POLITECHNIKA POZNAŃSKA
WYDZIAŁ INŻYNIERII ZARZĄDZANIA

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PhD dissertation

Managing CO_2 emissions within sustainable supply chain

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Poznań, 2025

Pragnę serdecznie podziękować Promotorom, Pani dr hab. inż. Paulinie Golińskiej-Dawson, prof. PP, oraz dr hab. inż. Adamowi Kolińskiemu, prof. WSL za niezwykle cenne wskazówki, życzliwe wsparcie oraz inspirujące dyskusje, które towarzyszyły mi w trakcie realizacji niniejszej rozprawy doktorskiej. Ich zaangażowanie, otwartość i profesjonalizm stanowiły dla mnie nieocenione źródło wiedzy i motywacji.

Serdecznie dziękuję również mojej rodzinie za nieustanne wsparcie i wyrozumiałość.

I would like to sincerely thank my Supervisors, Ms. Paulina Golińska-Dawson, Ph.D., Prof. PP, and Adam Koliński, Ph.D., Prof. WSL, for their invaluable guidance, kind support and inspiring discussions throughout the preparation of this doctoral dissertation. Their commitment, openness and professionalism have been an exceptional source of knowledge and motivation.

I would also like to sincerely thank my family for their constant support and understanding.

„(…) fakty bowiem to mają do siebie, że racja jest zawsze po ich stronie.”
Stanisław Lem, Bajki Robotów, 1964

Streszczenie

Dążenie do realizacji procesów transportu dystrybucyjnego zgodnie z zasadami zrównoważonego rozwoju, skłania przedsiębiorstwa do uwzględnienia w procesie decyzyjnym perspektywy środowiskowej. W rezultacie przeprowadzonych badań stwierdzono, że włączenie odpowiedniego zarządzania emisjami procesów transportu dystrybucyjnego wykazuje pozytywny wpływ na redukcje kosztów, poprawę parametrów jakościowych i ilościowych, przy jednoczesnej mitygacji śladu węglowego w łańcuchu dostaw.

Przeprowadzone w pracy doktorskiej badania wskazały niewystarczający zakres istniejących metod zarządczych umożliwiających mierzenie poziomu emisji procesów transportu dystrybucyjnego, przy jednoczesnym włączaniu parametrów środowiskowych w proces zarządczy w zrównoważonym łańcuchu dostaw. W odpowiedzi na zidentyfikowaną lukę badawczą opracowano nowy model zarządzania emisjami procesów transportu dystrybucyjnego w zrównoważonych łańcuchach dostaw co stanowi główny cel naukowy pracy doktorskiej. Oprócz sformułowania precyzyjnej logiki modelu zarządczego zrealizowano również cel utylitarny. Udało się go osiągnąć poprzez stworzenie dedykowanego modelu obliczeniowego, wspierającego proces ewaluacji poziomu emisji wynikających z realizowanych procesów transportowych oraz umożliwiający włączenie uzyskanych wyników w proces decyzyjny. W ten sposób podejmowane w przedsiębiorstwie decyzje, dotyczące sposobu realizacji procesów transportowych, mogą opierać się na wyborze najkorzystniejszego scenariusza uwzględniającego parametry środowiskowe oraz kosztowe w zrównoważonym łańcuchu dostaw.

W pierwszym rozdziale pracy zbadano sposób realizacji procesów transportowych w ramach zrównoważonych łańcuchów dostaw. Zdefiniowano koncepcje zrównoważonego rozwoju oraz nakreślono warunki brzegowe realizacji procesów transportowych. Wskazano główne źródła motywacji mierzenia i zarządzania transportem dystrybucyjnym w perspektywie środowiskowej.

Rozdział drugi poświęcono analizie dotychczasowych podejść w zakresie mierzenia i zarządzania śladem węglowym w transporcie, w łańcuchu dostaw. Zweryfikowano kluczowe akty prawne, normy i standardy oraz przeanalizowano możliwości adaptacji zarządzania emisjami procesów transportowych w ramach istniejących metod zarządczych.

W rozdziale trzecim zidentyfikowano kluczowe parametry procesów transportowych, wpływające na poziom emisji w zrównoważonych łańcuchach dostaw. Na podstawie przeglądu literatury zaproponowano ich klasyfikację. Badania empiryczne z udziałem ekspertów pozwoliły określić poziom istotności wybranych czynników. W toku badań zweryfikowano również wpływ parametrów pojazdów, doboru jednostek ładunkowych, opakowań wielokrotnego użytku oraz możliwości zastosowania analizy wielokryterialnej w procesie zarządzania transportem w zrównoważonym łańcuchu dostaw.

W rozdziale czwartym przedstawiono logikę wypracowanego nowego modelu oceny poziomu śladu węglowego. Z uwagi na różnice w poziomach jakości dostępnych danych z przedsiębiorstw zaproponowano dwa warianty ewaluacji emisji - szczegółowy i uproszczony. W rozdziale przedstawiono również sposób wykorzystania i rolę analizy wielokryterialnej w zarządzaniu emisjami.

Rozdział piąty poświęcono walidacji wypracowanego rozwiązania, odnosząc jej przebieg do zdefiniowanej logiki nowego modelu oceny poziomu emisji procesów transportowych w zrównoważonym łańcuchu dostaw. Potwierdzono użyteczność rozwiązania oraz precyzyjnie wskazano jego praktyczne możliwości zastosowania w przedsiębiorstwach realizujących procesy transportu dystrybucyjnego.

Przeprowadzone badania literaturowe oraz empiryczne pozwoliły na sformułowanie wniosków przedstawionych w rozdziale szóstym. Odpowiedziano na postawione pytania badawcze i wskazano ograniczenia stworzonego rozwiązania. Przedstawiono również aktualnie realizowane ścieżki wdrożeń wypracowanego rozwiązania. Wskazano także kierunki dalszego rozwoju.

W wyniku przeprowadzonych badań i walidacji wykazano, że zaproponowany model ma użyteczny charakter i może z powodzeniem zostać zaimplementowany w istniejących przedsiębiorstwach. Wypracowane rozwiązanie może stanowić istotne wsparcie przedsiębiorstw w zakresie podnoszenia efektywności procesów transportowych w zrównoważonych łańcuchach dostaw, poprzez uwzględnienie w procesie decyzyjnym poziomu emisji.

Słowa kluczowe: ślad węglowy, procesy transportowe, zrównoważony łańcuch dostaw, zrównoważony rozwój, zarządzanie śladem węglowym

Abstract

The pursuit of implementing distribution transport processes in line with the principles of sustainable development encourages enterprises to take the environmental perspective into account in the decision-making process. As a result of the conducted research, it was found that incorporating appropriate emission management in distribution transport processes has a positive impact on cost reduction, improvement of qualitative and quantitative parameters, while simultaneously mitigating the carbon footprint in a supply chain.

The doctoral research identified the limited scope of existing managerial methods that enable the measurement of emissions from distribution transport while simultaneously incorporating environmental parameters into the management process. In response to this gap, a new model for managing emissions from distribution transport in sustainable supply chains was developed, which constitutes the main scientific aim of the thesis. Alongside the formulation of a clear managerial logic, a utilitarian aim was also achieved. This was realised through the creation of a dedicated computational model supporting the evaluation of emissions generated by transport processes and enabling the integration of results into decision-making. In this way, enterprise-level decisions concerning the organisation of transport can be based on the selection of the most advantageous scenario, taking into account environmental and cost parameters.

Chapter One examines the implementation of transport processes within sustainable supply chains. It defines the concept of sustainable development and outlines the boundary conditions for transport operations within this framework, identifying the main motivations for measuring and managing distribution transport from this perspective.

Chapter Two analyses existing approaches to measuring and managing the carbon footprint of transport in a sustainable supply chain. It reviews key legal acts, norms and standards, and considers the potential for integrating emission management into existing managerial methods.

Chapter Three identifies the key parameters of transport processes that affect emission levels. Based on a literature review, a classification of these parameters was proposed. Empirical research with experts made it possible to assess the significance of selected factors. The study also verified the influence of vehicle characteristics, the choice of load units and reusable packaging, as well as the potential of multi-criteria analysis in transport management in a sustainable supply chain.

Chapter Four presents the logic of the newly developed model for assessing the carbon footprint of transport processes. Given differences in the quality of available enterprise data, two evaluation variants were proposed – a detailed and a simplified one. The chapter also discusses the use and role of multi-criteria analysis in emissions management in a sustainable supply chain.

Chapter Five is devoted to the validation of the proposed solution, following the logic defined in the new model. The usefulness of the solution was confirmed, and its practical applicability in enterprises carrying out distribution transport processes was clearly demonstrated.

The literature review and empirical research enabled the formulation of conclusions, which are presented in Chapter Six. The research questions were answered, the limitations of the solution identified, and the current implementation pathways of the model were outlined, together with directions for future development.

The research and validation confirmed practical value of the proposed solution and can be successfully implemented in existing enterprises. The developed model provides significant support for companies in improving the efficiency of their transport processes by including emission level perspecitve into the decision-making process in a sustainable supply chain.

Keywords: carbon footprint, transport processes, sustainable supply chain, sustainable development, CF management

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Introduction

Contemporary supply chains are complex, multilayer networks of mutual interconnections. Such complex structures require appropriate tools and approaches to model their effectiveness. The need to optimise processes within distribution supply chains and the ability to influence their efficiency level forms the foundation of sustainable development of transport processes. The current trend towards reducing emissions in supply chains, motivated by legislative changes, the need to reflect aspects of Corporate Social Responsibility (CSR), and the integration of elements characteristic for Environmental, Social and Governance (ESG) reporting, as well as stakeholders' expectations, creates opportunities for the development of management methods orientated on carbon footprint level, devoted to transport processes.

Carbon dioxide (CO_2) emission level is one of the most important of the United Nations (UN) environmental indicators, as they provide the quantitative link between human activities related to fuel combustion, industrial processes, and land-use changes resulting GHG emissions. By assigning a standard CO_2 equivalent value per unit of activity these factors enable consistent, comparable reporting across countries and sectors. UN approach is essential for tracking progress towards international goals such as the Sustainable Development Goals (SDG). Among the 17 Goals adopted by the United Nations, Goal 11 "Sustainable Cities and Communities" and SDG 13 "Climate Action" apply to sustainable transport management (UN, 2024a). Simultaneously, SDG 12 is also crucial in emphasising the need to enhance logistics processes to reduce environmental effects such as emissions and excessive consumption of resources. Sustainable transport practices, including optimised routing, improved load efficiency, and the use of low-emission vehicle technologies, directly contribute to this goal by reducing the carbon footprint of distribution activities. Additionally, adopting responsible sourcing strategies and ensuring transparency within supply chains help companies integrate sustainability into their procurement and logistics decisions. Aligning supply chain management with SDG 12 enables the efficient and responsible delivery of goods and services with reduced ecological impact. Those goals specifically promote sustainable transport systems, which include low emission transport solutions and emphasise incorporation of electric vehicles and efficient road transport.

UN statistical yearbooks focus on providing detailed parameters of the global economy. Among several groups of indicators, in addition to parameters relating to population, currencies and population density under General Information indicators, Economic indicators and Social Indicators, there are also Environmental and infrastructure indicators. An example of the inclusion of the CO_2 equivalent index in years 2015 – 2024 is presented in the **Tab. 1** below.

Tab. 1 Key environmental indicators followed by United Nations within yearbooks
Source: own elaboration based on UN, 2024b

Environment and Infrastructure Indicators	2015	2020	2024
Individuals using the Internet (per 100 inhabitants)	39.9	59.3	67.4
Research & Development expenditure (% of GDP)	1.7	2	1.9
Forested area (% of land area)	31.3	31.1	31.1
CO_2 emission estimates (million tons / tons per capita)	314 685/ 4.2	312 390/ 4.0	331 470/ 4.2
Energy production, primary (Petajoules)	569 646	589 086	609 909
Energy supply per capita (Gigajoules)	74	72	76
Important sites for terrestrial biodiversity protected (%)	41.9	44.1	44.3
Population using safely managed drinking water (urban / rural, %)	80.4/ 55.9	81.2/ 60.9	81.1/ 62.2
Population using safely managed sanitation (urban / rural, %)	45. / 35.6	49.2/ 43.0	49.6/ 45.9
Net Official Development Assistance received (% of GNI)	0.52	0.56	0.55

The approach presented by the UN indicates the need to measure and manage the carbon footprint from various sources. The UN's approach to measuring global emissions highlights their importance and points to the need to improve the quality of emissions measurement in each economic sector. However, aggregating global data at such a high level requires focusing on individual sources of emissions from various origins. It is necessary to improve methods for measuring the carbon footprint of basic processes in many areas of the economy, including transport processes. Conducting a reliable assessment of the emission levels of primary transport operations will help improve the efficiency of their management. Execution of SDG 11, "Sustainable Cities and Communities" and SDG 13 "Climate Action" requires the use of an appropriate method to measure and managing the transport processes to mitigate it. The UN set another ambitious goal related to mitigating the anthropogenic impact on the environment was set by the UN in 2015. The Paris Agreement is a global climate treaty adopted by the United Nations. Its main objective is to keep the rise in global average temperature significantly below 2°C compared to pre-industrial times, while also striving to limit the increase to no more than 1.5°C (UN, 2015a). To achieve this, countries have agreed to reduce the amount of greenhouse gases that they release into the atmosphere. Each country creates its own climate action plan, known as a Nationally Determined Contribution (NDC), which outlines how it will reduce emissions. These plans must be updated every five years to reflect greater efforts. The agreement encourages a shift towards cleaner energy, more sustainable transport, and technologies that reduce environmental impact. Ultimately, the Paris Agreement aims to achieve net zero emissions globally by around the middle of the century, meaning any remaining emissions must be removed from the atmosphere through natural processes or technology. Hence, the pursuit of accurate measurement and management of emissions must begin at the level of processes carried out within individual organisations. This creates an opportunity for the development of methods for managing transport emissions within sustainable supply chains.

Further research and development of transport process management methods is necessary in order to achieve the adopted UN goals of reducing anthropogenic impact on the environment. Further research is also required into the management of the carbon footprint of individual processes, including transport. The regulatory acts, policies and legal framework, both globally and in Europe, indicate a need for scientific development in the area of transport process management regarding their emissions. It is also necessary to undertake research aimed at linking transport process management with the achievement of sustainable development goals. Conducted research has identified these as inseparable and mutually influential elements.

Composition of global and European GHG emissions

Greenhouse gas emissions originate from various sectors of the economy. According to the report by the Intergovernmental Panel on Climate Change the largest source is the energy sector, particularly electricity and heat production(IPCC, 2022). This accounts for around 34% of all emissions, primarily due to the combustion of fuels such as coal and natural gas. The second largest source is industry, producing around 24%. This includes activities such as manufacturing goods, producing cement, and creating chemicals. Agriculture, forestry, and changes in land use account for around 22%, primarily due to raising livestock, growing crops, and deforestation. The transport sector is responsible for 15%, with most of these emissions coming from cars, lorries, aeroplanes, and ships. Buildings account for 6%, primarily due to heating, cooking, and other energy usage. Each of these sectors releases different greenhouse gases, such as carbon dioxide, methane, and nitrous oxide. Understanding how each sector contributes is crucial for devising effective strategies to combat climate change. In order to present the significance of emissions resulting from transport processes, the global GHG composition is presented in **Fig. 1** below. According to IPCC data, emissions resulting from transport processes are the fourth largest source of world's GHG emissions, which indicates their significant nature.

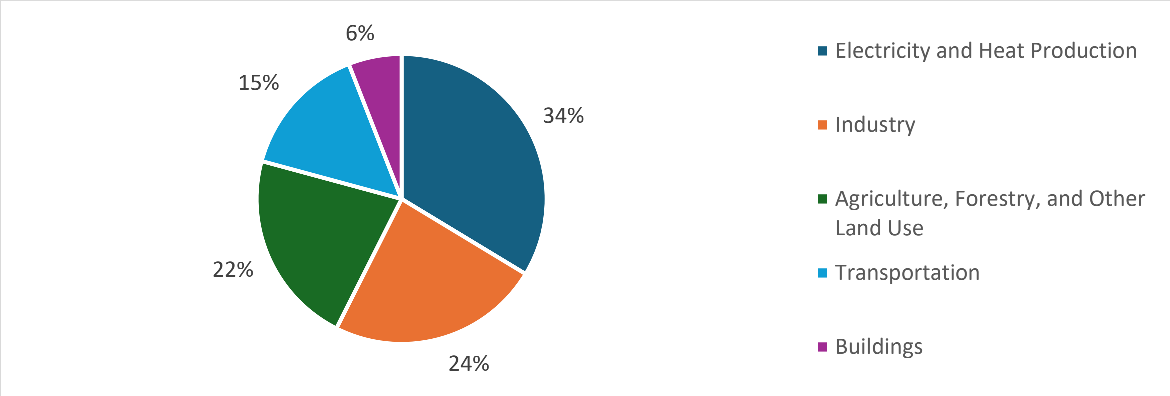


Fig. 1 Global GHG emissions by economic sector
Source: own elaboration based on IPCC (2022).

A detailed verification of the composition of global emissions classified as transportation is presented in **Fig. 2**. The dominating share of emissions from road mode of transport has been identified. In this category, 45% of emissions come from passenger vehicles, followed by 29% from freight trucks(IPCC, 2022). Such a composition of emissions within the world's transportation sector reveals a high potential for optimising transport processes by mitigating their emission levels. This aspect is also highlighted by Guzman et al. (2016) in their research.

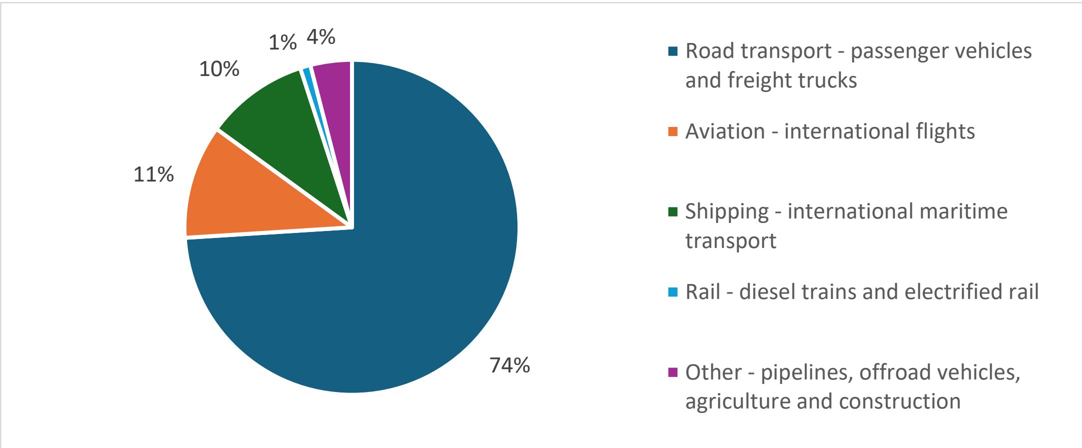


Fig. 2 Composition of global emissions within the transport sector
Source: own elaboration based on IPCC (2022).

According to reports of European Environmental Agency (EEA), the main modes of transport responsible for emissions in Europe have been analysed in depth. Since 1990, greenhouse gas emissions (GHG) from European navigation, European aviation, and rail transport have decreased. However, according to EEA estimations these emissions are expected to stay mostly steady in the coming years(EEA, 2024). Changes in emission levels originating from various modes of transport are presented in **Fig. 3** below. Emissions resulting from road transport processes are the only ones projected to decline. The emission values for aviation and maritime transport presented in **Fig. 3** refer to global emission levels and are presented for comparison with the values achieved by different modes of transport in Europe. Road transport is the largest source of transport related emissions. In 2022, it accounted for 73,2% of all EU transport greenhouse gas emissions, including both European and out of Europe international transport. According to EEA, road transport emissions are expected to go down due to incorporation of EU level policies and planned actions that are focused on reducing road transport emissions. By 2030, the largest increases in emissions are expected from aviation and international shipping. This follows a long-term upward trend that has been happening since 1990. As road transport emissions fall, aviation and shipping are expected to make up a larger share of total transport emissions. It can be observed in **Fig. 3**, that COVID-19 pandemic temporarily interrupted these trends. International aviation emissions dropped by 58% in 2020 compared to 2019. Eventually, emissions from air travel rose by 25% in 2021 and increased by another 57% in 2022. Flight numbers are expected to return to their 2019 levels by 2025.

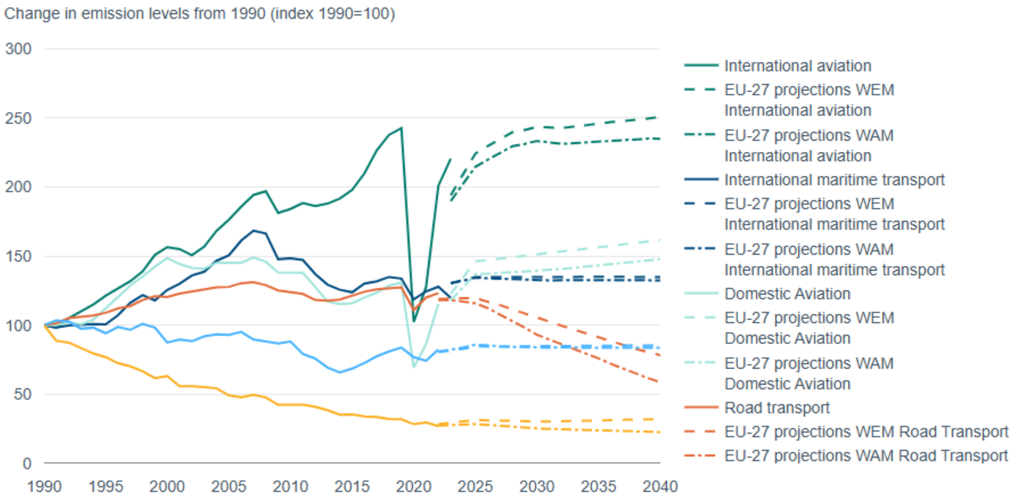


Fig. 3 Greenhouse gas emissions resulting from different types of transport in Europe in Million tonnes of CO_2 equivalent ($MtCO_2e$)
Source: (EEA, 2024)

The transport sector remains a major contributor to greenhouse gas emissions within the European Union, with limited progress in cutting emissions over the past few decades. Although measures like expanding the use of electric vehicles have been implemented, overall emissions have not declined much since 2005. Preliminary data for 2023 shows only a slight decrease of 0,8% compared to 2022. EU Member States anticipate that emissions from domestic transport will drop below 1990 levels by 2032 (EEA, 2024). Further EEA emissions estimations up to 2040 are presented on **Fig. 4** below.

