitation identified as well. This research did not cover any other context than wooden buildings. This research did not investigate other potential carbon-neutral materials, such as geopolymer, that has the potential to increase the building product's handprint. In addition, the investigation about productizing footprint elements was limited, as the areas are fairly new in the construction industry and knowledge about it was limited. Future research could include, aside from addressing the above-described limitations, analyzing the detailed role of productization and product structure in increasing the products handprint from commercial and technical perspectives.

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APPENDICES

Appendix 1: Semi-structured questionnaire

List of questions

1. Please briefly introduce your company. When it was established, what were its business areas, and does it just do business in Finland? Where do you do business on a global scale?
2. What are the main products of your company?
3. Who are your key customers of the company, those the company wishes to influence?
4. From your point of view, what are the elements of carbon footprint overall in construction?
5. Which of these elements have a high potential to be replaced or reused in the construction process in your business?
6. What are the benefits of your products/services in a decrease in construction footprint/increase in construction handprint?
7. How do your products/services (wood construction) affect the environment?
    a. How much does it reduce carbon emissions when compared to other construction methods?
    b. Does wood, compared to i.e. steel or concrete, cause an increase in CO2 emission in any area?
8. What are the benefits of wooden buildings compared to, i.e. steel or concrete in a decrease in construction footprint/increase in construction handprint?
9. In your business, what are the *tentative features/sales items* that consumers may value *(as part of the wood building)*
10. Could you name a product (X) or service that has already a carbon footprint?
11. What is the product (X) structure?
    a. Bill of materials,
    b. Components and
    c. Assembly process?
12. Which one of these materials could be replaced for producing product X with a lower footprint?
13. Which one of these practices/processes could be replaced for producing product X with a lower footprint?
14. Who is a potential customer of the product?
15. By what means can the product or service influence the customer?
    a. Material use,
    b. Energy use,
    c. Waste, Lifetime and Performance,
    d. Carbon capture and storage, etc.
16. How can we encourage consumers to use these new elements?

17. What is the role of centralized product information in carbon footprint reduction?
18. How could the systematization of the elements of an offering (Productization) affect the reduction in the carbon footprint of a product?
    - ✓ *Productization refers to the transformational process where* *__product information and materials__* *are* *__systematized and standardized__* *through* *__replicable methods__* *and* *__transparent formats__* *and concerns* *__all activities before a product is ready commercially.__*
19. In your opinion, how data related to the final product could be managed in a sustainable- low

carbon footprint way?

20. In your opinion, what are the most critical challenges in low footprint construction?
21. Please, let us know your suggestion to achieve low carbon construction?