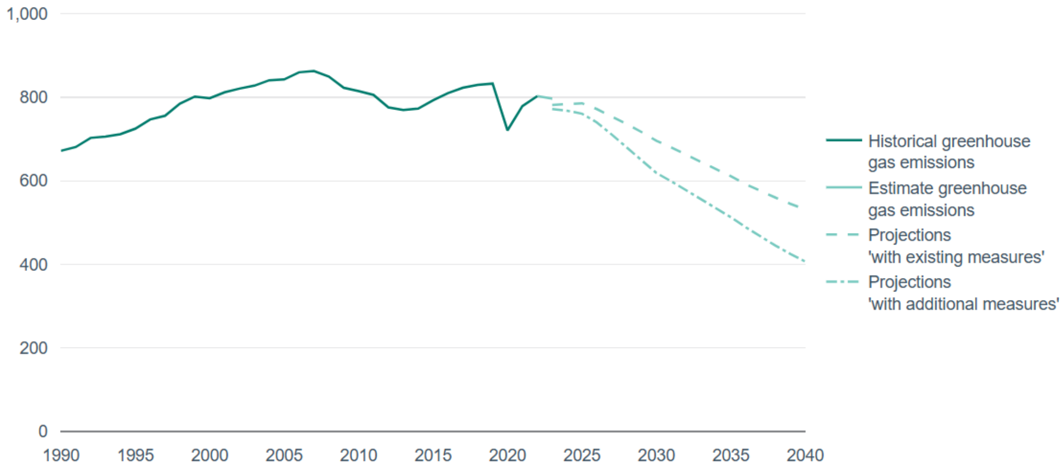


Fig. 4 Change in GHG emissions from transport in Europe since 1990, with estimated trends to 2040 in Million tonnes of CO_2 equivalent (MtCO2e)
Source: (EEA, 2024)

Motivation for CO_2 emissions management solution development

The significance of measuring and managing the carbon footprint of transport processes has been revealed not only in statistics and their composition reports of global and European emissions. Companies involved into execution of various operations within supply chain can benefit by taking into account both the environmental concerns, and the operational excellence indicators (Wojtkowiak and Cyplik, 2020). The Carbon Footprint indicator (CF) is recommended to measure the environmental performance of a supply chain (Sherafati et al., 2020). The CF quantifies the impact of a product, process or activity in terms CO_2 emissions (Patella et al., 2019).

Simultaneously the policy makers worldwide aim for significant reduction of CO_2 emissions. The European Commission in the White Paper on Transport aims to reduce greenhouse gas emissions in the transport sector by around 20% compared to 2008 levels by 2030. The Paris agreement signed in 2015 by 196 worldwide parties aims to minimize global warming effect and decrease average temperature by 1,5 – 2 degrees Celsius. (UN, 2015a). European Green Deal (EGD) proposes a legally binding target of zero net greenhouse gas emission by 2050 (European Commission, 2020). Current legal trends and policies oblige to take far reaching measures to improve the measurability of greenhouse gas emissions in the supply chains (EU, 2019). The management of carbon footprint in supply chains shall be strategic imperative, as it helps not only the climate change issues but also fulfil the legislative requirements (Jabbour et al., 2015).

In accordance with legislative changes occurring globally, including those in Europe, a decrease in emissions resulting from transport processes is estimated. However, achieving the desired emissions reduction will require action in many layers. It is imperative to introduce vehicles equipped with efficient combustion engines, modern electric and hybrid engines, as well as to implement effective vehicle fleet management and freight transport management systems (Ghisolfi et al., 2024). Therefore, there is a strong potential for the creation of a dedicated method for the proper management and evaluation of the level of carbon footprint within transport processes within sustainable supply chains.

An additional motivation for developing methods to manage and measure CO_2 emissions is companies' constant pursuit to improve process efficiency while minimising resource use. This approach is consistent with the concept of sustainable transport processes. Supply chains with better use of resources and means of transport are more resilient and ensure better continuity of transport processes execution(Moridpour et al., 2021). Moreover, the growing complexity of supply chains results in a continual increase in the number of control parameters, which may influence the reliable assessment of CO_2 emissions. **Fig. 5** below highlights the key sources of motivations for developing the new CF assessment and management model.

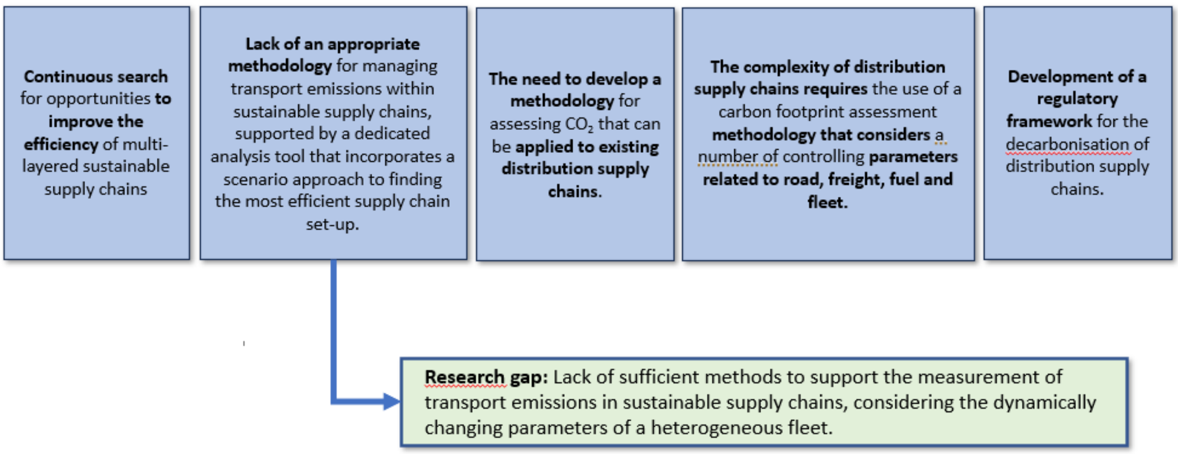


Fig. 5 Categorisation of sources of motivation for transport emissions management model development. Clarification of a research gap

Source: own elaboration.

During the identification of the main motivating factors for conducting the research and their categorisation, a research gap was recognised. It has been observed that there is a lack of adequate methods to support the measurement and management of the carbon footprint of transport processes in supply chains. This is a direct result of the complexity and multi-layered nature of current supply chains. The available tools do not fully support the assessment of the CF level of transport processes within the distribution supply chain and further management processes. The analysis identified potential for developing new approaches for measuring the carbon footprint of transport processes and transport process management solution that takes into account the current level of transport emissions. Filling the research gap requires linking scientific research, exploiting the results of existing scientific research in this area and conducting own research (conducted and described in this doctoral thesis). Furthermore, it is vital to align scientific findings with the expectations of supply chain stakeholders, and to adapt the new model of measuring and managing the carbon footprint of transport processes for use in the real market conditions.

Aim of the research

The preliminary literature analysis identified a lack of appropriate methodologies to support the management of heterogeneous fleet emissions within sustainable supply chains (Ayadi et al., 2024). Research conducted by Lin and Wang, (2022) revealed a lack of appropriate algorithms that take into account economic, social and CO_2 emission factors in multi-objective optimisation models dedicated to transport processes in a supply chain.

However, it was found that partial solutions are available that provide a wide range of emission factors, tools to support emission level assessment, or cover specific vehicle types or emission standards. Nevertheless, it was noted that there is a gap that could be filled by a holistic management methodology, including an actionable calculation model. Consequently, it was determined that a comprehensive approach is necessary, encompassing all the elements that are characteristic of the methodology, including large datasets incorporation into management process (Urbano et al., 2025). Hence a new holistic management methodology must enable emissions to be assessed using large sets of detailed data. The possibility of incorporating a multi-criteria decision-making method as one of the forms of processing the obtained results indicates the potential for maximising the efficiency of management processes (Zając et al., 2024). Research conducted by Feng et al. (2022) indicates that improving the efficiency of transport process execution is based on the analysis of the obtained parameters of emission level assessments in various logistics organisation variants.

A holistic methodology for managing transport emissions must take into account barriers between various economic sectors in modern economy. One of the main problems in assessing the carbon footprint of transport supply chains is their diversity, which results in difficulties in accessing basic data and differences in its quality(Batini et al., 2009). This state requires the creation of a method that is resistant to data quality loss during emission level assessment. Research by Luthra et al. (2022) also points to the important role of accurate identification of legal regulations, standards and frameworks in order to define the functional scope of the new holistic management method and overcome the cross-sector barriers.

The new model for assessing and managing the carbon footprint of transport processes must also take into account the specific parameters of different vehicle within fleet, existing CF assessment methods, and all boundaries related to the development of sustainable supply chains. Therefore, it is necessary to consider the heterogeneous nature of the vehicle fleet operating within a single supply chain. Thus, a detailed Scientific Aim was articulated.

Scientific Aim

Creation of a holistic model for managing CO_2 emission within supply chains, considering transport processes emissions generated by the heterogeneous fleets

Further initial literature analysis pointed to research conducted by Nedelko et al. (2015). Their research indicated that the use of appropriate tools supporting theoretical methods has a positive impact on the willingness of supply chain members to incorporate elements of environmentally-orientated management methods. The availability of appropriate tools to support the decision-making process increases the willingness to apply the method within the company. The research also identified organisational factors that influence the adaptation of management methodologies in existing enterprises(Nedelko, 2021). A survey conducted by Nedelko et al. (2021) among actual company representatives whose logistics processes are undertaken in accordance with the Industry 4.0 concept identified that increasing the level of education of personnel supports the application of Six Sigma management methods, Strategic Planning (SP) and Knowledge Management (KM) supports also awareness of the need for process emissions reduction.

Hence, according to the concept of new model of transport process emissions management within sustainable supply chains is intended to be implemented in existing supply chains through evolution rather than revolution. It will be necessary to provide an appropriate mechanism to support its adaptation in existing organisations. The creation of a dedicated emission assessment tool to support the implementation of the new management method will allow for its better adaptation and will meet the defined needs of its potential end users. As a result of preliminary literature research on the needs of enterprises and potential limitations in the implementation of a new management solution, a Utility Aim was defined.

Utility Aim

Development of a CF assessment approach supported by the holistic computational model within sustainable supply chains

It is also important to identify the interdependencies between the elements of the logistics model and their influence on the final assessment on carbon footprint level. Simultaneously the main parameters that determine the growth of the carbon footprint of transport processes within supply chains will be identified. Differences in transport process regarding operational region and fleet characteristics identified the significant role of specific transport process parameters and its influence on overall transport emissions level (Liu et al., 2021). According to research conducted by Liu et al., (2021), growing awareness of the significance of measuring the carbon footprint of transport processes and the popularisation of emission measurement have highlighted the significant role of terrain topography on Carbon Emission Intensity (CEI). However, it should be noted that the parameters of supply chains, whose fluctuations can influence the increase or decrease in emission levels, are considerably broader. Appropriate process planning and legal frameworks that define the obligatory manner of transport process execution have a direct impact on those. Research conducted by Aminzadegan et al., (2022) pointed to the significance of technological advancement of enterprises, economic conditions and demand for transport services. In connection with the preliminary research conducted, the aim was to define in more details the parameters determining the changes in the level of transport process emissions and to determine their significance. Initial literature research revealed a need to fully define the mechanisms and factors regulating and influencing changes of the emission levels of individual transport processes. The initial literature review research resulted in the formulation of the following Cognitive Aim.

Cognitive Aim

Identification of a key sustainable supply chain parameters influencing changes in CO_2 emissions resulting from transport processes both in literature and real market conditions

The interplay between these three aims is crucial for developing a methodology that is both grounded in scientific principles and practical in application. This balanced approach enhances the potential for the commercialisation of the proposed approach. In order to maintain the scope of this research, the following research questions are defined, enabling the formulation of appropriate conclusions and the successful achievement of the stated objectives.

Research Questions

Based on the literature review and in accordance to the scientific, cognitive and utility aims, four research questions were posed. The formulation of research questions allowed to specify the direction of the conducted research. The information gathered in the course of the research supported the achievement of the objectives set. The following four research questions are presented below.

RQ 1 - How to manage emissions from vehicles in heterogeneous fleets in supply chains?

RQ 2 - Which sustainable supply chain process parameters are crucial for managing emissions?

RQ 3 - How to gather the basic data necessary to assess the carbon footprint of transport processes and coordinate their flow between participants within the supply chain?

RQ 4 How to ensure the quality of the exchange of basic process data necessary to assess the CO_2 emissions of all sustainable supply chain participants?

RQ 5 - What elements should be reflected in holistic emissions management method supporting measuring transport processes?

Subject of study and research methodology

The adopted research methodology is based on both literature analysis and empirical research. The research concentrated on verifying the state of science and confirmation of the validity of the new CF assessment approach dedicated to the transport processes. Simultaneously, it was essential to identify the basic parameters regulating the efficiency of transport processes within sustainable supply chains, as well as to consider how these processes could be optimised. Concurrently, historical data was gathered from companies in order to conduct detailed research and work on the logic of the carbon footprint management method for the transport sector and dedicated calculation models. Attention was paid also to differences in data availability and quality during the research, resulting in the creation of two calculation models to support the assessment of the carbon footprint of transport processes. The aim was to ensure the method of assessing emissions remained useful and applicable regardless of the quality of the available data within a company interested in CF assessment of their transport processes.

Based on the research, the main principles and assumptions of CO_2 emissions management methodology within sustainable supply chains were formulated. In accordance to the research results obtained, the functionality of the High and Low Data Quality emission assessment models was also defined. It has enabled creation of two approaches of Simplified and Detailed CF emission assessments within sustainable supply chains. The logic of the research has been presented in the **Fig. 6** below.

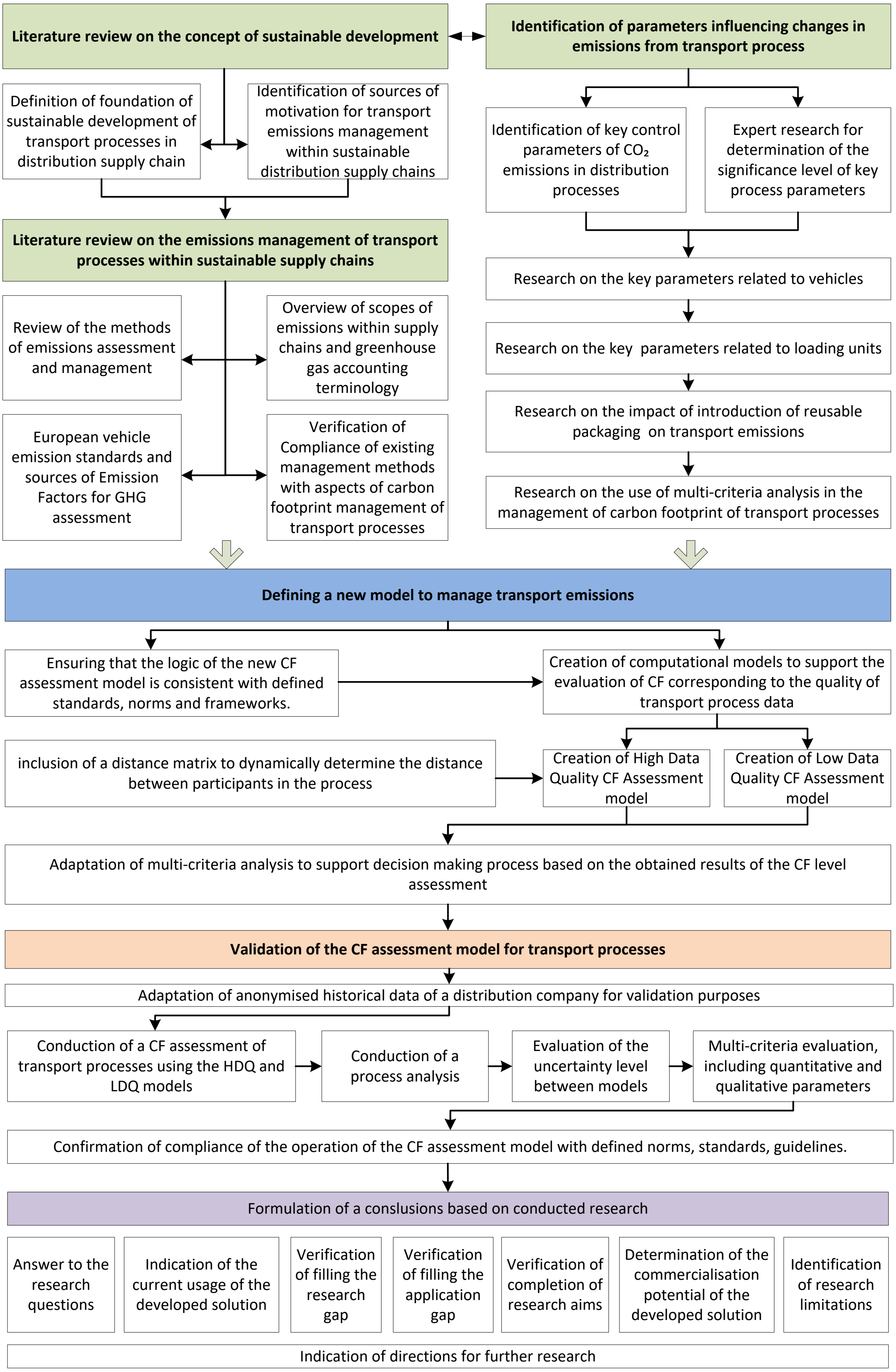


Fig. 6 Research methodology adopted in the PhD thesis

Source: own elaboration.

The first chapter focuses on a precise definition of the concept of sustainable development according to the literature reviewed. A thorough understanding of the basic principles of this approach is directly related to the logic of the new carbon footprint management method for transport processes and defines its functionality. This chapter also verifies the characteristics of transport processes undertaken in a sustainable and environmentally friendly manner. The first chapter also verifies the motivations of stakeholders to measure and manage the carbon footprint of transport processes. Since the sources of motivation, including legal regulations and legislative requirements, are based on the concept of sustainable management.

The second chapter focuses on the analysis of global methods of management and assessment of emission levels. It was essential to verify the lack of sufficient methods that could support the assessment of carbon footprint and the implementation of management mechanisms aimed at optimising transport processes from the perspective of their emissions. The focus was also on the emission scopes indicated in the guidelines and terminology related to GHG emissions management (i.e. GHG Protocol). European vehicle emission standards and sources of emission factors that could be used in the methodology were also verified. The use of global emission factors (EF) supports the high standard of transport process emission assessment and guarantees its reliability. Within this chapter, it was essential to identify the most important EF sources. The literature research was based on the latest literature in this field. Due to companies' efforts to implement new management methods through evolution, the potential for adapting existing management methods and the possibility of incorporating emissions management into existing management methods were verified. The impact of external factors and risks identified in the literature on the increase in transport process emissions was also verified and outlined within this chapter.

The third chapter focuses on the verification of parameters regulating the level of transport emissions. Expert Research method was applied to indicate the significance of parameters present in transport supply chains and to understand the specific characteristics of companies in terms of measuring and managing their carbon footprint. Simultaneously, the results of research were presented and verified on the basis of historical data from a distribution company operating within the Fast-Moving Consumer Goods (FMCG) industry. The importance and impact of vehicle age on the dynamics of emissions was analysed in quantitative research covering empirical research involving the development of an age based vehicle emission growth factor derived from historical operational data. Simultaneously the impact of the use of appropriate loading units on the level of transport process emissions was verified through case studies. Furthermore, the impact of the use of reusable packaging on the level of transport emissions was verified. Finally, the impact of the choice of appropriate mode of transport FTL and LTL on the level of emissions reported by the company was analysed.

The fourth chapter outlines the principles and logic of a new model for managing and measuring CO_2 emissions from transport processes. This chapter focuses on the correct application of the findings from the research presented in previous chapters. A simplified approach and a detailed approach have been proposed, depending on the quality of the basic data available from the assessed company. It also presents a decision-making approach referring to multi-criteria analysis in reference to the CF level obtained for analysed transport processes.

The fifth chapter is devoted to validating the new model proposed for assessing and managing the carbon footprint of transport processes. The proposed method was adapted and then verified on the example of an existing company as part of the As-Is process. The implementation of the method in the To-Be process was also indicated. The results obtained were subjected to a final assessment and comparison, which indicated the most effective, from environmental perspective, organisational setup of transport processes.

The sixth chapter summarises the results and presents the main conclusions. The limitations of the new model are identified and directions for further research are presented. The commercialisation potential of the proposed method for managing and measuring the carbon footprint of transport processes within sustainable supply chains is also addressed. In the end of this PhD thesis a list of illustrations and tables is provided, as well as a list of appendices.

The following **Tab. 2** presents a list of the chapters mentioned above, along with the research methods that were employed. **Tab. 2** presents also a linkage between chapters, research methods, formulation of answers to the specific Research Questions and Aims realisation.

Tab. 2 Research methods employed in individual chapters and sources of answers for RQ and Aims realisation
Source: own elaboration.

Chapter	Research method	Aim of the research	Answer to the RQ	Aim Realisation
1. Sustainable development concept	- Literature research	Verification of the state of literature in the researched area in order to indicate the potential for applying a new model of transport process emissions management within sustainable supply chains. Understanding the essential elements of the concept of sustainable development is important for formulating the logic of a new management method.	RQ4, RQ5	Scientific Aim
2. Emissions management of transport processes within sustainable supply chains	-Literature research -Risk Assessment -Analysis of norm, standards and regulations in the field of ESG reporting.	Analysis of norms, regulations and standards to ensure that the new model complies with global guidelines. Risk analysis was conducted to indicate the significance level of risks identified during the literature review that may affect transport processes.	RQ1, RQ2, RQ3, RQ4, RQ5	Scientific Aim Cognitive Aim
3. Parameters influencing changes in transport process emissions	- Expert Research - Quantitative research covering empirical research involving the development of an age based vehicle emission growth factor derived from historical operational data - Operational research - Case study - Comparative analysis	Expert research was conducted to determine the significance of individual parameters of transport processes within supply chains. Quantitative research was conducted using historical data from an FMCG company to identify the parameter of emission growth with vehicle age. The calculated parameter has been applied in computational models of a new model for managing and measuring carbon footprints. A case study was conducted to determine the impact of using appropriate loading units and reusable packaging. The vehicle filling parameter was taken into account in the Detailed approach and the High Data Quality CF computational assessment model. A comparative analysis was used to analyse emission related efficiency of different modes of transport and their impact on emission levels (FTL and LTL).	RQ1, RQ2, RQ4, RQ5	Scientific Aim Cognitive Aim
4. A new model for transport processes emission management	-	Creation of a holistic method for managing transport processes from the perspective of their emissions, with consideration of emissions from a heterogeneous fleet. This chapter is based on the results of the research described and presented in chapters 1, 2 and 3.	RQ1, RQ5	Scientific Aim Cognitive Aim Utility Aim
5. Model validation	Comparative analysis	Comparison of results obtained as a result of model validation. Application of created dedicated tools (High data Quality and Low data Quality) for assessing the carbon footprint of transport processes. Identification of differences between various scenarios of transport process settings and their impact on the achieved level of CO_2 emissions.	RQ1, RQ2, RQ3, RQ4, RQ5	Scientific Aim

Innovation of the proposed solution and Application Gap

The innovative character of the new model of transport process emissions management results directly from the identified needs of real market enterprises. The needs of companies were identified during a review of the latest literature, and also result from commercial analyses carried out by the author in logistics companies in professional work at the Poznań Institute of Technology, Łukasiewicz Research Network. It has been pointed out that various management methods are already in place in existing enterprises where transport processes are undertaken. Stakeholders expect new management solutions to be implemented within existing transport supply chains without distortion of the main transport processes. Hence, the new model of managing the carbon footprint of transport processes is suitable for application within existing SC structures. In this way, the integration of transport process emissions management can be achieved through the way of continuous process improvement and don't require significant investments or changes.

The innovation of the proposed solution is the development of a holistic approach to determine the key actors in distribution supply chains that are responsible for the growth of CO_2 within the supply chain. In this approach it is essential to identify the control parameters that have a significant impact on the growth or reduction of emissions within the transport supply chain. Hence to determine the impact of supply chain control parameters on the result parameters, and to develop mechanisms to coordinate the activities of the individual actors in order to reduce these emissions is a valid foundation of proposed carbon footprint management methodology.

The literature analysis conducted, expert research and review of existing carbon footprint management methods revealed a lack of sufficient methods for managing the carbon footprint of transport processes. The available guidelines and standards regulating carbon footprint measurement, such as the GHG Protocol, ISO 14 064 and PAS 2050 supports general CF assessment, however doesn't provide direct answers how to configure transport processes according to their CF level.

Based on research conducted on various parameters of a heterogeneous fleet, the new emission management method allows for the consideration of different vehicle parameters and modes of transport in order to accurately determine the emission level of transport processes. Vehicle age, gross vehicle mass (GVM) and fuel type have a direct impact on changes in transport process emissions. Modes of transport, including Less than Truckload (LTL) and Full Truck Load (FTL) have also been considered in the new model of managing transport process emissions.

The new model of managing transport process emissions is supported by dedicated calculation tools that take into account the guidelines, standards, regulations and emission factors identified in the course of the research. The assessment of transport process emissions performed with the dedicated calculation models can be used in companies' ESG reporting and covers the necessary scope specified in the European Sustainability Reporting Standards (ESRS).

The main innovation aspects highlighted in the new model for measuring and managing transport process emissions are illustrated in **Fig. 7** below.

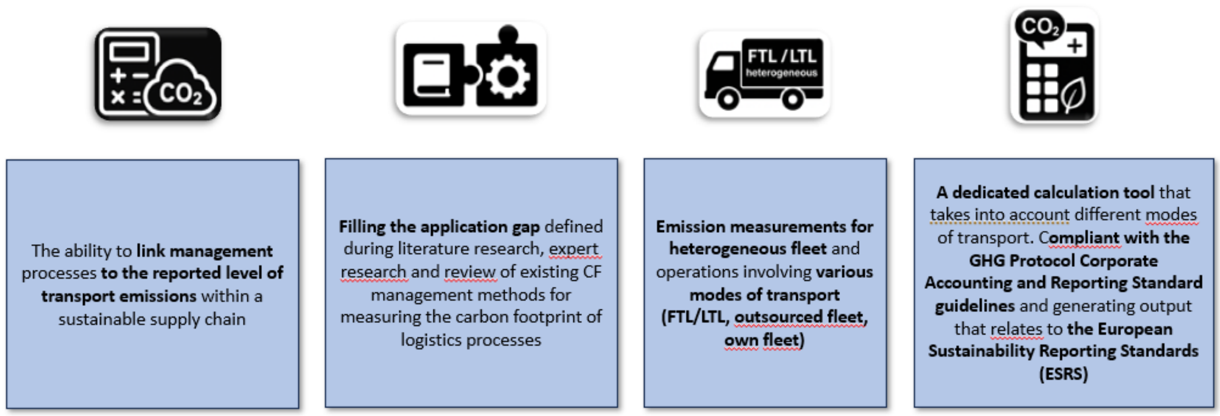


Fig. 7 Innovations of a new model for transport emissions management

Source: own elaboration.

The application gap consists in including transport process management with consideration of their emission levels. A conditioning factor for the fulfilment of the application gap is the consideration of elements identified as innovations in the new model for measuring and managing the carbon footprint of transport processes. It is also necessary to include in the new model all the control parameters within the supply chains identified in the literature review and revealed during the empirical research. The application gap may also be filled by accurate identification of the concept of sustainable development, due to the interest of contemporary companies in implementing transport processes in distribution supply chains.

The following chapters of this PhD thesis presents a detailed scope of research conducted to obtain the answer the research questions and to achieve the adopted aims.

1. Sustainable development concept

The concept of sustainability derives from the Latin word "sustinere", which means "to hold up", "to support" or "to endure". However, the use of the German term "Nachhaltigkeit" by Hans Carl von Carlowitz in the 18th century is treated as the introduction of elements of sustainable development at the organisational level of specific process (Grober, 2012; Carter and Rogers, 2008). The idea evolved significantly in the late 20th century and gained global recognition with the Brundtland Report "Our Common Future", published by the World Commission on Environment and Development (WCED) in 1987, which defined sustainable development as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987). According to a more current example of referring to the concept of sustainable development when creating development policies was proposed in 2015 by the United Nations. A more current example of the reference to the concept of sustainable development in the creation of development policies was proposed in 2015 by the United Nations. The report "Transforming our world: The 2030 Agenda for Sustainable Development" presents sustainable development as a holistic concept that integrates economic, social, and environmental dimensions (UN, 2015b). Simultaneously, more detailed and obligatory laws for supply chains operating in the European Union, such as the 'Treaty on European Union'. According to this Act, all EU state members should promote the sustainable development of the whole of European economic area, based on balanced economic growth, a high level of environmental performance and inclusion of social concerns(EU, 2012).

A variety of frameworks can support organisations in increasing their level of sustainability. The Triple Bottom Line (TBL) framework is one of the most widely recognised and focuses on three essential areas: social responsibility, environmental responsibility and economic values. The TBL concept encourages businesses to balance economic goals with environmental and social responsibilities, leading to sustainable development. Considering all the elements indicated by TBL allows for long-term planning instead of focusing on short-term effects. The individual elements of the TBL framework are presented in the following **Fig. 1.1.**

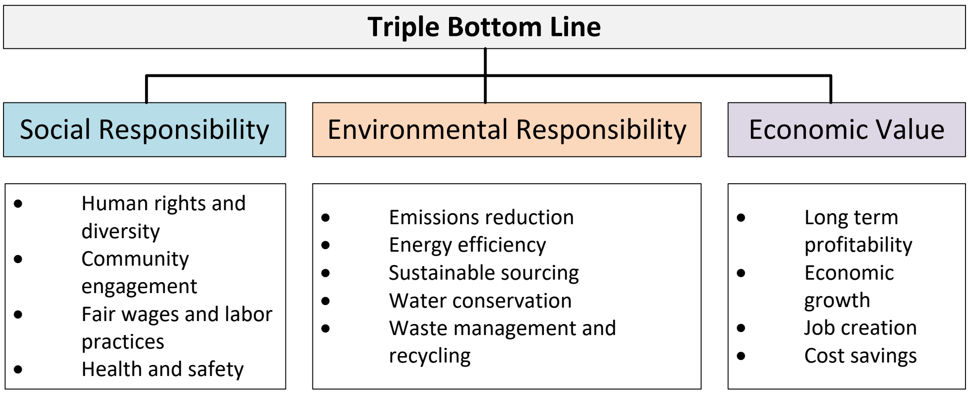


Fig. 1.1 The main principles of the Triple Bottom Line (TBL) framework
Source: own elaboration based on Elkington, (1998)

Research by Barauskaite and Streimikiene (2021) has identified a connection between social aspects and financial performance. It has been identified that excluding social aspects from the management process prevents supply chains from remaining on a sustainable development path. A study conducted by Bagratuni et al. (2023) based on a survey of an expert panel from the oil and gas industry, revealed that corporate social responsibility support the sustainability and implementation of the UN Sustainable Development Goals.

A study by Cichosz et al. (2025) shows that sustainable supply chains depend on recognising and managing paradoxical tensions, rather than achieving a fixed optimal design. Proper transport operations require balancing cost efficiency, service reliability, and emission reduction through dynamic capabilities such as agility, innovation, and collaboration. Therefore, sustainability in logistics is an ongoing process of navigating trade-offs across sourcing, delivery and reverse logistics. This further emphasises the importance of the TBL concept. Witkowski and Kiba-Janiak (2012) study demonstrated the impact of transport logistics parameters on citizens' quality of life. The respondents indicated that freight transport generates noise and contributes to traffic congestion in urban areas. They suggested that introducing restrictions on heavy goods vehicles, or even prohibiting their passage through city centres, could substantially enhance the quality of life for urban residents. Simultaneously, the research shows the dependency of decision-making in supply chains and determines how transport processes are managed in relation to noise and environmental parameters (Jacyna et al., 2017). Therefore, a connection between environmental and social responsibility has been outlined. The research of Tundys and Wiśniewski (2023) illustrate that the management of transport processes should be aligned with the principles of the Triple Bottom Line. From an environmental perspective, the study underlines the importance of reducing emissions and resource consumption, while socially it emphasises the benefits of enhanced liveability and stronger stakeholder involvement. Economically, the results demonstrate that optimised logistics and innovative solutions can improve efficiency, thereby showing that all three dimensions of sustainability must be addressed in an integrated manner.

All development and management concepts have their strengths and weaknesses. The resilience of supply chains is closely linked to the extent to which sustainability principles are integrated. Nevertheless, applying the TBL concept can also introduce specific risks (Tundys et al., 2024). It is therefore essential to develop strategies to manage these risks, which have been recognised as a critical parameter of effective supply chain management. The sustainable development also has areas that need to be considered when implemented within the organisation. It is essential to recognise the strengths and weaknesses, as well as the opportunities and threats that may be associated with the implementation of sustainable development elements within a supply chain. A comprehensive understanding of sustainability within supply chains is the foundation for further analyses of the state of the art in terms of managing transport processes in such an organisational environment. In her research, Drastichová (2024) presented an interesting approach to the analysis of the characteristics of sustainability by conducting a SWOT analysis of the sustainable development concept. However, the research conducted did not take into account the context of transport processes that may influence the detailed direction of further literature analyses of the management of those processes within sustainable supply chains. Therefore, an extended SWOT analysis based on additional research was prepared and presented in the following **Tab. 1.1** (Strengths and Weaknesses) and **Tab. 1.2** (Opportunities and Threats).

Tab. 1.1 Characteristics of sustainable supply chains, SWOT analysis – Strengths and Weaknesses

Source: own elaboration based on literature review.

Strengths		Weaknesses	
Description of element	References	Description of element	Reference
Inclusion of sustainable development as a fundamental concept of supply chain development.	(Drastichová, 2024)	Supply chain participants can interpret sustainability from a different perspective, which can lead to incorrect conclusions and actions.	(Drastichová, 2024)
Achieve a balance between all the company's needs and opportunities.	(Drastichová, 2024)	Greenwashing can be considered as a challenge when organisations only mark an action while its result doesn't lead to a genuine improvement of the sustainability level of processes.	(Drastichová, 2024)
Increase the degree of flexibility of the supply chain in responding to changes in the business environment. The disruption of supply chains caused by the global COVID-19 pandemic has highlighted the greater resilience and flexibility of supply chains based on the principles of sustainable development. Research conducted by Settembre-Blundo et al. (2021) fills up a research gap related to importance and influence ratio of risk management onto supply chain resilience and flexibility. Researchers proposed to apply advanced theoretical logic of evaluation model to risk mitigation and operational framework for multidimensional risk assessment. It is believed that inclusion of those elements supports supply chain resilience and flexibility leading to better sustainability level.	(Settembre-Blundo et al., 2021)	A wide range of sustainability level indicators from all key areas within the supply chain can influence and complex the process of drawing conclusions.	(Drastichová, 2024)
Loucanova et al. proposed a business logistics efficiency index and a sustainable development index for EU countries to determine the level of sustainable development. They pointed out that compliance with legislative requirements and the legal framework shows a strong correlation with the level of efficiency of logistics processes, including transport. The research also identified a geographical correlation. Countries located in close proximity influence each other and implement solutions characteristic of the concept of sustainable development more willingly.	(Loucanova et al., 2024)	Limited access to good quality data from low-tech or underdeveloped suppliers and other supply chain participants.	(Batini et al., 2009)
Incorporate risk management elements within supply chains in a systematic way	(Pojasek, 2023)	Maintaining a balance between cost and environmental aspects lead to introduction of complex decision-making process among stakeholders.	(Sethi et al., 2024)

Tab. 1.2 Characteristics of sustainable supply chains, SWOT analysis – Opportunities and Threats
Source: own elaboration based on literature review.

Opportunities		Threats	
Description of element	Reference	Description of element	Reference
An important opportunity faced by supply chains implementing the principles of sustainable development is the possibility of achieving costs savings through increased process efficiency. Research conducted in Bangladesh on Green Supply Chain Practices (GSCP) identified that identifying key drivers and boundary conditions for sustainable supply chains can determine a company's competitiveness. Selecting the right GSCPs is an essential element of larger strategies aimed at increasing sustainability and represents an opportunity for companies.	(Khan et al., 2024)	Creating new concepts for optimising processes without scientific justification, replacing existing concepts with new ad hoc ones.	(Drastichová, 2024)
Research conducted by Dominguez et al. (2022) reveals that sustainable supply chains are characterised by a higher degree of diversification, transparency and decentralisation of the decision-making process. Such an effect can be achieved by improving the flow of information at the lower nodes. Apart from improving the efficiency of the process and reducing costs, it is also possible to reduce the bullwhip effect throughout the supply chain by increasing the degree of collaboration.	(Dominguez et al., 2022)	The lack of adequate knowledge flow, including knowledge management within the supply chain, can result in decreased sustainable performance of transport supply chains. Perceiving change as a threat to process stability. A lack of change can result in a decrease in the company's competitiveness and supply chain efficiency. Simultaneously, knowledge and its flow within the supply chain promotes the adaptability of sustainable solutions. In this context, it can be concluded that proper knowledge management can be seen as an opportunity and not a threat.	(Intezari, 2015; Szuster and Szymczak, 2016)
Research conducted in 37 countries on a very large sample of 100,956 respondents by Piao and Managi (Piao and Managi, 2023) indicates a positive correlation between the level of education and the tendency to support circular strategies and demand for recycle-sourced products what characterises the principles of sustainable development. Raising the level of awareness among the population influences efforts to create sustainably-oriented supply chains, which contributes to better economic performance.	(Piao and Managi, 2023)	Supply chains within developing countries can reduce the importance of social sustainability aspects in the management process. Growing interest has been observed towards innovative supply chain management concepts, especially in developing economies(Khan et al., 2021). The use of the Multi-tier sustainable supply chain management (MT-SSCM) concept is a good example, since it is an excellent tool for modelling multilayer and complex logistics models. Nevertheless, the risk of neglecting social aspects in the management process is pointed out by the researchers. They consider this to be a significant threat to increasing the level of sustainability within the supply chain. The solution to this problem may be the application of advanced management methods, including MT-SSCM.	(Khan et al., 2021)

Opportunities		Threats	
Description of element	Reference	Description of element	Reference
Sustainably managed supply chains are more likely to attract investment. Potential investors see sustainably managed organisations as progressive and worthy of investment.	(Drastichová, 2024)	Implementation of sustainable development elements within the supply chain in a simplistic manner. Research conducted by Kot (2018) focusing on medium-sized enterprises (SMEs) indicates their essential role in all global economies. The research pointed out that due to their significant contribution to the national economies, it is important that SMEs implement sustainable development elements within their supply chains in a comprehensive manner. The study also pointed out that it is important to avoid implementing only selected elements characteristic of sustainable development in the environmental, social and management aspects. This was identified as the main risk of competitiveness loss for SMEs.	(Kot, 2018)
Sustainable models are characterised by a strong partnership between the participants of the supply chain. The transparency of the processes encourages the individual suppliers and recipients to support each other in the value chain. The implementation of sustainability creates an environment for synergies to develop. Research on the sources of innovation in supply chains conducted by Polater (2023) identified the need to increase the level of interaction between participants. A survey of suppliers in the area of relation view (RV) and Promotive Voice Behaviour (PVB) identified that increasing the involvement of participants in the execution of logistics processes could be an opportunity for the development of supply chains.	(Polater, 2024)	The usage of buzzwords instead of serious actions to emphasise the engagement for introduction of sustainable development elements within a supply chain.	(Drastichová, 2024)
		An example of research conducted with experts from the transport sector on freight forwarders in Austria shows the impact of selected factors on compliance with environmental management issues in sustainable transport supply chains. The main criteria influencing the risk of not taking environmental aspects into account in sustainable supply chain management include: company size, industry sector, level of market competition between companies in a particular sector, and internationalisation of the supply chain. International freight forwarders in charge of arranging transport processes show a greater tendency to consider environmental aspects in their management processes. Simultaneously, local transport supply chains may neglect environmental and social criteria, focusing exclusively on economic aspects.	(Oberhofer and Dieplinger, 2014)

According to the analysis conducted, it can be assumed that the TBL method plays an important role in the effort to increase the level of sustainability, especially in the context of transport-oriented supply chains. The importance of the TBL elements points to the need of including these aspects in the developed method for measuring and managing the carbon footprint of transport processes. The parameters categorised under 'Environmental Responsibility' and 'Economic Value' were identified as essential parameters to be evaluated in the calculation model. The efforts to maintain the sustainability of the supply chains under environmental evaluation will indirectly refer to the elements indicated in the 'Social Responsibility' framework. Improving the efficiency of transport supply chains in terms of their environmental impact and financial efficiency will also have an impact on social aspects. This points to the complex structure of common supply chains and the extended mutual interdependencies between their participants.

Based on the analysis of literature and regulatory acts, it could be concluded that supply chain sustainability refers to the integration of environmental, social and economic aspects at each stage of the process. It starts at the level of sourcing raw materials and ends with the delivery of finished products to end customers. It aims to minimise negative environmental impacts, ensure fair labour practices and promote long-term economic viability of organisation. Sustainability promotes responsible sourcing, energy efficiency and waste reduction, reflecting the LCA approach. Organisations adopt sustainable supply chains to reduce risk, meet stakeholder expectations and contribute to global sustainability goals. The literature review identified that the implementation of sustainable development elements provides an opportunity to increase the competitiveness of supply chains. Sustainable development aspects related to the logistics processes, such as transport, are essential elements that require appropriate modelling to increase the level of overall sustainability of logistics model.

In following **chapter 1.1**, further research was conducted on elements characteristic of the ESG perspective to ensure that the new CO_2 assessment model developed is consistent with this approach and consider its key elements.

1.1. Sustainable development of transport processes in distribution supply chains

The development of organisational concepts of transportation logistics processes has its origins in military requirements (Jaroenjitrkam et al., 2024). Military practice has also shown that the ability to deliver supplies in a sustainable manner to a specific location in lack of stability and predictability conditions depends on efficient management supported by proper mathematical modelling for SC resilience support(Andrii et al., 2024). Conducted literature research revealed that majority of these elements are reflected in modern civil-oriented logistics concepts. The development of logistics concepts is dynamically driven by the increasing level of globalisation, the multi-layered nature of global supply chains and the growing degree of digitisation of logistics processes(Oluwafunmilayo Esan et al., 2024). Sustainable transport can also be achieved by using simulations of alternative supply chain organisation options. Simulations allow the potential emissions of transport processes to be determined (Jacyna et al., 2014). This is important from the perspective of the new CF assessment model for transportation processes and the management process. Simultaneously, it was shown that the development of the digitalisation of supply chains necessitates the simultaneous implementation of solutions characteristic of the circular economy. The development of these two areas must take place simultaneously because of their complementary nature (Nowicka, 2021). The modern, digitalised supply chains depends on capabilities of current Enterprise Resource Planning (ERP) solutions and Supply Chain Management (SCM) platforms enable the proper use of acquired process data and the implementation of effective process management (Bayu Setyo Nugroho et al., 2024).

To gain a deeper understanding of the emissions management of transport processes, a broader view is required. To accurately identify the key aspects related to emissions management of transport processes, it is crucial to gain a more detailed understanding of the conditions under which such management approach occurs. Analysis of the literature on transport processes sustainable development within the supply chain is directly related to the sustainable usage of energy resources and related to them Green House Gasses (GHG) inventory and management. Hence, transport emissions evaluation, management and mitigation is perceived as a part of supply chain management approach (Barbosa-Póvoa, 2009; Garcia and You, 2015; Seuring and Müller, 2008). Therefore, analysing the management concept of sustainable supply chains presented in the literature is a must from this perspective.

Attempt to define the organisational boundary conditions of supply chains in which transport emissions management occurs can refer primarily to the existing literature reviews carried out. Seuring and Müller (2008) proposed the following definition of SSCM:

"Sustainable SCM is the management of material, information and capital flows as well as cooperation among companies along the supply chain while integrating goals from all three dimensions of sustainable development, i.e., economic, environmental and social, which are derived from customer and stakeholder requirements. In sustainable supply chains, environmental and social criteria need to be fulfilled by the members to remain within the supply chain, while it is expected that competitiveness would be maintained through meeting customer needs and related economic criteria" (Seuring and Müller, 2008, page 1549).

With reference to the quoted definition, it can thus be stated that sustainable management of supply chains is based on the following key elements presented on **Fig. 1.2** below. Each of these elements must be taken into account during the development of transport processes, their execution and final evaluation of their effectiveness.

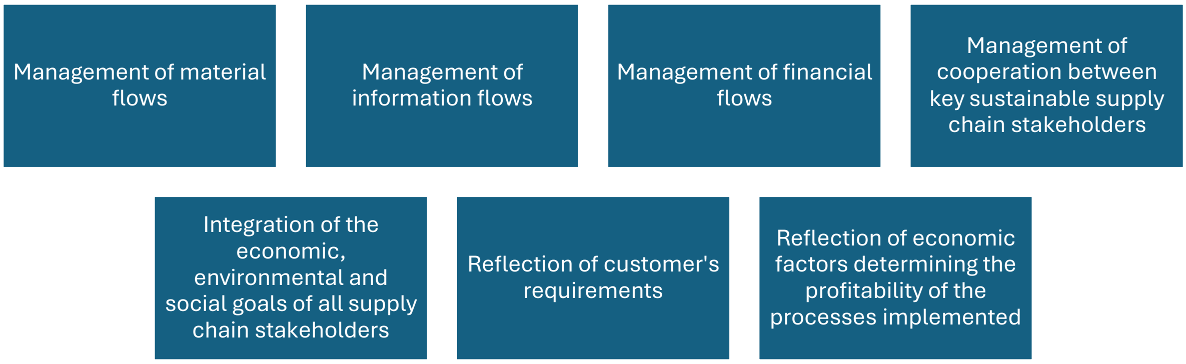


Fig. 1.2 Key elements of a Sustainable Supply Chain Management (SSCM) approach for emission-focused transport management

Source: own elaboration based on Koberg and Longoni (2019) and Seuring and Müller (2008).

A different perspective on the issue of SSCM is provided by Koberg and Longoni (2019). Proposed by those researchers' primary range of SSCM criteria covers the most important elements such as coordination of information, material and financial flows, but their concept of SSCM management points to the essential role of the physical distance between participants within Global Supply Chains (GSCs). Wide spread of participants within GSCs determines even higher level of cooperation and improvement of mutual connections. Another important element of GSCs that influence the pace of development of global supply chains is globalisation. The introduction of foreign suppliers into GSCs may lead to a competitive advantage due to lower labour and production costs in remote areas of the world (Gereffi and Lee, 2016).

Another perspective, not only on sustainable supply chain management but on sustainability in general, was presented by Carter and Liane Easton (2011). According to the researchers' experience, there is a risk of overlapping important aspects of sustainability within supply chains that may lead to misunderstanding. To avoid this risk, the researchers proposed their own conceptualisation of sustainability elements within the supply chain. According to Carter and Liane Easton (2011) research SSCM principles have to be consistent with the following four supply chain features presented on **Fig. 1.3.** The new management method involving the management of transport emissions must take into account both the key elements indicated in **Fig. 1.2** and the characteristics of the SSCM management method defined in **Fig. 1.3** below.

Strategic alignment

systematically and intentionally selecting specific SSCM (Sustainable Supply Chain Management) initiatives that resonate with and reinforce the organisation's overarching sustainability goals.

Risk management

incorporating proactive measures, including contingency planning, to address potential challenges in both upstream and downstream segments of the supply chain.

Organisational culture

fostering a deeply embedded culture of organisational citizenship characterized by strong ethical principles and high expectations, which serve as foundational elements for SSCM, alongside a commitment to societal and environmental respect both within and beyond the organisation.

Transparency

actively engaging and communicating with critical stakeholders while ensuring traceability and visibility across all levels of upstream and downstream supply chain operations.

Fig. 1.3 Key features of a Sustainable Supply Chain Management (SSCM) approach for emission-focused transport management

Source: own elaboration based on Carter and Easton (2011).

An interesting approach for sustainable management of transport processes is supported by the metaheuristic algorithms. The research carried out by Abualigah et al. (2023) provides an insights into the SSCM key control parameters. A review of the latest state of the research in the area ensures that the most recent findings on SSCM management are included. Among the essential elements incorporated into the management concept are: choice of appropriate algorithms involved in SSCM management, basic data quality gathered from the stakeholders and GSCs participants and complexity of the whole model. It is important to reflect multilayer structure of current SC. According to the alternative SSCM and ESG approaches presented in the literature, the most beneficial and efficient method for SSCM performance evaluation could be the introduction of emissions management of related processes. According to the alternative SSCM and ESG approaches presented in the literature, the most beneficial and efficient method for SSCM performance evaluation could be the introduction of emissions management of related processes. Therefore, a proposed visualisation of the interdependencies between the key drivers of SSCM expressed as sustainability elements and ESG approach is presented **Fig. 1.4.**

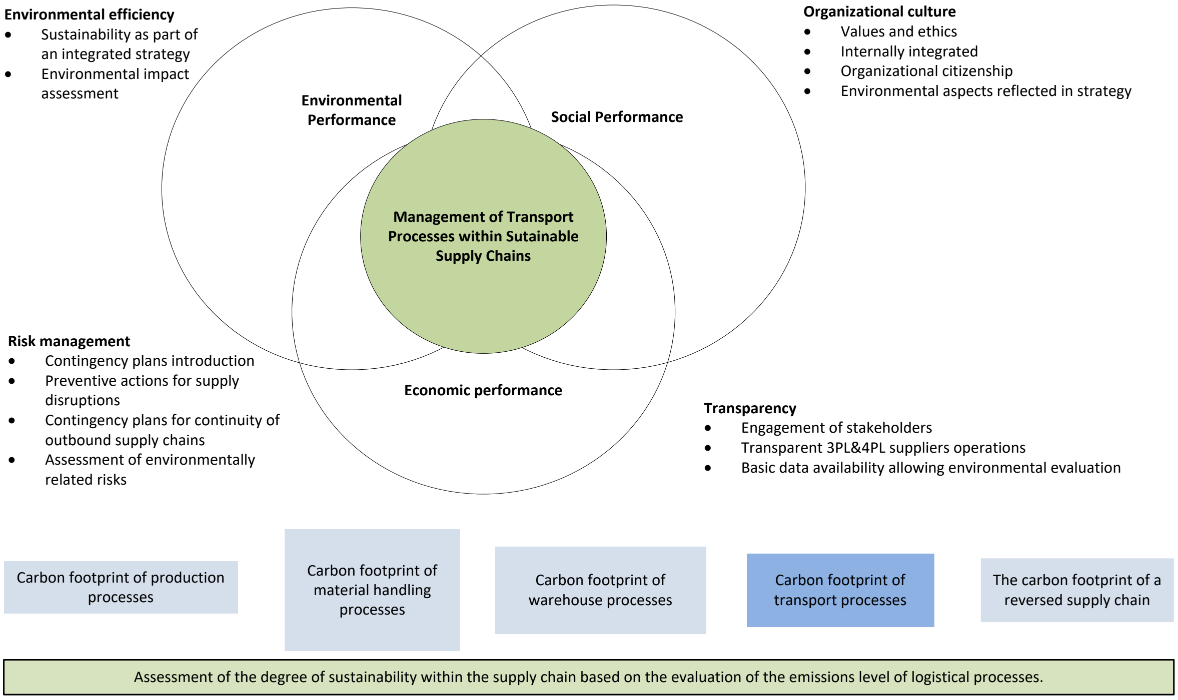


Fig. 1.4 Mutual interdependencies between ESG elements utilized within sustainable supply chain management approach.

Source: own elaboration based on Carter and Easton (2011).

The literature research that was conducted identified the inseparable nature of the principles of sustainable management of transport supply chains and the need to manage the emissions of transport processes. The essential aspects of sustainable supply chain management, as shown in **Fig. 1.4** are all indirectly related to the research area of transport process emissions management. It has been concluded that introduction of emissions management into the supply chains, can cause opportunity for even higher level of sustainability to be achieved within the entire supply chain.

Importance of innovation within management process of 3PL and 4PL service providers have been underline in another research by Cichosz et al. (2017). Those operate in highly competitive environments where retaining and satisfying existing customers is more effective than pursuing new ones(Shin and Thai, 2016). Successful innovation in logistics depends on overcoming barriers and achieving strong alignment with customers, particularly when developing tailored or radical service innovations. A higher innovation level can be obtained by introduction of environmental efficiency indicators that reflect emission level.

The literature review revealed the important role of transport process management in sustainable supply chains. Measuring and managing the carbon footprint of transport processes is in line with the concepts of improving the level of sustainable development within supply chains, conducting processes in accordance with the ESG approach, and the SSCM concept. Simultaneously, the literature review defined the concept of transport process efficiency. Effective execution of transport processes refers to the best possible utilisation of available means of transport from an organisational and cost perspective for the process owner. Research in the agricultural sector has shown that the selection of appropriate suppliers and types of transport has an impact on the efficiency of transport operations carried out (Niewiadomski and Merkisz-Guranowska, 2024). It is crucial to identify the parameters affecting the level of efficiency in each type of supply chain and transport process. Effective execution of transport processes refers to a balance between the cost, time and quality parameters of a transport operation. The environmental efficiency of transport processes also refers to the effective implementation of transport processes, however, it additionally considers environmental aspects. The effective implementation of transport processes strives to achieve a balance between the environmental parameters of transport, cost parameters, time parameters and quality parameters.

1.2. Sources of motivation for transport emissions management within sustainable distribution supply chains

The motivation for evaluating the carbon footprint of transport processes in supply chains, originates at multiple levels. Enterprises operating in a sustainable manner look for opportunities to improve the quality, efficiency and effectiveness of their transport processes, and a defined level of emissions can indicate the degree of their excellence (Carter and Liane Easton, 2011; Cichosz and Pluta-Zaremba, 2019). Research conducted by Liu et al. (2024) indicates that the increasing value of the economic indicator GDP in China is not consistent with the efficiency level of transport processes. The researchers point to the important role of the TSE (Transportation System Efficiency) index and its association with the level of technological advancement of supply chain. The Technological Efficiency Change (TEC) and Technological Change (TTC) indexes are employed to assess changes in supply chains efficiency level. The increased digitalisation of supply chains, including the transport planning, organisation and execution, has a positive impact on the mitigation of emissions, which in consequence leads to an improved efficiency of transport processes(Nowak et al., 2022). Simultaneously, in addition to improving the efficiency of logistics processes, another important motivating factor for measuring and managing the carbon footprint of transport processes is the legal framework within which current supply chains operate. Research by Okereke (2007) conducted among companies listed in the UK's FTSE 100 (Financial Times Stock Exchange) has identified a number of motivating factors for companies to measure and manage their transport chains. The results of the research point to factors such as: corporate financial efficiency, competition for credibility and subsequently influence in climate policy development circles, and fiduciary obligations. According to the research, most CEOs admit that climate change is beginning to be considered as a fiduciary issue. Furthermore, another important motivating factor identified in the research is minimising the risk of losing market share as a result of neglecting efforts to mitigate environmental impacts of logistics processes. Simultaneously, insurance companies are linking the risk level of the company they are assessing to the level of environmental sensitivity, and sustainability. Those factors, according to Okereke (2007) further influences the motivation of companies to measure their upstream and downstream emissions levels under each of scopes (Scope 1, Scope 2 and Scope 3 – According to GHG Protocol classification, detailed in chapter **2.2**. In order to identify the sources of motivation for measuring the carbon footprint of transport processes, recent research was consulted to obtain a comprehensive overview of the motivating factors among distribution supply chains.

In the management approach currently employed in logistics, which takes into account environmental, social and governance (ESG) aspects and elements of CSR programmes adopted by many organisations, including European ones, the focus on the credibility of reporting is an important element. The issue of the quality of emission assessment and reporting in annual non-financial reports has been addressed in COMMUNICATION FROM THE EUROPEAN COMMISSION, Guidelines on non-financial reporting: Supplement on reporting climate-related information (2019). In order to avoid the risk of greenwashing, described in literature as an attempt to feign action to reduce emissions(Nemes et al., 2022), according to European Commission it is necessary consider *“6 key principles for good non-financial reporting, namely that disclosed information should be: (1) material; (2) fair, balanced and understandable; (3) comprehensive but concise; (4) strategic and forwardlooking; (5) stakeholder-oriented; and (6) consistent and coherent.“* (EC, 2019, page 3) However, the realisation of these six essential principles requires the inclusion of many other elements and can result in the pursuit of improved efficiency, cost reduction, and the inclusion of environmental management elements in processes. Examples of these pursuits can be seen in subsequent literature and related studies.

The literature analysis conducted indicates a multi-source motivation to measure and manage carbon footprint of transport processes within the supply chain. Further research results indicate various factors influencing the composition of these motivations. Research carried out by Pålsson and Kovács (2014) among heads of logistics within companies operating in Sweden focused on identifying the main factors motivating these to incorporate emissions management elements, identified that legal regulations are the main factor influencing the degree of a company's involvement in measuring its emissions. However, the combination of several motivating factors, such as the company's need to establish the image of an environmentally neutral supply chain and the simultaneous identification of potential cost savings, are the strongest motivators for implementing management elements aimed at reducing the emissions of transport processes.

Research into the impact of the parameters within the supply chain on energy efficiency (EE) and emission levels was verified using a quantile regression model in China (Yunxia and Yuqing, 2025). Data from 2005 to 2019 from Chinese provinces Ningxia, Hainan and Qinghai, was incorporated into the dedicated calculation model to verify the impact of legal regulations on changes in emission levels. It was identified that the introduction of high penalties for excessive emissions contributed to an improvement of the technological advancement by companies in those regions. As a result of the legislative changes, companies decided to make significant investments, which increased their overall competitiveness. The changes in technological level influenced the reorientation of companies' strategies towards more sustainable models.

According to Osintsev and Rakhmangulov's research (2025), the importance of a cost motivation factor in the GHG assessment has been underlined. The cost and emissions evaluation of transport processes within supply chain may be supported by multi criteria decision making method, to determine the optimal supply chain configuration and selection of its participants. It has been observed that such an approach can be seen as supporting element to increase the efficiency of logistics processes. Research in dairy industry shows that a relatively low emissions level of the transportation processes offered by an external transportation service provider can lead to the achievement of a better sustainability level. (Peterson and Mitloehner, 2021). Simultaneously it has been observed that a lower emissions level of transport processes associated with a transport service provider is connected with a lower operating costs and contributes to increasing the sustainability level within the supply chain.

Research shows that stakeholder pressure is becoming an increasingly important motivator for companies to measure their carbon footprint and plan how to reduce their environmental impact(Wieland and Creutzig, 2025). Customers and stakeholders expect companies to implement programmes and plans to reduce emissions from transport processes. The company's approach to emission control aspects is an element that stakeholders assess in the context of the overall value of its products and services(Pålsson and Kovács, 2014). Supply chains that consider environmental management elements, including the management of transport-related emissions, are perceived as supply chains with a higher level of resilience(Singh et al., 2024).

Research by Kuzior et al. (2022) shows that emissions can be reduced by minimising energy consumption. A method of supporting the reduction of emissions is the implementation of Corporate Social Responsibility (CSR) programmes by enterprises within their transport supply chains. Researchers point to the significant role of emissions from transport processes, but emission reduction programmes do not have to be reserved only for these processes. According to research, implementing CSR strategies can bring benefits not only to local society, but also contribute to increasing the efficiency of company processes, which is an important motivating factor for measuring and reducing emissions. Including environmental factors in regular reports submitted by companies in accordance with CSR programmes is also an important motivator.

Research conducted by Sullivan (2009) among 125 of the largest European companies has identified that the most organisations implement management systems for better emissions management. Supply chains involving the measurement of these parameters are more resilient to risks and align with CSR programmes by introducing SC control parameters that lead to the proactive implementation of CO_2 mitigation solutions.

Review of the literature led to the identification of essential categories of motivation. It was concluded that a proper understanding of the drivers for carbon footprint measurement in sustainable supply chains can influence the scope of the carbon footprint assessment process. The main sources of motivation for measuring the carbon footprint of transport processes are presented in the following **Fig. 1.5.**

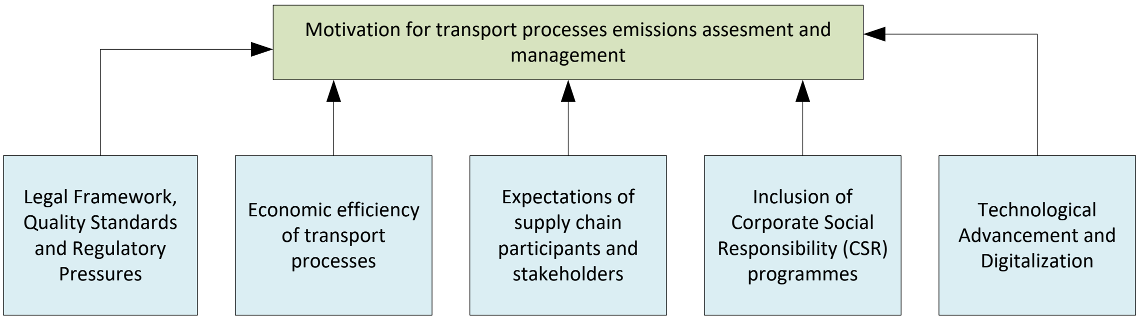


Fig. 1.5 Sources of motivation for evaluating the carbon footprint of the transport processes in distribution supply chains
Source: own elaboration.

It was observed that categories related to improving process efficiency, stakeholder expectations, incorporating corporate social responsibility (CSR) programmes and striving to improve process efficiency through increased digitisation are voluntary in most cases. However, the first of the defined categories, indicating legal acts and regulations as a source of motivation, is in most cases mandatory. Carbon footprint assessment process may vary depending on the area in which a supply chain operates. Therefore, **Tab. 1.3** below focuses on the main legal acts and regulations of the European Commission applicable within the European Union

Tab. 1.3 Summary of a major European Directives and Standards determining scope of transport processes CF assessment
Source: own elaboration.

European Directives and Regulations	Issue date/ year	Scope of the legal act	Obligatory (Yes/ No)
EU Corporate Sustainability Due Diligence Directive (CSDDD). Directive (EU) 2019/1937 and Regulation (EU) 2023/2859.	Published n 13th of June 2024.	Adopted by the EU Parliament in April 2024, the CSDDD directive requires large companies with more than 1,000 employees and €450 million in revenue to measure, limit and propose mitigating actions to lower their impacts in their operations and supply chains. This also includes an obligation to implement a climate transition plan, in line with the goals of the Paris Agreement. Companies could face penalties of up to 5 percent of their global revenue for not meeting the directive requirements.	Yes. Act of law refers to all enterprises operating within EU.
European Sustainability Reporting Standards (ESRS). Commission Delegated Regulation (EU) 2023/2772.)	Published on 22nd of December 2023.	The ESRS sets several obligations for companies to manage emissions and measure carbon footprints within their supply chains. Companies must evaluate both upstream and downstream activities. Thus, suppliers, logistics, product use and end-of-life disposal are included. perspective, the ESRS standards support the incorporation of life cycle assessment elements typical of a sustainable management approach. The ESRS standard requires companies to report on their greenhouse gas (GHG) emissions, including Scope 1 (direct emissions), Scope 2 (indirect emissions from energy), and Scope 3 (all other indirect emissions, such as those from the supply chain).	Yes. Act of law refers to all enterprises operating within EU.

European Directives and Regulations	Issue date/ year	Scope of the legal act	Obligatory (Yes/ No)
Corporate Sustainability Reporting Directive (CSRD). Directive (EU) 2022/2464.	Published on 31th of July 2023.	The Directive extends the requirements for sustainability reporting by companies operating in the EU. It affects large EU companies, listed SMEs (excluding micro-enterprises) and non-EU companies. Companies must report on the impact of sustainability issues on their business, as well as the impact of their operations on people and the environment. The Directive requires detailed disclosure on environmental, social and governance (ESG) issues using standardised European Sustainability Reporting Standards (ESRS). The reporting requirements are being introduced in stages from 2024 to 2028, depending on the size and type of company. The CSRD aims to increase corporate accountability, promote sustainable investment and align business practices with the EU's climate change objectives.	Yes. Act of law refers to all enterprises operating within EU.
The European Green Deal	Published on 11th of December 2014.	The European Green Deal is the European Union's plan to achieve carbon neutrality by 2050. It covers all sectors of the economy, including energy, transport, agriculture, construction and industry. The primary objective is to reduce greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels. The European Green Deal plan supports the transition to a circular economy, the use of cleaner energy sources, the protection of biodiversity and the development of sustainable food production systems. A key component of the plan is the 'Fit for 55' package, which updates EU legislation to reflect the 2030 climate targets.	Yes. Act of law refers to all enterprises operating within EU.
COMMUNICATION FROM THE COMMISSION Guidelines on non-financial reporting (methodology for reporting non-financial information) (2017/C 215/01)	Published on 6th of December 2014.	The Guidelines are focused on improving the relevance, consistency and comparability of environmental, social and governance (ESG) information disclosed by companies. The guidelines help companies report on environmental aspects, social and employee issues, human rights, anti-corruption, and diversity. It supports a focus on information that is most relevant to stakeholders and the company's performance. They have been designed to be compatible with various existing international frameworks. The Guidelines promote transparent and responsible corporate behaviour by improving the quality of non-financial reporting in the EU.	Yes. Act of law refers to all enterprises operating within EU.
WHITE PAPER Roadmap to a Single European Transport Area –	2011	The framework focuses on reducing greenhouse gas emissions. The European Union member states have set a target of reducing emissions from transport by 60% by 2050 compared to 1990 levels.	Yes. Act of law refers to all enterprises

European Directives and Regulations	Issue date/ year	Scope of the legal act	Obligatory (Yes/ No)
Towards a competitive and resource efficient transport system		The directive highlights the potential of intermodal transport as a means of reducing emissions from transport processes. Road transport has been identified as the least efficient mode, and therefore the specific targets include a 30% shift of road transport to rail. The framework also supports the development of multimodal transport as a solution to improve the environmental performance of road transport. An additional objective is to reduce the number of vehicles equipped with internal combustion engines (ICE) used for last-mile deliveries and passenger transport within strict city centres.	operating within EU.

The pursuit of minimising of the carbon footprint of transport processes is reflected in legal acts and regulations of individual state members. Besides local regulations that directly affect the planning, organisation and implementation of transport processes, there are also international conventions. A number of local legal acts, which describe the CF assessment process in details refer to these international conventions and frameworks. The **Tab. 1.4** presents a key international conventions and regulations that participate in the development of international efforts focused on reducing the carbon footprint of economies and has a significant impact on the worldwide logistics operations, including transport processes.

Tab. 1.4 Worldwide regulations, conventions and acts of law determining scope of transport processes CF assessment
Source: own elaboration.

International Conventions and Agreements	Issue date/ year	Scope of the legal act
United Nations Framework Convention on Climate Change (UNFCCC)	1992	The United Nations Framework Convention on Climate Change (UNFCCC) was adopted in 1992 during the Rio Earth Summit. Its main objective is to tackle the global issue of climate change. The convention seeks to stabilize greenhouse gas concentrations in the atmosphere at levels that prevent harmful human impact on the climate system(UNFCCC, 1992). It offers a globally recognized framework for negotiating specific international climate agreements. The UNFCCC has 198 member parties and hosts annual Conferences of the Parties (COP), where nations review progress and discuss future climate action.
Kyoto Protocol	1997	The Kyoto Protocol is an international treaty that was adopted in 1997 and came into force in 2005. Act was signed by the representatives of 191 countries and the European Union. It aims to reduce greenhouse gas emissions and reduce global warming(UNFCCC, 1997). The Kyoto Protocol was eventually replaced in 2015 by the Paris Agreement, which includes both developed and developing countries.
Paris Agreement	2015	Agreement emphasised the urgent need to significantly reduce global greenhouse gas emissions. An idea is supported by the

International Conventions and Agreements	Issue date/ year	Scope of the legal act
		developed and developing countries. The common goal is to keep climate change below 2°C. To achieve this, the EU needs to reduce its emissions by 80-95% by 2050 compared to 1990 levels, in line with the broader reduction targets required of developed countries collectively(UN, 2015a).
Glasgow Climate Pact	2021	Its main aim is to accelerate global climate efforts to stay within the 1.5°C temperature limit by encouraging countries to strengthen their 2030 emissions targets. It is the first COP agreement to specifically mention the need to "phase out unabated coal power" and reduce fossil fuel usage(UNFCCC, 2021). The agreement also highlighted the importance of increasing climate financing, specifically for adaptation efforts in developing countries.

Indicated acts of international law provide a framework for policies to reduce CO_2 emissions and prevent climate changes. Despite of acts of law, there are many references in management concepts to standards regulating the quality of production, management and transport processes. The most popular ones are the ISO standards. The International Organisation for Standardization (ISO) is a non-governmental Swiss organisation established in 1947. According to the organisation's website, the standards published by ISO "also guide businesses in adopting sustainable and ethical practices, helping to create a future where your purchases not only perform excellently but also safeguard our planet" (ISO, 2025). ISO standards cover management systems including quality, environmental, and energy management. Their main benefits include helping organisations improve performance, meet regulatory requirements, and facilitate global trade.

Tab. 1.5 Summary of a key emissions management motivators to be reflected in developed management method.

Source: own elaboration.

Motivation category	Area of impact of the management methodology developed	Key standards, policies or legal framework	Impact for Sustainable Supply Chains reporting process
Source of motivation I - Standards	Compliance with the environmental management system and reporting standards	- ISO 14 064 – 1 - GHG Protocol Corporate standard	- Provides a transparent methodology for collecting basic process data and categorises processes appropriately, enabling emissions to be classified under Scope 1, Scope 2 and Scope 3. - Enable continuous improvement tasks to implement environmental performance indicators. - Maintain the readiness of the supply chain using the methodology to demonstrate compliance with international legal requirements for

Motivation category	Area of impact of the management methodology developed	Key standards, policies or legal framework	Impact for Sustainable Supply Chains reporting process
			transport carbon footprint control. - Enable companies to implement environmental management elements as a tool for supply chain development. - Enables the analysis of the environmental impact of the transport process. - The application of standards in the supply chain management process enables the fulfilment of ESG reporting requirements. The application of appropriate standards and the resulting guidelines allows social, environmental and governance elements to be included in reporting.
Source of motivation II – International policies	Striving for climate-neutral transport processes	- The European Green Deal - Transport White Paper Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system - Fit for 55	Establishing clear climate targets of reducing road freight over 300 km to rail or waterborne transport by 30% by 2030 and cut EU GHG emissions by 55% by 2030 supports sustainability level improvement. Knowledge of clearly defined climate targets enables companies to take appropriate measures to increase the sustainability of specific transport processes.
Source of motivation III – Corporate ESG reporting	Corporate reporting	- Corporate Sustainability Reporting Directive (CSRD). Directive (EU) 2022/2464. - European Sustainability Reporting Standards (ESRS). Commission Delegated Regulation (EU) 2023/2772. - Directive (EU) 2022/2464 of the European Parliament and of the Council of 14 December 2022 amending Regulation (EU) No 537/2014. - Directive 2004/109/EC, - Directive 2006/43/EC. - Directive 2013/34/EU with	The regulations and directives support the measurement, management and reporting of the social, environmental and governance impact of transportation processes carried out within the supply chain. The obligatory character of reporting enables comparison of companies with similar business profiles in terms of their efficiency. Reference to the level of transport process emissions simultaneously enables

Motivation category	Area of impact of the management methodology developed	Key standards, policies or legal framework	Impact for Sustainable Supply Chains reporting process
		regard to corporate sustainability reporting.	indication of the technological advancement of the reporting company.

The analysis of motivating factors for measuring and implementing solutions based on the assessment of process emissions in sustainable supply chains identified an application gap. The developed method for managing transport process emissions indicates broad potential for its application in real market conditions. The identified sources of motivating factors shown in **Fig. 1.5** indicate the existence of an application gap that can be filled by the developed methodology for managing transport processes in terms of their emissions.

2. Emissions management of transport processes within sustainable supply chains

The transport sector is one of the largest contributors to global greenhouse gas (GHG) emissions, playing a critical role in the ongoing climate crisis (McKinnon, 2024). According to the Intergovernmental Panel on Climate Change (IPCC) in its Climate Change 2022 – Mitigation of Climate Change report (2023), transport accounts for approximately 15% of total GHG emissions and around 23% of global energy-related CO_2 emissions. These figures underline the sector's significant impact on climate change mitigation efforts. Moreover, the scale of transport activity continues to grow. As reported in the Transport and Environment Report 2022 by the European Environment Agency, the volume of freight transport—measured in tonne-kilometres—increased by 23% between 2000 and 2019 (European Environment Agency., 2022). This growth spans all modes of transport, including road, rail, maritime, and aviation, highlighting a consistent upward trend in global transport demand. In this context, managing emissions within sustainable supply chains has become increasingly vital. However transport processes are a key component of modern supply chains, and its emissions directly influence the overall environmental footprint of global trade and logistics. Effective emissions management not only supports climate targets but also enhances operational efficiency, regulatory compliance, and corporate sustainability performance. By integrating carbon footprint monitoring and reduction strategies into transport logistics, supply chains can evolve to meet both economic and environmental objectives.

By analysing the state of the art within the field of supply chain management from an emissions perspective, it was found that existing management methodologies may serve as the basis for the proper measurement and management of the carbon footprint of transport processes. The supply chain management methods identified in the literature share a common goal of continuous improvement of the efficiency of logistics processes. In order to achieve higher levels of efficiency, efforts may be put toward the better SC adaptation to specific commodity requirements (Rudi et al., 2016), the improvement of quality of processes due to their appropriate design (Garcia and You, 2015) and the development of information exchange between stakeholders (Hofmann, 2017). The impact of CO2 management on the value of companies is also being investigated. Using the example of the automotive industry, the relationship between market value and the effectiveness of process emissions management is proven (Salehi et al., 2022). A fundamental element of all transport process management methods is the efficient utilisation of available infrastructure (Sokhansanj and Hess, 2009) including maximisation of transport means filling grade (Caputo et al., 2006). The new model for the carbon footprint assessment of transport processes within sustainable supply chains needs to take into account existing management approaches and their specificities. The management of transport processes in terms of their carbon footprint should be able to be an addition to existing management practices utilized within existing companies supply chains. The main focus during the literature review was put on the identification of constraints in the management of transportation supply chains. As it is presumed that the constraints identified have a direct impact on the effectiveness of carbon footprint measurement and management (Gao et al., 2024). The research focus was put on the definitions of transport process emissions within supply chains presented in the literature. The analysis undertaken provides a better understanding of the nature of transport process emissions and will highlight the state of the art in this area. The new CF assessment methodology and the accompanying computational tools will need to consider each of the identified literature findings on the management of emissions within sustainable supply chains. The sources of company motivation influencing the willingness to implement transport emissions management were also reviewed. The influence of standards and legislation on company decisions has been analysed. The next step was to review existing transport emissions management methodologies. The focus was on their geographical coverage and verification of the scope of their application. Simultaneously potential sources of emission factors were identified to be incorporated into a calculation model to be developed along with transport processes emissions management method.
A logic behind conducted literature review within this chapter has been presented on below **Fig. 2.1.**

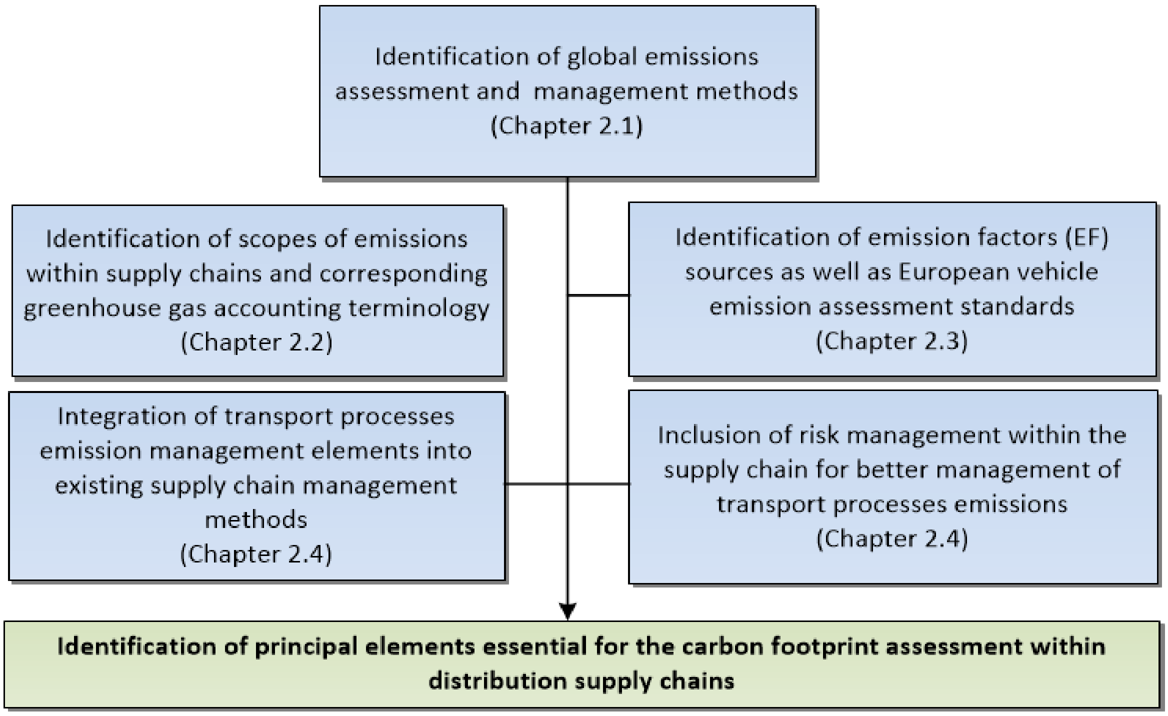


Fig. 2.1 Scope of the research presented within chapter 2
Source: own elaboration.

The purpose of this chapter is to examine the key elements involved in measuring the carbon footprint of transport processes. In addition to identifying emission sources, attention is given to the relevant legal frameworks and global management approaches. Since sustainable supply chains became the environment in which transport processes are carried out, the chapter also reviews how existing management practices influence emission reduction. Moreover, the perspective of risk management is considered as an important factor that can support the mitigation of the carbon footprint of transport activities within distribution networks.

2.1. Review of the methods of emissions assessment and management

The global recognition of climate change as a critical issue has led to the development of scientific, policy and economic frameworks for the measurement, management and reduction of greenhouse gas (GHG) emissions. The motivating factors identified in **Chapter 1.1** point to the need to adapt to legal regulations. Due to the great diversity of economies in different world regions, numerous approaches supporting measuring and reporting the carbon footprint of logistics processes, including transport, have emerged around the world. The most important methods identified are listed in **Tab. 2.1** below. The gathered information in table is grouped by the world region.

Tab. 2.1 Review of the emissions assessment methods by world region

Source: own elaboration based on Dubisz and Golinska-Dawson (2021).

Worldwide applicable methods	European methods	North American methods	Asia-Pacific methods
Carbon Disclosure Project	French Bilan Carbone	US Regional Greenhouse Gas Initiative	Japanese Voluntary ETS (J-VETS)
WBCSD/WRI GHG Protocol	EU Emissions Trading Scheme	US Climate Registry General Reporting Protocol	Japanese GHG Reporting Scheme
IPCC 2006 GHG Workbook	UK Department for Environment, Food and Rural Affairs (DEFRA) Guidelines	USEPA GHG Rule	Australian Carbon Pollution Reduction Scheme
ISO 14064: 2006 (Parts 1 and 3)	UK Carbon Reduction Commitment (CRC)	US Securities and Exchange Commission (SEC) Guidance	Australian National Greenhouse and Energy Reporting Scheme
Climate Disclosure Standards Board (CDSB)	UK Climate Change Levy Agreement (CCLA)	Californian Climate Action Registry	
Enterprise Carbon Accounting	Dutch Energy Covenant	US EPA Climate Leaders Inventory Guidance	
International Local Government GHG Emissions Analysis Protocol	The Carbon Trust Standard	Environment Canada GHG Emissions Reporting Program	
Global Reporting Initiative		Chicago Climate Exchange	
API/IPIECA GHG Compendium		US GHG Protocol Public Sector Standard	

The analysis of available methods, regulations, guidelines, and legal frameworks for measuring the carbon footprint of transport processes identified that numerous measurement and emission management methods are in use worldwide at the national (J-VETS - Japanese Voluntary ETS) or continental (EU ETS - European Trading Scheme) level. Simultaneously, some of the approaches also indicate precise emission factor values (US DEFRA - UK Department for Environment, Food and Rural Affairs and US EPA - Climate Leaders Inventory Guidance), However, not all methods provide emission factors. The reliable sources of emission factors used to assess emission levels are outlined in chapter **2.3**. Reference is also made to the emission factors published by UK DEFRA, which has been used in the new model for managing the carbon footprint of transport processes within sustainable supply chains. The UK Department for Environment, Food and Rural Affairs (DEFRA) emission factors were considered due to their universal nature. However, in order to precisely define the scope of a new model for measuring and managing transport emissions, it is necessary to conduct further analysis of the most relevant regulations, guidelines, and frameworks affecting transport processes in a specific area. Therefore, this was followed by an in-depth analysis of the approaches that have the greatest impact on distribution supply chains operating transport processes across Europe. The **Tab. 2.2** below presents the essential methods and indicates their area of impact. Additionally, it was determined whether the method is mandatory or voluntary for entities.

Tab. 2.2 The regulatory framework and methods for assessing emission levels most relevant in Europe.
Source: own elaboration.

Method or regulatory framework	Coverage, country or region of influence	Functional scope	Regulatory status
UK DEFRA Guidelines	UK	GHG accounting and reporting	Guidance
ISO 14064:2006 (Parts 1 & 3)	International	GHG accounting and verification	Guidance
GHG Protocol (WBCSD/WRI)	International	GHG accounting and reporting	Guidance
EU Emissions Trading Scheme (EU ETS)	EU	Emissions Trading Market	Mandatory
UK Carbon Reduction Commitment (CRC)	UK	Regulatory or compliance	Mandatory
UK Climate Change Levy Agreement (CCLA)	UK	Regulatory or compliance	Mandatory for specific economy branch companies, voluntary for medium and small businesses
French Bilan Carbone	France	GHG accounting and reporting	Voluntary
Dutch Energy Covenant	Netherlands	Voluntary disclosure, opportunity for organisation's process improvement	Voluntary
The Carbon Trust Standard	UK	Voluntary Certification	Voluntary
Carbon Disclosure Project (CDP)	International	Voluntary Disclosure & Transparency	Voluntary

The UK DEFRA Guidelines are published by the Department for Environment, Food & Rural Affairs (DEFRA) to help organisations measure and report their greenhouse gas (GHG) emissions. These guidelines provide standardized emission factors and methodologies for calculating emissions from various activities, including energy use, transportation, waste, and industrial processes. They are updated annually to reflect the latest scientific data and are aligned with international standards like the GHG Protocol. While not legally binding for all organisations, they are often used to support compliance with other UK regulations such as the Streamlined Energy and Carbon Reporting (SECR) framework. Public sector bodies, companies, and consultants frequently use DEFRA's emission factors for consistency and comparability in reporting. The guidelines aim to promote transparency, improve the quality of environmental disclosures, and support the UK's climate change objectives. One of the principal advantages of this methodology is its capacity to generate precise indicators for the quantification of greenhouse gas (GHG) emissions based on fuel consumption across various modes of transportation, including road, rail, air, and intermodal systems. The total carbon footprint associated with distribution activities can be calculated using parameters such as fuel consumption, distance travelled, and vehicle classification according to Gross Vehicle Mass (GVM) categories. Moreover, the method facilitates the assessment of emissions arising from energy-intensive processes, with energy consumption quantified in kilowatt-hours (kWh). The resulting emissions are expressed in terms of carbon dioxide equivalents ($kgCO_2e$), with the potential for a more detailed disaggregation into constituent gases such as methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O). Despite its analytical rigor, the method presents a significant challenge due to the complexity inherent in the measurement and calculation of final emissions. The application of published emission factor tables necessitates a high degree of specificity and accuracy in the parameterisation of internal processes to ensure the validity and reliability of the resulting carbon footprint estimations.

ISO 14064:2006 is an international standard that provides a framework for quantifying, reporting, and verifying greenhouse gas (GHG) emissions and removals. Part 1 focuses on organisational-level GHG inventories, guiding how companies measure and report emissions across Scopes 1, 2, and optionally Scope 3. It includes requirements for defining boundaries, selecting methodologies, and ensuring consistency and transparency. Part 3 covers the validation and verification of GHG statements, setting out principles and procedures for third-party assurance. This part is especially useful for organisations seeking independent verification of their emissions data for regulatory, voluntary, or financial disclosure purposes. Together, the standard supports credible, comparable, and internationally recognized GHG reporting.

The GHG Protocol is the most widely used international standard for accounting and reporting greenhouse gas emissions. Developed by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD), it provides comprehensive guidance for organisations to measure and manage their emissions. The Protocol divides emissions into three scopes: direct emissions (Scope 1), indirect emissions from purchased energy (Scope 2), and all other indirect emissions across the value chain (Scope 3). It includes separate standards for corporate reporting, project-level accounting, and value chain (Scope 3) assessments. Many governments and reporting initiatives, like CDP and ISO 14064, align their frameworks with the GHG Protocol. Its goal is to promote transparent, consistent, and credible emissions reporting worldwide.

The EU Emissions Trading Scheme (EU ETS) is the European Union's flagship policy for reducing greenhouse gas emissions through a market-based mechanism. It operates on a cap-and-trade principle, where a limit is set on the total emissions allowed from covered sectors such as power generation, manufacturing, and aviation. Companies receive or buy emission allowances, which they can trade with one another depending on their actual emissions. The cap is reduced annually, driving gradual emissions reductions over time. The EU ETS is mandatory for large emitters and has been a central tool in the EU's strategy to meet its climate targets under the Paris Agreement. Emission allowances are tradable on a unified market platform, enabling flexibility among participants. In the long term, member states that invest in renewable energy can potentially sell their surplus allowances to countries reliant on fossil fuels and requiring additional emissions capacity. A key challenge, however, is the absence of a universally accessible tool for calculating carbon footprints. While the framework permits the use of various validated methodologies, these approaches may vary significantly in scope and results (Quemin, 2022). The J-VETS method has a functional scope that is comparable to that of the EU ETS. Its primary assumptions are focused on limiting greenhouse gas emissions from the major emitters and regulating the trade of emission allowances. J-VETS is a cap-and-trade scheme that operates in Japan. Herrador et al. (2022) state that the main challenge of the J-VETS scheme is its regional character, which limits its incorporation in locations other than Japan. However, it must be admitted that the general logic of this method is comparable to that of the EU ETS. It provides even more detailed information about specific emission factors.

The UK Carbon Reduction Commitment (CRC) was a mandatory emissions reduction scheme aimed at improving energy efficiency in large public and private sector organisations. Launched in 2010, it targeted entities that used more than 6000 MWh of electricity. Participants were required to monitor their energy use, report emissions annually, and purchase allowances to cover their carbon output. The CRC aimed to reduce emissions in sectors not covered by the EU ETS, particularly commercial buildings and the public sector. It also included a financial incentive through league tables that ranked participants based on their energy performance. The scheme was closed in 2019, replaced by the Streamlined Energy and Carbon Reporting (SECR) and adjustments to the Climate Change Levy.

The UK Climate Change Levy Agreement (CCLA) is a voluntary scheme that allows energy-intensive industries to receive discounts on the Climate Change Levy (CCL), a tax on energy use. To qualify for the discount, organisations must enter into agreements committing to improve their energy efficiency or reduce carbon emissions over a set period. These agreements are negotiated between industry trade associations and the UK government, with the Environment Agency overseeing compliance. Participants who meet their targets receive up to 90% discount on electricity and 65% on gas CCL rates. The scheme supports competitiveness while encouraging investment in energy-saving technologies. It plays a key role in the UK's strategy to reduce industrial emissions and transition to a low-carbon economy.

The French Bilan Carbone is a carbon accounting methodology developed by ADEME (the French Environment and Energy Management Agency) to help organisations, municipalities, and individuals measure their greenhouse gas emissions. It takes a comprehensive life-cycle approach, covering direct (Scope 1), indirect energy-related (Scope 2), and other indirect emissions (Scope 3) such as transportation, purchased goods, and services. The tool is widely used in France and has influenced emissions reporting practices across Francophone countries. It encourages users not only to quantify their carbon footprint but also to identify emission hotspots and reduction strategies. The methodology is compatible with international standards like the GHG Protocol and ISO 14064, but emphasizes educational value and participative engagement. Organisations that use Bilan Carbone often apply it to develop action plans for carbon neutrality or climate resilience.

The Dutch Energy Covenant refers to a series of voluntary agreements between the Dutch government and industrial sectors aimed at improving energy efficiency and reducing greenhouse gas emissions. These agreements, such as the Long-Term Agreements (LTA) and the Energy Agreement for Sustainable Growth, involve companies committing to energy-saving targets over multi-year periods. In return, participants receive regulatory relief, support, and recognition from the government. The covenant approach emphasizes collaboration, transparency, and continuous improvement, often including sector-specific benchmarks and reporting requirements. It has played a key role in mobilizing private sector engagement in national climate policy without imposing binding legal obligations. The model is considered a best practice for fostering voluntary climate action through negotiated commitments and shared accountability.

The Carbon Trust Standard is a voluntary certification awarded to organisations that demonstrate real and measurable reductions in their carbon footprint. It is issued by the Carbon Trust, a UK-based organisation that helps businesses, governments, and institutions transition to a low-carbon economy. To achieve the standard, companies must provide verified data showing year-on-year reductions in greenhouse gas emissions, as well as evidence of effective carbon management practices. The certification covers not just emissions but also how organisations embed sustainability into operations and decision-making. It serves as a credible, independent endorsement of an organisation's climate leadership and commitment to continuous improvement. Many organisations use the Carbon Trust Standard to enhance their environmental reputation and meet stakeholder expectations.

The Carbon Disclosure Project (CDP) is a global non-profit organisation that runs the world's leading environmental disclosure platform. It invites companies, cities, states, and regions to voluntarily report their greenhouse gas emissions, climate risks, and environmental strategies. CDP provides standardized questionnaires covering climate change, water security, and deforestation, which organisations submit annually. The data is used by over 700 institutional investors and stakeholders to assess environmental performance and inform decision-making. High-performing respondents are publicly recognized through CDP scores, encouraging transparency and climate leadership. By promoting disclosure and accountability, CDP helps drive action toward a low-carbon, sustainable economy. The Carbon Disclosure Project (CDP) provides a standardized framework for assessing carbon footprint levels, accompanied by publicly available rankings that disclose the carbon footprints of participating entities. The global scope of the initiative, combined with its parameterized methodology for quantifying greenhouse gas (GHG) emissions at each stage of the supply chain, enhances the methodological credibility and facilitates its adoption among leading international producers. Its principal strengths lie in its universal applicability and the high degree of investor confidence in the data it disseminates. However, a significant methodological concern involves ensuring the validity, consistency, and robustness of the input data necessary for conducting such complex assessments. The research, based on data from 19 Indonesian companies, allowed to verify the significance of various organisational parameters in the context of CDP emissions reporting. The focus was on company size, the size of the board of directors and its independence of decision making process (Riantono and Sunarto, 2022). It has been verified in relation to CDP emissions reporting. It was identified that the most difficult aspect of obtaining reliable information was the complexity of supply chains and their diverse character, which hinders the standardisation of the assessment process. The assessment of emission levels requires an individual approach in each specific case. Based on the analysis conducted, several fundamental distinctions were identified among the examined methods. These differences primarily concern:

- the level of detail in the measurement processes, which varies from high-resolution, process-specific data to more generalized estimations.
- the intended function or goal of each method, ranging from regulatory compliance and internal benchmarking to external reporting and performance optimisation.
- the comprehensiveness of the procedural descriptions for evaluating process-related emissions, with some methodologies offering detailed step-by-step guidelines while others provide only high-level frameworks.
- the approaches used to interpret the outcomes, including whether the results are quantitative, qualitative, or based on comparative indicators.
- each method aligns or integrates with existing tools, benchmarking systems, and established quality or sustainability standards.

The comparative analysis of various management methods and conceptual frameworks revealed that, due to their design characteristics and operational objectives, these approaches are inherently compatible with the principles of Low Carbon Supply Chain Management (LCSCM). LCSCM, as defined by Das and Jharkharia (2018, page 403) is "a strategy that integrates CO_2, CO_2-equivalent, or greenhouse gas emissions as a constraint or target in supply chain design and planning." This concept underscores the growing need to embed carbon reduction considerations directly into the core structure of supply chains. Research in the field of LCSCM is broadly categorized into two principal thematic domains:

- the operational aspects of supply chain management, which include procurement, production, distribution logistics, network configuration, and coordination among supply chain actors.
- resource efficiency and carbon accountability dimension, which emphasizes optimal resource utilisation, accurate carbon accounting, and effective management of an organisation's overall carbon footprint.

In the development of a new CF assessment model, supported by dedicated digital tool focused on the perspective of carbon footprint of distribution transport processes. The emphasis was placed specifically on the operational components of supply chain activities—particularly distribution and freight transport, which are significant contributors to overall emissions according to literature reviewed. Following a comprehensive literature review, a critical assessment of existing management methodologies, and an in-depth examination of the LCSCM framework, several essential criteria were outlined and further incorporated in new CF assessment model. General assumptions were perceived:

- A new CF assessment model must demonstrate compliance with current regulatory frameworks, particularly those applicable within the European Union, and be grounded in the strategic guidelines outlined by the European Green Deal.
- The emission calculation model must account for the full spectrum of emission sources, including both direct emissions (e.g., fuel combustion in vehicles) and indirect emissions (e.g., emissions from energy production or outsourced logistics operations). The supplementary calculation tool should empower users to evaluate the carbon impact of processes based on clearly defined emission categories.
- The new emission assessment model must rely on standardized emission factors for the quantification of emissions, ensuring consistency, comparability, and scientific accuracy in the evaluation of transport-related emissivity.

The research approach supports the precision, usability, and relevance of carbon footprint assessments in the transport sector, while ensuring alignment with global sustainability objectives and industry best practices. Detailed research of existing methods has identified that, in terms of the new management model dedicated to the management of the carbon footprint of transport processes, the following guidelines should be considered: the GHG Protocol, as a document setting out the main guidelines and logical foundation for environmental evaluation, and PAS 2050, which supplements the GHG Protocol with an LCA approach if necessary. Another important element determining the quality of the assessment and result in usability of evaluation must be possibility of inclusion of results in the decision-making process, supported by recognised decision making solution. The final classification of emissions has to cover all identified emission scopes. This will ensure compliance with international standard ISO 14064 and GHG Protocol. Essential factors used in the calculations will include coefficients published by UK DEFRA due to their precise scope relating to vehicle capacity, fuel type, vehicle GVM and enabling the conversion of emissions from one kilometre travelled. The EU ETS Cap and Trade Scheme has been chosen as the foundation for the reporting logic of international companies within the European Union according to the CSRD Directive (along with ESRS guidelines). In the event of limited data on kilometres travelled, the coefficients published by the US EPA could be used when it is necessary to carry out an assessment from the perspective of fuel consumed. The conducted analysis of global methods, standards, frameworks and guidelines for measuring and reporting carbon footprints, as well as case study-based literature review indicating methods of their application, revealed essential differences between the methods presented in **Tab. 2.3** below.

Tab. 2.3 Comparison of key standards, frameworks and guidelines for managing and measuring emissions

Source: own elaboration.

Standard, Framework, Guidelines	Organisation issuing the standard, framework, guidelines	Scope of impact	Purpose	Scope of Application	Emission Coverage (Scopes)	Methodological approach	Data Requirements	Purpose of use
GHG Protocol	World Resources Institute & World Business Council for Sustainable Development (WRI & WBCSD)	Global	Corporate, supply chain, and product GHG accounting	Organisations, supply chains, products	Scope 1, 2, and 3	A framework setting out guidelines and principles for the reliable assessment of carbon footprints in various organisations, companies and supply chains. Covering a very broad scope.	Flexible approach. From a highly detailed approach to calculations to a more general.	Organisation, process, or product
PAS 2050	British Standards Institution (BSI)	International but UK dedicated	Estimation of product carbon footprint along with LCA assessment	Products and services	Life cycle GHG emissions	Focus on product LCA, including its carbon footprint	In order to carry out a life cycle assessment in a reliable way, detailed data is required.	Product or service
ISO 14064	International Organisation for Standardisation (ISO)	Global	Quantification and verification of the carbon footprint of the organisation implementing the standard.	Organisations and GHG projects	Scope 1, 2, 3	A standard suitable for application within the existing supply chain. A set of guidelines on how to measure the carbon footprint of various logistics processes.	Depending on the user's needs and the purpose of the evaluation results.	Organisation or project

Standard, Framework, Guidelines	Organisation issuing the standard, framework, guidelines	Scope of impact	Purpose	Scope of Application	Emission Coverage (Scopes)	Methodological approach	Data Requirements	Purpose of use
US EPA	United States Environmental Protection Agency (US EPA)	U.S. dedicated	U.S. Government published guidance and emission factors supporting carbon footprint assessment of organisation and services	US-based facilities and organisations	Scope 1, 2, 3	Guidelines for assessment supported with emission factors	Flexible approach. From a highly detailed approach to calculations to a more general.	Process or service
UK DEFRA	UK Department for Environment, Food and Rural Affairs (UK DEFRA)	UK dedicated	UK Government published guidance and emission factors supporting carbon footprint assessment of organisation and services	UK based organisations and reporting entities	Scope 1, 2, 3	Guidelines for assessment supported with emission factors	Flexible approach. From a highly detailed approach to calculations to a more general.	Organisation, process, or product
EU ETS	European Commission (EC)	The European Union area. It also covers non-EU companies offering services within the EU (Aviation industry).	"Cap and trade" system for CO_2 emissions	EU based companies. Production plants, industry and aviation sectors. It also covers non-EU companies offering services within the EU (Aviation industry).	Scope 1 - direct emissions	A framework supporting the measurement and reporting of emissions resulting from the carried out processes.	Very detailed, requires continuous monitoring of processes and reliable reporting within the "cap and trade" system.	Industry installation organisation or reporting service provider

In the next step, selected guidelines and frameworks were analysed in terms of the use of their elements in a new model for measuring and managing the carbon footprint of transport processes. The analysis results are presented in **Tab. 2.4.**

Tab. 2.4 Further verification of essential parameters of selected global methods. Assessment of the adaptability of elements in the New Evaluation Method for Emissions Assessment of Transport Processes.
Source: own elaboration.

Standard, Framework or Guidelines (SFG)	Compatibility	Calculation tool to support the assessment	Supports Corporate ESG reporting	Enables logistics processes assessment within Sustainable Supply Chain	Supports LCA of product	Adaptability of SFG elements in the New Approach to Measuring and Managing the Carbon Footprint of Transport Processes
GHG Protocol	ISO 14 064, CDP, SBTi	Yes. Excel spreadsheet and product standards	Yes	Yes	Yes	Yes
PAS 2050	ISO 14040/44 (LCA standards)	No. Framework and guidelines only.	No. PAS2050 is designed to address mainly the methodological aspects of product LCA, additionally including its carbon footprint.	No	Yes	No
ISO 14064	GHG Protocol, CDP	No. Framework and guidelines only.	Yes	Yes	Limited as ISO 14 064 is designed to address mainly the methodological aspects of organisation and overall process carbon footprint. LCA is not a main	Yes

Standard, Framework or Guidelines (SFG)	Compatibility	Calculation tool to support the assessment	Supports Corporate ESG reporting	Enables logistics processes assessment within Sustainable Supply Chain	Supports LCA of product	Adaptability of SFG elements in the New Approach to Measuring and Managing the Carbon Footprint of Transport Processes
					focus of this standard.	
US EPA	Limited alignment with ISO 14 064	Yes. Simplified GHG emission calculator is provided along with emission factors.	Yes	Depending on the level of detail of the data used for GHG assessment.	No	No
UK DEFRA	Limited alignment with ISO 14 064	Yes. Emission factors are supported by CF reporting template.	Yes	Depending on the level of detail of the data used for GHG assessment.	No	Yes
EU ETS	Aligns with ISO 14 064 and its results are comparable with other global MRV (Monitoring, Reporting, and Verification) frameworks	Yes. EU ETS Cap and trade system is supported by ETS Reporting Tool dedicated for industry, templates and calculators.	Yes	No	No	No

The analysis revealed a lack of adequate methods to support the management process from an emission-level perspective. However, it should be noted that each of the reviewed methods provides valuable information and recommendations on how to improve the effectiveness of measuring the carbon footprint of various processes, including transport operations. The new transport process management model must refer to the guidelines and recommendations presented in existing methods to ensure consistency with global trends in the area of sustainable supply chains development.

Due to the needs of transport companies revealed in expert research (**Chapter 3.2),** it is necessary to incorporate emissions-based process management into existing management methods. Conclusions drawn from the literature and expert research indicate the need for changes in existing processes to be implemented in an evolutionary manner rather than revolutionary.

The identification and analysis conducted indicated that the GHG Protocol as having the greatest potential for using logic foundations in estimating the emissions from the transport process. It is also possible to incorporate its elements into the decision-making process within a new management approach to transport processes from the perspective of their emissions. The GHG Protocol approach is consistent with ISO quality standards. This method of measuring carbon footprint covers emissions within different scopes (1, 2, 3 downstream, upstream and direct). The GHG Protocol allows the use of elements of the logic framework in assessing the level of emissions from transport processes, as well as from products (LCA).

GHG Protocol

As stated above in the initial assessment of worldwide methodologies conducted in this chapter, the Greenhouse Gas (GHG) Protocol is the most widely used international accounting tool for government and business leaders to understand, quantify, and manage greenhouse gas emissions. Developed through a multi-stakeholder partnership convened by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD), the GHG Protocol provides comprehensive global standardized frameworks to measure and manage emissions from private and public sector operations, value chains, and mitigation actions. Due to the dominant nature, widespread use, global recognition of the method and numerous references to the GHG Protocol in the literature, it was decided to conduct an in-depth analysis of the logic of assessing the level of process emissions presented in this international set of guidelines. The GHG Protocol is composed of a suite of standards and guidance documents that cover different levels and types of greenhouse gas (GHG) accounting and reporting. Its structure is designed to address both corporate-level and project-level emissions, as well as emissions across the value chain. The core scope of the emissions measurement covered by this guidance is presented in Fig**. 2.2** below.

GHG Protocol Standards (WRI & WBCSD) coverage and composition						
General Corporate Accounting and Reporting Standard (Covers Scope 1, Scope 2 and Scope 3 emissions)	Scope 2 guidance supporting Accounting and Reporting Standard regarding purchased electricity, heat and cooling	Scope 3 guidance supporting emission assessment across whole Corporate Value Chain. Supports both downstream and upstream emissions	Product LCA (Life Cycle Assessment) standard supporitng product carbon footprint evaluation	Project Accounting standard supporting CF mitigation within specific project (not entire supply chains and value chains)	City-dedicated CF assessment guidances for Cities and communities. Supports urban carbon footprint assessment	Guidance and reporting standards for land use and removals-related emissions.

Fig. 2.2 GHG Protocol Standards for organisation's carbon footprint assessment decomposition
Source: own elaboration.

Each of the dedicated emission assessment standards proposed under the GHG Protocol should be verified individually and selected according to the processes carried out in the company. For companies carrying out transport processes, the focus should be on the first three standards indicated in **Fig. 2.2.**

Considering the detailed guidelines indicating the logic behind assessing the carbon footprint of transport processes within supply chains, the components of the GHG Protocol specified in the General Corporate Accounting and Reporting Standard and Scope 2 and Scope 3 guidance for supporting emissions are important from the perspective of a new model for transport emissions management within sustainable supply chains. An analysis of the General Corporate Accounting Standard and Scope 3 guidance indicates that three basic steps must be taken into consideration when assessing the level of emissions resulting from transport processes. The GHG Protocol provides a structured methodology for quantifying greenhouse gas emissions, broken down into a series of key steps. These steps are designed to ensure accuracy, consistency, transparency, and relevance across reporting entities. The general approach to measuring carbon footprint can be summarised in three following steps presented in **Fig. 2.3**

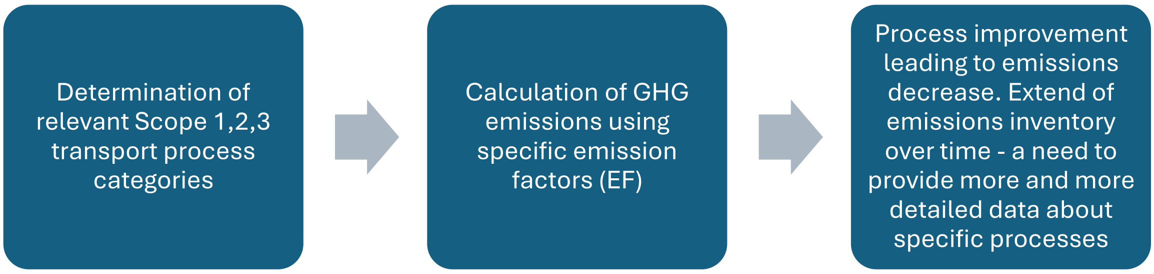


Fig. 2.3 Key GHG emissions evaluation steps within transport processes based on GHG Protocol
Source: own elaboration based on WRI and WBCSD (2004).

The general logic of measurement under the GHG Protocol is presented in **Fig. 2.3** but it is necessary to clearly comprehend how to interpret and assign individual transport processes to specific categories and scopes. The detailed scope of each Scope 1, 2 and 3 type is presented in chapter **2.2.** However, due to the need to focus on measuring emissions arising from transport operations, and the possibility of incorporating emissions measurement and management into a new model of transport process control within sustainable supply chains, a detailed analysis was required. **Tab. 2.5** below shows how the scopes are split into categories and emission types. Additionally, the table provides guidance on interpreting the scope in the context of reporting emissions from transport processes.

Tab. 2.5 Analysis of GHG Protocol Scope decomposition in the context of transport processes
Source: own elaboration.

Scope Name	Emission Type *(Upstream, Downstream, Direct)*	Scope or category explanation in terms of transport or means of transport related emissions
Scope 1	Direct	Emissions from owned or controlled transport means of transport. Emissions resulting from company owned trucks
Scope 2	Direct (indirect energy)	Emissions from purchased electricity, used to power Electric Vehicles
Scope 3 - Category 1. Purchased Goods and Services	Upstream	Emissions from transport of raw materials and goods before reaching the company.
Scope 3 - Category 3. Fuel- and Energy-Related Activities	Upstream	Emissions from producing and transporting fuels used in transport vehicles.

Scope Name	Emission Type *(Upstream, Downstream, Direct)*	Scope or category explanation in terms of transport or means of transport related emissions
Scope 3 - Category 4. Upstream Transportation and Distribution	Upstream	Emissions from third party logistics providers transporting goods to the company. Covers all outsources transport services. Transport of supplies into the company's location within supply chain.
Scope 3 - Category 6. Business Travel	Upstream	Emissions resulting from employee travel via plane, train, or cars. However, those means of transport can't be owned by a company.
Scope 3 - Category 9. Downstream Transportation and Distribution	Downstream	Emissions from third party logistics service provider transporting goods from the company to end customers. Distribution transport to the end customers executed by external transport service providers.
Scope 3 - Category 11. Use of Sold Products	Downstream	Emissions from the fuel combustion of manufactured means of transport. This category covers emissions generated by the end-user during the operation of the product, especially from burning fuel or electricity while the product is being used for transport.

The detailed scope used for the appropriate classification of transport process types has been defined in a separate **chapter 2.2**, but in order to indicate the significance of individual scopes in the new transport process management method from the perspective of their emissions, it is important to correctly define the scopes specified in **Tab. 2.5** above. Therefore, the new model must cover processes undertaken by own transport (Scope 1, Direct emissions), charging of electric vehicles for transport processes (Scope 2) and supply transport processes undertaken by a fleet of rented vehicles (Scope 3, Upstream), as distribution transport processes carried out to end customers by a rented fleet (Scope 3, Downstream).

GHG Protocol CF main assessment approaches

The assessment of CO_2 emissions in accordance with the GHG Protocol guidelines should be performed using one of three approaches. The fuel-based method refers to the number of different types of fuel consumed by various vehicles. In this approach it is necessary to determine the number of litres or kWh of fuel consumed to power the vehicles. According to GHG Protocol guidelines this approach is suitable for Scope 1 and Scope 2. However, it is still important to use appropriate emission factors. The GHG Protocol guidelines indicate the possibility of using existing emission factors published by the UK DEFRA or US EPA. The second method refers to the distance-based method and covers all emissions Scopes. After determining the distance travelled and indicating the types of means of transport used for the transport processes, it is possible to precisely define the carbon footprint, taking into account the GVM of the vehicles. The third approach to assessing the level of emissions from transport processes refers to costs. The spend- based method allows the level of emissions to be estimated on the basis of recorded transportation costs. This method is mainly reserved for assessing emissions related to business travel. Assessing the level of emissions for the transportation of goods would be ineffective due to the large differences in freight rates resulting from the current market situation and their spot nature.

An important element of assessing the carbon footprint of processes is determining how GHG emissions are going to be evaluated. Based on an analysis of the guidelines presented in GHG Protocol Category 4: Upstream Transportation and Distribution, it has been identified that the method of assessing transport process emissions depends on the level of detail of the basic data used for the analysis. The logic of the evaluation in the case of available detailed data on transported goods and in the case of limited data is presented in **Fig. 2.4** below.

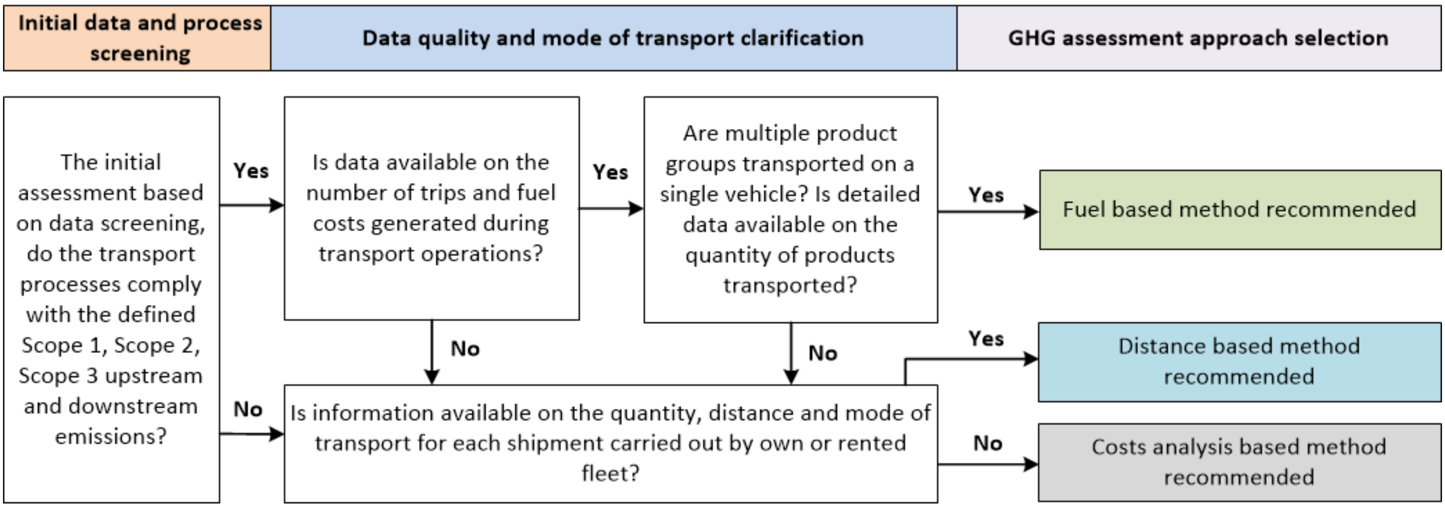


Fig. 2.4 Decision points of emissions assessment for measuring Scope 1,2,3 emissions specified in the GHG Protocol
Source: own elaboration based WRI and WBCSD (2013).

Each of the approaches proposed in the GHG Protocol guidelines requires an appropriate calculation method. The GHG protocol sets of guidelines provide precise calculation formulas for determining fuel consumption based on recorded costs or vehicle weight and weight emissions assessment. The most essential basic calculation formulas that need to be considered in the new approach to measuring and managing the carbon footprint of transport processes are presented below. **Formula 1** below shows how to assess the carbon footprint for different types of combusted fuel. This fuel based formula can be applied for heterogeneous fleets CF assessment, composed of various fuel powered vehicles.

Formula 1 GHG Protocol CF calculation formula supporting fuel-based method
Source: own elaboration based on WRI and WBCSD (2013).

$$\Sigma_{(\text{sum across fuel types})} = Quantity\ of\ fuel\ consumed\ _{(litres)} * Emission\ Factors\ for\ fuels_{(kgCO2e/litre)}$$

A valid CF assessment of transport processes within sustainable and transport-oriented supply chains must cover the indirect emissions of electric vehicles. According to the GHG Protocol, emissions related to transport processes involving electric vehicles can also be included. However, since electric vehicles do not emit CO_2 themselves, the composition of emissions related to the production of 1 kWh must be considered. These values may vary depending on the region or country. This is related to the different energy mixes of local economies, which indicate the sources of electricity production. Therefore, local emission factors for the production of 1 kWh must be considered when assessing emission levels. The following **Formula 2** shows the approach to estimate emissions associated with the execution of transport processes using electric vehicles.

Formula 2 GHG Protocol Carbon Footprint calculation formula supporting the assessment of the carbon footprint of electric vehicles.
Source: own elaboration based on WRI and WBCSD (2013).

$$\Sigma_{\left(\substack{\text{sum across}\\ \text{grid regions}}\right)} = Quantity\ of\ electricity\ consumed\ _{(kWh)} * Emission\ Factors\ for\ electricity\ _{\left(\frac{kgCO2e}{km}\right)}$$

The GHG Protocol's baseline approach, which provides the most accurate CF assessment results, involves reference to the distance travelled. Knowledge of the distance travelled, vehicle weight and fuel type burned allows for a very precise assessment of the carbon footprint of transport processes. A simplified method of assessing the carbon footprint of transport processes according to this approach is presented in **Formula 3** below.

Formula 3 Calculation formula for the distance-based method concerning payload weight
Source: own elaboration based on WRI and WBCSD (2013).

$$\Sigma_{\binom{sum\ of\ mass}{related\ emissions}} = Mass\ of\ payload_{\left(\substack{tonnes \\ or \\ volume}\right)} * Distance\ travelled_{(km)} * Emission\ Factors_{\left(\frac{kgCO2e}{km}\right)}$$

The GHG Protocol outlines potential ways to assess carbon emissions depending on the quality and availability of data. It has been determined that in the new model for measuring and managing transport emissions within sustainable supply chains, the consideration of basic product parameters and distance will be essential in assessing the carbon footprint of transport processes. The GHG Protocol enables the assessment of emission levels based solely on cost parameters, however, this approach will hinder the management of transport processes, which is essential in the created methodology. Therefore, the fuel-based method and the distance-based method will be applied in the new approach.

The next **Fig. 2.5** shows the essential steps necessary to assess the level of transport emissions within sustainable supply chains. With regard to these steps, the corresponding functionality of the new model for measuring and managing the carbon footprint has been defined, thereby allowing the application gap to be further specified. Details of the functionality of the new approach are presented in **Fig. 2.5** below along with defined Application Gap based on the key assessment steps. The detailed scope of the new approach to carbon footprint measurement and management is presented in **chapter 4** and considers the broader context of the conducted research in terms of emissions measurement logic, sources of emissions factors and the significance of individual supply chain parameters influencing its design.

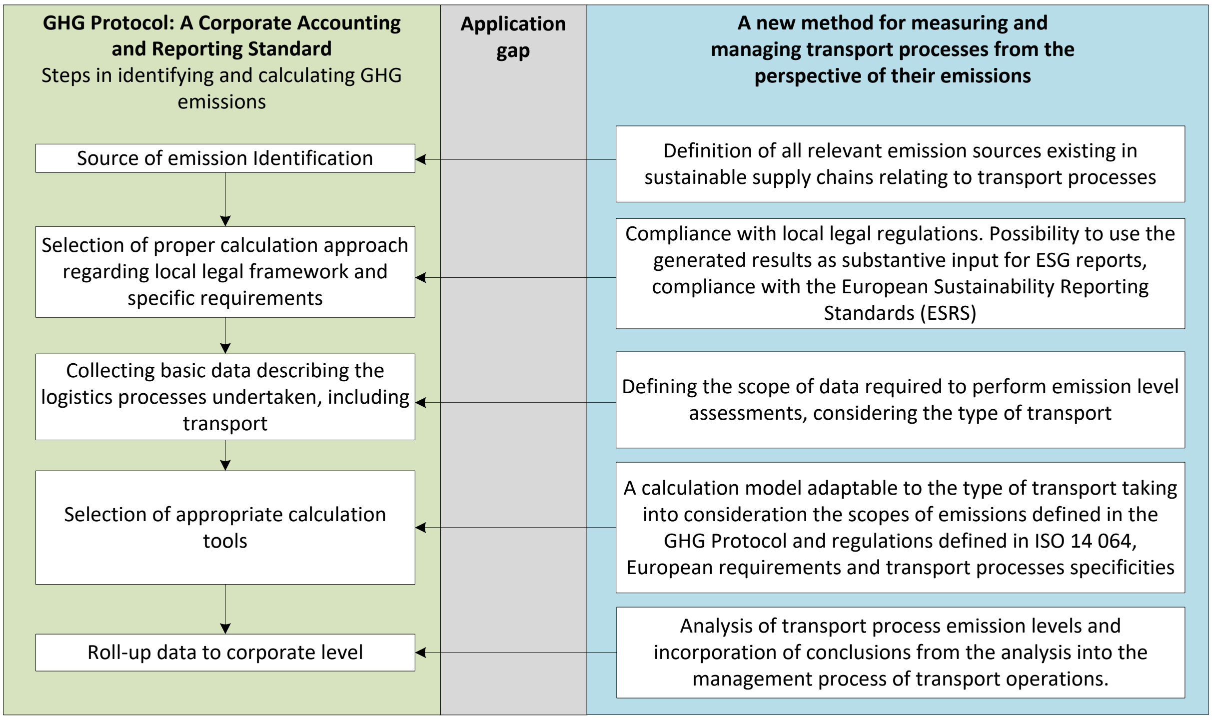


Fig. 2.5 Essential steps for measuring transport emissions as defined in the GHG Protocol A Corporate Accounting and Reporting Standard. Preliminary outline of the functionality of a new model for measuring and managing transport emissions. Application gap.
Source: own elaboration based on WRI and WBCSD (2004).

To define the application gap more precisely, the functionality of the new model and the supporting calculation tools for assessing the carbon footprint of transport processes were specified. Appropriate definition of the basic steps indicated in the GHG Protocol and alignment of the target functionality of the new CF management and measurement model allows the created measurement method to remain compliant with the global standard, and the results obtained to be used in annual non-financial ESG reports. As a response to the first step defined as 'Sources of emission identification', the new model will precisely point to the sources of emissions resulting from transport processes conducted within sustainable supply chains. Research based on a literature review will help identify essential participants, key points of the logistics network and stakeholders. Regarding the need to analyse local legal acts indicated in the GHG Protocol, it is necessary to respect the relevant legal acts in Europe. Therefore, an in-depth analysis of European and global acts determining the scope and range of carbon footprint assessment resulting from transport processes was conducted. The foundation of the new model for assessing the carbon footprint and incorporating environmental indicators into the decision-making process within the supply chain is to ensure its compliance with applicable legal acts, regulations and standards. Therefore, the new model is consistent with ESG reporting standards and directives, and the calculated CO_2e emission parameters will provide a reliable contribution to the company's emissions reports. According to both literature and the GHG Protocol assumptions, data quality and its coverage are crucial for the assessment of emission levels. Therefore, the new model will take into account differences in basic data quality, enabling the evaluation of emissions in supply chains characterised by low quality data, and supply chains gathering precise information on transport processes and transported goods. Supply chains incorporating more advanced tools such as ERP (Enterprise Resource Planning) and TMS (Transport Management System) allow more in-depth emission assessment based on high quality data. The classification between simplified and detailed emission assessments will be a core feature of the new carbon footprint measurement method, allowing the outcome parameters to be incorporated into the decision-making process. An important functionality of the new model for measuring and managing the carbon footprint of transport processes is the access to appropriate dedicated calculation models that take into account the GHG Protocol recommendation on the use of appropriate tools. By creating appropriate solutions to support carbon footprint assessment in multilayer and complex supply chains, it will be possible to perform evaluations for large data sets. Proposed calculation solution supporting a new CF assessment method will ensure that evaluations can be carried out in transport supply chains even of complex structure. However, it should be noted that the basic logic of measuring the carbon footprint of transport processes can be expressed in the following simplified formula (**Formula 4**). The detailed method of calculation depends indirectly on the selected Emission Factors, whose type determines the precise method of calculation.

Formula 4 Simplified formula for GHG assessment under GHG Protocol

Source: own elaboration based on WRI and WBCSD (2004).

$$\mathbf{Emissions} = \text{Activity Data} \times \text{Emission Factor}$$

The detailed method for calculating the emission levels of individual transport processes is set out in **chapter 2.3**. Each set of emission factors enforces the use of an appropriate calculation approach to ensure the reliability of the carbon footprint assessment process for transport processes. The GHG Protocol recommendation defined as 'Roll up data to corporate level' is reflected in the logic of the new CF assessment method. The proposed solutions enable the analysis of large data sets and the inclusion of the results of the CO_2 emissions assessment of transport processes in the decision-making process using a multi-criteria matrix, characteristic of the Multi-Criteria Decision Making (MCDM) approach. The carbon footprint evaluation result can be used as input for non-financial reports in corporations.

Norm ISO 14 064-1:2018 Greenhouse gases — Part 1: Specification with guidance at the organisation level for quantification and reporting of greenhouse gas emissions and removals

ISO 14064 is an international standard that provides guidelines for quantifying, reporting, and verifying greenhouse gas (GHG) emissions and removals (ISO, 2018a). It helps organisations measure their carbon footprint and manage their environmental impact more effectively. The standard is divided into three parts, addressing organisational-level emissions, project-level emissions reductions, and requirements for validation and verification. By following ISO 14064, organisations can enhance transparency, credibility, and consistency in their climate-related disclosures.

As presented in **Fig. 2.6**, the ISO 14064 standard (as identified in its Annex C) defines three basic steps for conducting an emission assessment. The first step is data collection, followed by mapping the organisational model for the execution of specific processes within the organisation. The subsequent stage is to determine all the restrictions, rules and principles of flow organisation. Hence, it is possible to proceed to the actual assessment of emission levels in different areas of the organisation, including a focus on the assessment of emissions related to the execution of transport processes.

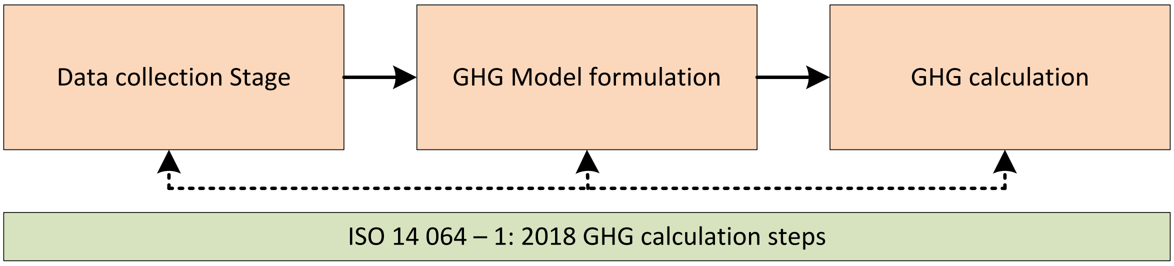


Fig. 2.6 Steps for assessing the carbon footprint of processes within an organisation in accordance with ISO 14 064:2018
Source: own elaboration based on ISO (2018b).

The data collection for transport processes involves gathering detailed information on fuel consumption and vehicle activity associated with organisational operations. This includes direct emissions (Scope 1) from company owned or controlled vehicles such as trucks, vans, and passenger cars. Additionally, information about fuel type, its quantity combusted, and distance are essential during the valid GHG assessment. For indirect emissions (Scope 3), organisations should also track outsourced transportation services including detailed information about modes of transport load weights, and transport order details. Reliable activity data should be matched with appropriate emission factors sourced from national inventories to estimate CO_2 emissions. Ensuring accurate and consistent data from fleet logs, fuel purchase records, GPS systems, and transport service providers is crucial for a robust and verifiable GHG inventory. The ISO 14064 standard does not provide precise guidelines on how to determine the CF of transport processes. It points to the need to use existing international methods such as the GHG protocol, PAS 2050, and EU ETS.

Under ISO 14064-1:2018, formulating a GHG inventory model involves developing a structured framework to quantify and report greenhouse gas emissions and removals across defined organisational and operational boundaries. This model must align with the principles of relevance, completeness, consistency, transparency, and accuracy. It typically includes categorizing emissions by scope direct (Scope 1), energy indirect (Scope 2), and other indirect (Scope 3)—and identifying relevant emission sources such as stationary combustion, mobile sources, purchased electricity, and outsourced activities. The inventory model relies on standardized calculation methodologies, combining activity data such as amount of fuel combusted, electricity consumption, distance travelled with corresponding emission factors. Assumptions, data sources, and calculation methods must be documented clearly to ensure traceability and facilitate verification.

ISO 14064 is structured into three parts that collectively support effective greenhouse gas (GHG) management. Norm ISO 14064 part 1 provides a framework for organisations to quantify and report their GHG emissions and removals, enabling them to assess their carbon footprint, set baselines, and monitor progress over time. Norm 14064 part 2 focuses on GHG reduction or removal enhancement projects, offering methodologies for planning, executing, and documenting CF mitigation initiatives. Norm ISO 14064 part 3 establishes requirements for independently validating and verifying GHG information, ensuring the reliability and integrity of reported data. Together, these standards promote a transparent, consistent, and verifiable approach to GHG accounting and reporting.

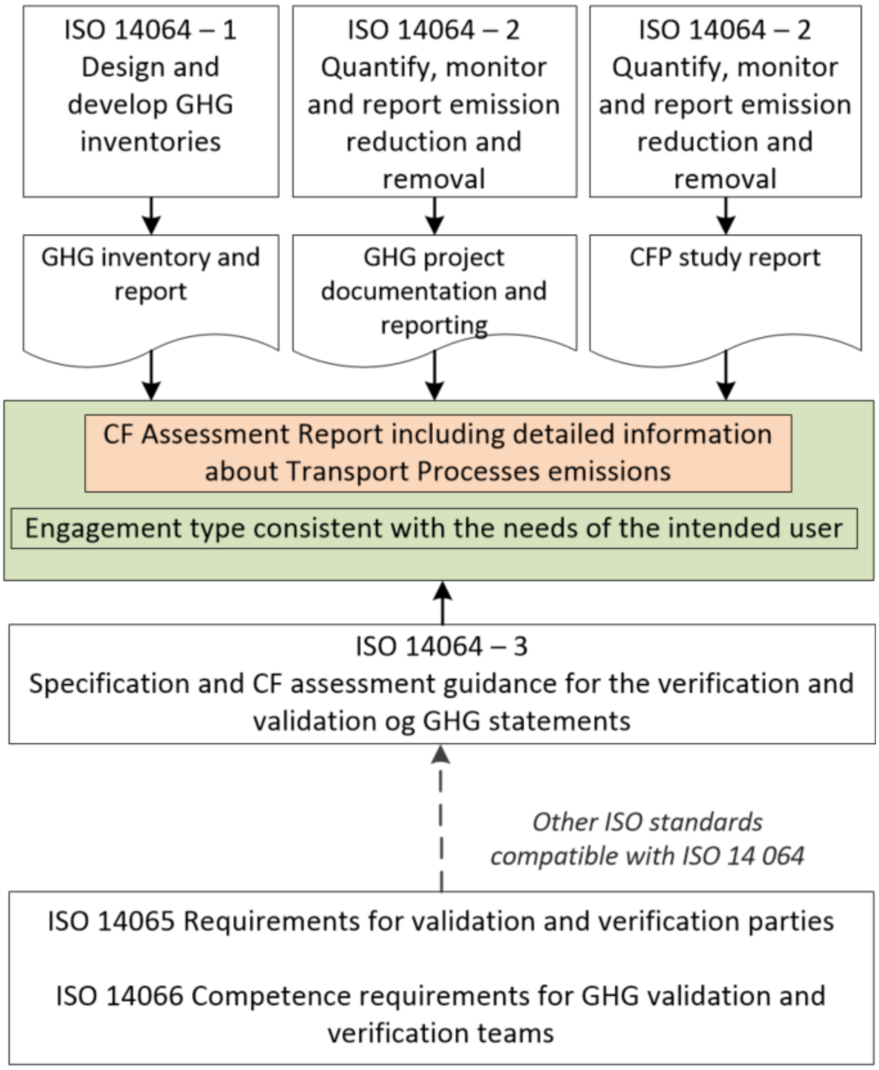


Fig. 2.7 Application of individual Parts of ISO 14 064:2018

Source: own elaboration based on ISO (2018b).

The carbon footprint (CF) assessment validation element presented in norm ISO 14 064 Part 3 is an important step in measuring the carbon footprint of transport processes. The new model for assessing the CF level of transport processes has therefore been validated, and the results are presented in **chapter 5**. These results were also utilized to formulate the final conclusions.

Properly designed GHG inventory model enables consistent year reporting and supports effective emissions management and reduction planning. ISO standard indicates recommendations for the structure of data in final result summaries in order to ensure compliance with the standard.

Appropriate presentation of carbon footprint measurement parameters enables their use in annual company reporting. Based on the provisions and recommendations presented in the standard the following **Fig. 2.8** presents template for the key CF assessment elements. The essential elements of the carbon footprint report indicate the need to report direct and indirect emissions and to determine the level of their mitigation. In the case of emissions storage within the organisation, this area should also be included in the annual CF report. Carbon Financial Instruments is a section where additional information on emission allowances, offsets and carbon credits should be provided. In addition to carbon dioxide emissions, the ISO 14064 standard indicates the need to define emissions of methane (CH_4) and nitrous oxide (N_2O). Hence all these elements have been taken into account in the new model for measuring and managing transport emissions. A CF reporting template based on ISO standard, containing all necessary elements has been prepared in **Appendix 1 - CF report template based on ISO 14064.xlsx**

Reporting organisation	*Full name of the reporting organisation*
Reporting period	*Date range*
Representatives	*Contact person details*
Process boundaries	*Attachment*
Reporting limitations	*Attachment*

Emissions						
	Total CO_2e	Carbon dioxide (CO_2)	Methane (CH_4)	Nitrouns oxide (N_2O)	Quantitative uncertainty [%]	Qualitative uncertainty [B-C]
Direct emissions and removals [tCO_2e] Category 1 - Direct emissions from transport combustion						
Indirect emissions [tCO_2e] Cathegory 3 - Indirect GHG emissions from transport						
Removals Direct removals in tonnes CO_2e						
Storage Total storage in tonnes CO_2e						
Carbon Financial Instruments Carbon Credit, Offset or Emission Allowance						
Other information All additional details identified as an important element of CF assessment and reporting						

Fig. 2.8 The template for the CF reporting based on the guidelines presented in the ISO 14064:2018 standard
Source: own elaboration based on ISO (2018b).

The norm ISO 14 064 allows for the determination of quantitative uncertainty levels in the annual companies' CF report. The uncertainty value can be expressed as a percentage. This element has also been taken into consideration in the new model for assessing the carbon footprint of transport processes. The new CF assessment model validation presented in **chapter 5** indicates the percentage uncertainty between the detailed approach and the simplified CF assessment approach within proposed model.

Simultaneously, ISO 14 064 allows the assessment of the level of uncertainty based on the assessment of the quality of input data. The proposed letter symbols from A to D allow, in the event of the inability to determine the percentage uncertainty of the emission assessment, the determination of a predefined uncertainty category. Predefined uncertainty categories for application in transport process emission reports are indicated in following **Tab. 2.6**

Tab. 2.6 Uncertainty categories under ISO 14064:2018
Source: own elaboration based on ISO (2018b).

Uncertainty category	Uncertainty Level	Transport processes data quality	Uncertainty category description
A	Low uncertainty	Very high quality of input data	Verified and complete input data enable a highly reliable assessment of transport process emissions. No assumptions required for CF evaluation due to the very high quality of input data.
B	Moderate uncertainty	High to moderate quality of input data	Good quality data allows for a reliable assessment of the level of emissions from transport processes. The assumptions are necessary for CF evaluation.
C	High uncertainty	Moderate to low quality of input data	Limited input data allows for the assessment of the level of transport process emissions based on the adopted assumptions. Higher error rate during CF assessment.
D	Very high uncertainty	Poor quality of input data	Data gaps or low-quality input data allow for a limited assessment of the level of transport process emissions. Broad assumptions and simplifications are necessary to conduct a CF level assessment.

Due to the importance of ISO 14064 during the CF assessment indicated in **chapter 2.1**, it was decided to implement the elements identified as essential in the new carbon footprint assessment model. The essential parameters indicating the emission unit, the source of its origin and the reporting structure in accordance with the guidelines of ISO 14 064 have been incorporated into the proposed model for assessing the carbon footprint of transport processes. Related details of a new model logic have been presented in **chapter 4**.

2.2. Overview of scopes of emissions within supply chains and greenhouse gas accounting terminology

Emissions resulting from transport processes within the supply chain differ in terms of their scope and origin. The correct categorisation of emissions allows for their efficient management. It is crucial to classify the source of emissions and indicate the supply chain participant directly responsible for its mitigation. However, it should be considered that current multi-layered supply chains allow all participants to be affected by the emission limitations of processes for which they are not directly responsible. Enforcing the reduction of emissions from transport processes carried out by third-party logistics service providers can be a part of the overall company's strategy, relating to ESG and CSR management principles(Gao et al., 2024; Kwilinski et al., 2023).

In research carried out by Yaman (2024), the impact of anthropogenic greenhouse gases on economic efficiency is indicated as becoming increasingly relevant. Hence, the need to mitigate the carbon footprint of various processes is pointed as an important step towards better environmental efficiency. However, to achieve a reduction in the carbon footprint, it is necessary to properly define the sources of emissions (Yaman, 2024). It has been proved that precise identification of emission sources has an impact not only on accuracy of CF assessment and reliability of GHG inventory reporting (Soares et al., 2025) but may also influence life expectancy level, according to researches carried out in Asia and Pacific region (Azam and Adeleye, 2024). This demonstrates the complex role of appropriate allocation of emissions to the relevant scopes of emissions. According to research conducted by Filonchyk et al. (2024), the main countries pointed as a key places of creation of greenhouse gasses are: the United States, China, India, Russia, Brazil, Indonesia, Japan, Iran, Mexico, and Saudi Arabia. Simultaneously, the main sources of emissions are the transportation of goods and people, energy consumption, waste management, and the use of urban land. This indicates a very large geographical dispersion of emission sources and a variety of processes that need to be evaluated. Therefore, a reliable assessment of the level of emissions requires a precise determination of the location of the emissions, the availability of data from supply chain participants, the determination of the type of emissions and the identification of the supply chain participant responsible for the process. In consequence a specific process can be linked with an appropriate scope in accordance with the globally accepted framework standard.

The range of emissions that are subjected to environmental assessment is precisely defined by a variety of laws, standards and frameworks. As identified in research conducted by Bacas and Dylla (2024), the correct identification of the scope and consideration of relevant logistics processes under assessment is essential for assessing the environmental performance of processes within sustainable supply chains. Research conducted by Anquetin et al. (2022) identified that assigning processes to the appropriate Scopes can support emission reduction. The researchers indicate that the classification of emissions into direct and indirect emissions within all three scopes can help reduce risk. Building a company portfolio that takes into account environmental aspects such as emission levels can increase the company's attractiveness to sustainability-aware stakeholders (Anquetin et al., 2022). However, the GHG Protocol, proposed by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD), is the main source of definitions on the basis of which other standards and frameworks have been developed. The GHG Protocol is the foundation for many other approaches due to its universal character and its comprehensive consideration of all processes in contemporary sustainable supply chains. The Greenhouse Gas Protocol (GHG Protocol) is a worldwide partnership that joins various stakeholders, including non-governmental organisations (NGOs), governments, representatives of businesses, and a wide range of institutions focused on the mitigation of emissions that influence carbon footprint levels (CF). However, other frameworks also need to be considered when determining the sources of the definition of the scope of operations to be subjected to environmental assessment. The ISO 14064 standard proposed by the International Organisation for Standardization (ISO, 2018a) contains detailed information on the quality of carbon footprint measurement, along with guidelines on how to evaluate and report it correctly. The standard also provides guidelines for potential areas where the carbon footprint of processes, including transport, can be mitigated. Implementing the ISO 14064 standard can contribute to increasing the credibility of the organisation and the reliability of published reports on the emissions of selected logistics processes. The scopes of individual emissions indicated in the ISO 14064 standard are closely logically linked to the GHG Protocol. The definition of the scopes of transport processes can be based on the Carbon Disclosure Project (CDP), whose logic is identical to the GHG Protocol. The approach to scoping is similar to that of the GHG Protocol, but the presentation of the results is intended to be stakeholder-friendly (CDP, 2023) . The CDP mainly serves as a reporting framework and as a support for cyclical reporting of emission levels to investors, businesses and public organisations. However, the GHG Protocol is still the logical basis for determining the scope of emissions within sustainable supply chains. The European Sustainability Reporting Standards (ESRS) is a standard that describes how to report the emissions of logistics processes of companies from the European Economic Area. The ESRS standard is applied when formulating the content of a report containing logistics processes emissions and overall sustainability level of a company's supply chain. The report is prepared by enterprises in response to the requirements of the Corporate Sustainability Reporting Directive (CSRD). The sources of emissions and the scope of the measured carbon footprint of transport processes refer to the basis of the emission scopes listed in the GHG Protocol (EU, 2022).

The categorisation of emissions within the supply chain proposed in the GHG Protocol allows for the appropriate classification of emissions. The indication of their point of origin and the precise identification of their source (WRI and WBCSD, 2004). Identifying emission points within the supply chain is essential for a proper GHG inventory hence incorrect identification of emission sources can lead to omissions in the CF assessment or to the assignment of emissions to the incorrect source (Majumdar et al., 2009). It is important to categorise the different types of activities appropriately. The activities within supply chain can be categorised into three main areas. Upstream activities are activities that take place before the company receives the product or service. Downstream activities are all activities that take place after the company sells the product or service. The third area includes all activities that are directly related to processes controlled by or belonging to the company. **Fig. 2.9** shows all key elements of CF emissions within the supply chain in accordance with the GHG Protocol. Processes that can be subjected to environmental assessment in the transport emissions management methodology that is being developed have been marked in green and included in the calculation model supporting CF assessment.

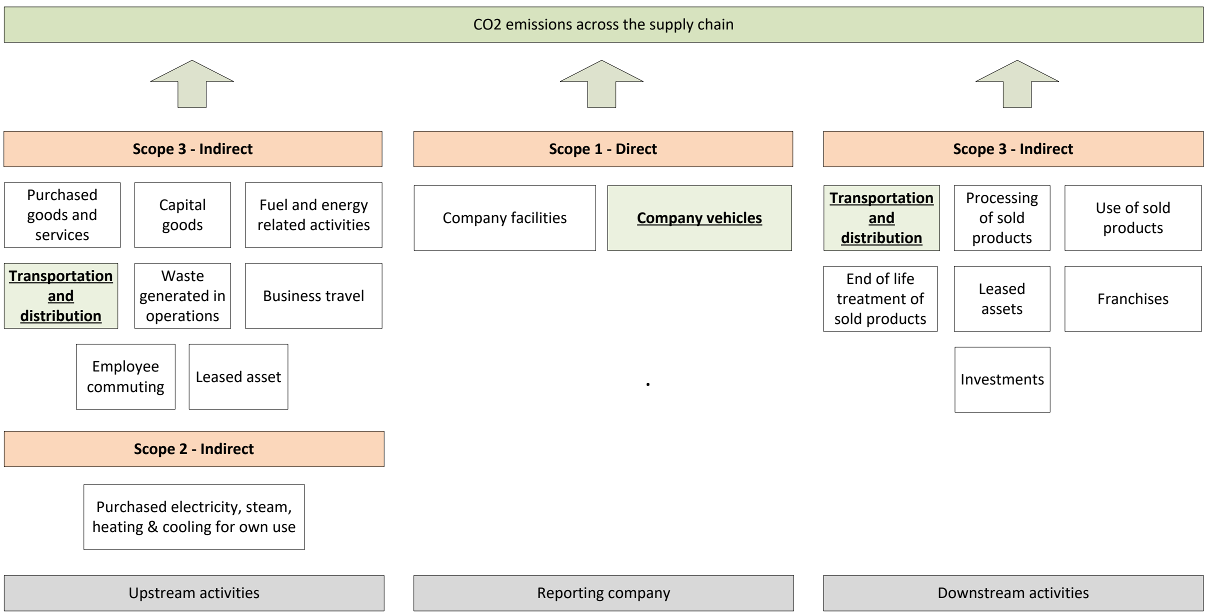


Fig. 2.9 Demonstration of emission sources and related activities across the supply chain according to GHG Protocol

Source: own elaboration based on WRI and WBCSD (2013b).

The GHG Protocol categorizes emissions into three scopes to support measure and manage their carbon footprint. Scope 1 is reserved for direct emissions from sources owned or controlled by the company. Scope 1 can cover such activities as fuel combustion in company owned vehicles, fuel combustion for heating purposes, emissions from industrial production processes. Scope 2 is dedicated to indirect emissions from energy. It may cover emissions from purchased electricity, steam, heating, or cooling used by the company. These emissions occur at the power generation source but are attributed to the company as they result from its energy consumption. Under Scope 2, in accordance with the guidelines set out in the GHG Protocol emissions resulting from the production of electricity used to charge electric vehicles can be reported (WRI and WBCSD, 2004). Scope 3 reflects the indirect value chain emissions of both upstream and downstream activities. Those activities are not owned or directly controlled by the company and are generated by subcontractors. The Scope 3 covers purchased goods and services, employee commuting to work and business travel, transportation and distribution, use of sold products, waste disposal.

Therefore, from the perspective of emission management of transport processes within sustainable supply chains, it is essential to understand how to determine emissions related to transport using your own fleet (Scope 1 - direct emissions) and exploit a subcontractor's fleet of vehicles (Scope 3 - upstream activities and downstream activities).

Scope 3 is typically the largest and most challenging to measure but is crucial for understanding the full carbon footprint of supply chain. According to Vieira et al. research (2024), scope 3 emissions are among the most difficult to assess. Multi-level supply chains with very complex networks of mutual interdependencies result in difficulties in accessing basic data, thus limiting the ability of reporting enterprise to manage the emissions of subcontractors. Many companies focus on Scope 1 and 2 initially and expand to Scope 3 for comprehensive sustainability strategies(Downie and Stubbs, 2012).

Tab. 2.7 Types of activity within each scope

Source: own elaboration WRI and WBCSD (2013b).

Scope 2 (Indirect)	Scope 3 (Indirect)	Scope 1 (Direct emissions)	Scope 3 (Indirect)
Upstream activities	Upstream activities	Reporting company	Downstream activities
• Purchased electric, steam, heating & cooling for own use. • Charging of electric vehicles out of power grid.	• Purchased goods and activities • Capital goods • Fuel and energy related activities • Transportation and distribution • Waste generated in operations • Business travel • Employee commuting • Leased assets	• Company vehicles • Company facilities	• Transportation and distribution • Processing of sold products • Use of sold products • End of life treatment of sold products • Leased assets • Franchises • Investments

Scope 1 Direct emissions

According to the GHG Protocol, all direct emissions from the transport processes carried out with a company's own vehicles are included in this scope. Transport activities also include transport between a company's own locations within the supply chain. The emissions measured under Scope 1 should cover all activities within the selected reporting year.

Scope 2 Indirect upstream emissions

Reporting of transport process emissions under Scope 2 can only be conducted for electric vehicles. Relevant reporting of emissions level in Scope 2 requires consideration of local country emission factors determining the carbon footprint of electricity production. For Poland, a recommended source of data on emissions per 1 MWh is Polish Electricity Emission Factors Benchmarks (KOBiZE, 2024).

Scope 3 Indirect upstream emissions

According to the GHG Protocol Technical Guidance for Calculating Scope 3 Emissions, this scope includes all activities in category 4 related to upstream transportation and distribution. This refers to emissions caused by the transportation of materials and inventories and the distribution (in the direction of the reporting company) of products purchased by the company reporting its carbon footprint in a specific year. These emissions include all services undertaken by direct first-tier subcontractors of the reporting company. These emissions do not include transport processes undertaken by the reporting company's fleet as those are reflected in Scope 1 activities. When assessing Scope 3 indirect upstream emissions, it is also necessary to consider transports carried out with vehicles not owned by the company, between locations in its own supply chain (SC)

Scope 3 Indirect downstream emissions

In line with the GHG Protocol's Technical Guidance for Calculating Scope 3 Emissions, these emissions are reported as category 9 "Downstream Transport and Distribution". It covers all outsourced transport activities related to the distribution of finished products to customers. The activities included in this category must be carried out by vehicles not owned by the company. These emissions shall cover all transport activities within the company's reporting year.

Scope 4 emissions

The scope 4 emissions proposed by The World Resources Institute and established in the GHG Protocol is related to the reporting of emission reductions resulting from actions taken by organisations (WRI and WBCSD, 2004). Scope 4 can present calculations that determine how a company's products or services contribute to reducing emissions in other organisations, such as tyres that help reduce fuel consumption or appliances that help reduce the usage of raw materials or energy. The academic discussion also includes various proposals for estimating the potential for reducing emissions. Young-Ferris et al. (2025), emphasise the need for great cautiousness when reporting the mitigation potential of products and services within Scope 4. These concerns are directly related to the risk of overestimating the reduction potential of the solutions created and double counting, which refers to the simultaneous indication of the emission reduction potential and the reporting of reduced emission levels within Scopes 1, 2 and 3. Incorrect assignment of processes to scopes, further reporting of their emissions and identification of reduction potential in Scope 4 can lead to ‘greenwashing’ (Ruggeri et al., 2025). Therefore, the environmental assessment process should be carried out in accordance with applicable standards and guidelines.

Terminology related to the management of transport emissions

An important element of developing a methodology for measuring and managing transport emissions within sustainable supply chains is to precisely define the basic terms and elements that must be taken into consideration when assessing emission levels. The terms used in the management methods and legal acts identified are based on two main sources: the GHG Protocol and the Kyoto Protocol. The GHG Protocol is a valuable source of definitions for terms that are referenced in many studies and legal acts. This is due to the comprehensive approach to ESG reporting by companies, which can be supported by the principles set out in the GHG Protocol. The bottom-up method defined in the GHG Protocol Corporate Standard (WRI and WBCSD, 2004) precisely names the measured parameters or defines their scope. The Kyoto Protocol, as an international treaty, sets the direction for changes in the management of the local economies of all its signatories (UNFCCC, 1997). The Kyoto framework refers more generally to the goal of mitigating anthropogenic impact on the environment. Subsequently, the Kyoto Protocol is an international document to which many global regulations and methods refer to. Therefore, similar to the GHG Protocol, the Kyoto Protocol is a valuable source of definitions and provides guidance on how to understand the most important terms. The **Tab. 2.8** lists the essential definitions that are crucial for the correct application and use within the developed methodology for managing transport emissions in sustainable supply chains.

Tab. 2.8 Essential terms in the process of transport emissions assessment in a supply chain. In accordance with the GHG Protocol and the Kyoto Protocol
Source: own elaboration.

Term	GHG Protocol	Kyoto Protocol
Greenhouse Gases	Quoting the definition from the GHG Protocol: "Greenhouse gases (GHGs) are gases that trap heat in the atmosphere and contribute to the greenhouse effect, leading to global warming and climate change. The GHG Protocol focuses on the following gases covered by the Kyoto Protocol: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6)" (WRI and WBCSD, 2004)	According to the definition formulated in the Kyoto Protocol (UNFCCC, 1997). Greenhouse gases cover a group of gases that reflect a positive impact on global warming and climate change. As mentioned in Annex A to the Kyoto Protocol, six primary gases have to be considered as Greenhouse Gases: carbon dioxide (C02), methane (CH4), nitrous oxide (N20), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF6). According to the United Nations Framework Convention on Climate Change (UNFCCC) organisation, there has been proposed a categorisation of GHG sources as per Tab. 2.9 below.
Global Warming Potential	According to GHG Protocol (WRI and WBCSD, 2004) Greenhouse Gases (GHGs) contribute to global warming by absorbing thermal radiation and reducing the rate at which energy escapes into space, functioning as an insulating layer around the Earth. Their warming effects differ based on radiative efficiency and the capacity to absorb energy. Global Warming Potential defines actual atmospheric lifetime understood as the duration they remain in the atmosphere. Since 1990, the Intergovernmental Panel on Climate Change (IPCC) has utilized Global Warming Potential (GWP) to quantify and compare the radiative forcing impact of different GHGs relative to carbon dioxide (CO_2) over a specified timeframe, typically 100 years. A higher GWP indicates a greater contribution to warming per unit mass. GWP serves as a standardized metric, facilitating emissions accounting across multiple gases and supporting policymakers in evaluating mitigation strategies across various sectors(WRI and WBCSD, 2004).	According to Kyoto Protocol ((UNFCCC, 1997) article 5, Point 3. The global warming potentials used to calculate the carbon dioxide equivalence of anthropogenic emissions by sources and removals by sinks of greenhouse gases listed in Annex A shall be those accepted by the Intergovernmental Panel on Climate Change and agreed upon by the Conference of the Parties at its third session. Based on the research by the Intergovernmental Panel on Climate Change and advice provided by the Subsidiary Body for Scientific and Technological Advice, the Conference of the Parties serving as the meeting of the Parties to this Protocol shall regularly review and, as appropriate, revise the global warming potential of each such greenhouse gas, taking fully into account any relevant decisions by the Conference of the Parties. Any revision to a global warming potential shall apply only to commitments under Article 3 in respect of any commitment period adopted subsequent to that revision.

Term	GHG Protocol	Kyoto Protocol
Carbon Dioxide Equivalent	According to GHG Protocol (WRI and WBCSD, 2004) Carbon Dioxide Equivalent (CO_2e) is a standardized unit used to quantify and compare emissions from different greenhouse gases (GHGs) based on their Global Warming Potential (GWP). For example, CO_2 has a GWP of 1, while methane (CH_4) has a GWP of approximately 28 over a 100-year period. This means that emitting 1 tonne of CH_4 has the same warming effect as 28 tonnes of CO_2. Since different GHGs have varying warming impacts, CO_2e provides a uniform measure to express and compare emissions across gases.	According to the Kyoto Protocol (UNFCCC, 1997) emissions must be reported in tonnes of CO_2 equivalent, but it doesn't provide a detailed standalone definition inside the treaty articles. However article 3, Point 1 of the Kyoto Protocol's definition of carbon dioxide indicates the need to reduce anthropogenic emissions of carbon dioxide equivalent of the greenhouse gases whose sources are listed in Annex A of Kyoto Protocol and presented in **Tab. 2.9** below.
Emission Factors	According GHG Protocol(WRI and WBCSD, 2004), an emission factor is used to calculate the GHG emissions for a given source, relative to units of activity. Emission factors (EFs) are standardized values that estimate the amount of greenhouse gas (GHG) emissions per unit of activity, fuel consumption, or production. They are essential for GHG inventories, allowing organisations, governments, and researchers to quantify emissions from different sources.	Emission factors are values accepted by international standards for measuring CO_2 emissions. However, the Kyoto Protocol does not define sources of obtaining emission factors. It refers to the IPCC Guidelines as a source of information for their acquisition. In accordance with the IPCC guidelines, emission factors should be considered in the context of universal factors and country-specific emission factors(IPCC, 2019).
Activity Data	Activity data is a key input for the calculation of GHG emissions and refers to the data associated with an activity that generates GHG emissions, such as litres of gasoline consumed from company cars (WRI and WBCSD, 2004). According to IPCC Guidelines for national Greenhouse Has Inventories (IPCC, 2019) this activity data is collected in physical units such as litres or gallons or energy units (kWh) and then combined with an emissions factor and the relevant greenhouse gas GWP value to calculate C02 equivalent. The collection of activity data is the primary responsibility of the reporting company and will often be the most significant challenge when developing a GHG inventory. Therefore, establishing robust activity data collection procedures is essential.	The Kyoto Protocol does not directly define "Activity Data" in its body, but the methods for assessing transport emissions under the Kyoto framework refer to the IPCC Guidelines, which indicate that activity data can be understood as an information on fuel consumption, distance travelled and mode of transport. Those information are essential for assessing transport emissions (IPCC, 2019).

Tab. 2.9 Sources of greenhouse gas emissions according to Kyoto Protocol, Annex A.
Source: own elaboration.

Sector	Source categories	Detailed categories
Energy	Fuel combustion	-Energy industries -Manufacturing industries and construction -Transport - Other sectors - Other
	Fugitive emissions	-Solid fuels - Oil and natural gas - Other
Industrial Processes	- Mineral products - Chemical industry - Metal production - Other production - Production of halocarbons and sulphur hexafluoride - Consumption of halocarbons and sulphur hexafluoride - Other	
Solvent and Other Product Use		
Agriculture	- Enteric fermentation - Manure management - Rice cultivation - Agricultural soils - Prescribed burning of savannas - Field burning of agricultural residues - Other	
Waste	- Solid waste disposal on land - Wastewater handling - Waste incineration - Other	

2.3. European vehicle emission standards and sources of Emission Factors for GHG assessment

Emission factors are an important element identified in carbon footprint measurement and management standards. Some global measurement methods provide their own emission factors, while others use external factors and indicate how they must be applied. Emission factors are a vital source of the basic information necessary to assess the carbon footprint of a transport process. Emission factors allow the unit emission level to be determined, taking into account the specific parameters of a vehicle or group of vehicles performing transport processes. The rest of this chapter identifies the essential sources of these factors. However, to fully understand their structure, it is necessary to be familiar with the basic emission standards imposed on vehicles depending on their age, type, and fuel type. The following **Tab. 2.10** presents current emission standards applicable to passenger cars (PC), light commercial vehicles (LCV), heavy-duty vehicles (HDV), vans and L-category vehicles. A complete list of EMEP & EEA emission standards is enclosed in **Appendix 2 - EMEP&EEA Tier2 Emission_Factors.xlsx**

Tab. 2.10 Types of European Emission Standards for vehicles
Source: own elaboration based on EMEP & EEA (2024).

Vehicle type	Fuel type	Emission standard	Start date	End date
All Trucks	Petrol	Euro 6 d-temp	2019	2020
		Euro 6 d/e	2021	2026
		Euro 7	2026 and later	and later
	Diesel	Euro 6 a/b/c	2014	2019
		Euro 6 d-temp	2019	2020
	LPG	Euro 6 a/b/c	2015	2016
		Euro 6 d-temp	2017	2019
	CNG	Euro 6 a/b/c	2015	2016
		Euro 6 d-temp	2017	2019
	Petrol Hybrid	Euro 6 a/b/c	2014	2019
		Euro 6 d-temp	2019	2020
	Petrol PHEV	Euro 6 a/b/c	up to 2019	2019
		Euro 6 d-temp	2019	2020
		Euro 6 d/e	2021	2026
	Diesel PHEV	Euro 6 a/b/c	up to 2019	2019
		Euro 6 d-temp	2019	2020
		Euro 6 d/e	2021	2026
	Battery electric	Euro 6 a/b/c	up to 2019	2019
		Euro 6 d-temp	2019	2020
		Euro 6 d/e	2021	2026

From the perspective of the new emissions management and assessment method, correctly identifying the components of emissions is essential. The European Emission Standard established by the European Union, is a regulatory framework that sets limits on the emissions of vehicles and is therefore a key component of the new approach to measuring and managing emissions from transport processes. The Euro Emission Standard is a regulatory framework established by the European Union with the aim of limiting air pollutants emitted by vehicles. It was first introduced in 1992 with Euro 1, with reductions in harmful gases such as carbon monoxide (CO), nitrogen oxides (NOx), hydrocarbons (THC), and particulate matter (PM) being targeted (Council of the European Communities, 1991). Euro Emission Standard applies to different vehicle categories, including passenger cars, light commercial vehicles, and heavy-duty vehicles, and have become progressively stricter over time. Compliance with each Euro stage requires manufacturers to adopt cleaner engine technologies and advanced emission control systems. This EU Emission standard is legally enforced through EU directives and regulations, with periodic updates reflecting the latest environmental and health research(Barbier et al., 2024). The **Tab. 2**.11 below presents emission limits for vehicles depending on individual Euro emission standards over the years. In addition to CO_2 emission limits, the standards also regulate other exhaust parameters. The definition of individual additional components can be found below the **Tab. 2**.11.

Tab. 2.11 Detailed regulations within Euro emission standards for diesel and petrol vehicles
Source: own elaboration based on

Relevant Euro Emission Standard	Date Introduced	CO_2 (Petrol)	CO_2 (Diesel)	THC** (Petrol)	NMHC*** (Petrol)	NOx**** (Petrol)	NOx**** (Diesel)	PM***** (Diesel)	PM***** (Petrol, DI)
Euro 1	July 1992	2,720	2,720	–	–	–	–	–	–
Euro 2	January 1996	2,200	1,000	0,500	–	0,500	0,700	–	–
Euro 3	January 2000	2,300	0,640	0,200	–	0,150	0,500	0,050	–
Euro 4	January 2005	1,000	0,500	0,100	–	0,080	0,250	0,025	–
Euro 5	September 2009	1,000	0,500	0,100	0,068	0,060	0,180	0,005	0,005 (GDI* only)
Euro 6	September 2014	1,000	0,500	0,100	0,068	0,060	0,080	0,005	0,005 (GDI* only)
Euro 6d	January 2021	1,000	0,500	0,100	0,068	0,060	0,080	0,005	0,0045 (GDI* only)

* GDI stands for Gasoline Direct Injection.
** THC stands for Total Hydrocarbons
*** NMHC stands for Non-Methane Hydrocarbons
**** NOx refers to nitrogen oxides, a group of reactive gases that contribute to smog and acid rain
***** PM stands for Particulate Matter

Euro vehicle emission standards are reflected in the identified main methods and emissions factors supporting measuring the carbon footprint within the supply chains. It is important to note that vehicle emission factors must not exceed the values specified in the Euro standard. **Tab. 2.12** below presents the main GHG assessment methods considered essential for the new transport management method. For each GHG assessment method, recommended emission factors sources are indicated.

Tab. 2.12 Emission Factors pointed in the key GHG Assessment methods and standards
Source: own elaboration based on WRI and WBCSD (2004)

GHG assessment method or standard	Reference to Emission Factors (EF)
GHG Protocol (Transport Tool)	IPCC, DEFRA, EEA, EPA
PAS 2050	DEFRA, EEA, IPCC
ISO 14064 (Parts 1 & 2)	EEA, IPCC, DEFRA
EU ETS	DEFRA, EPA, EEA

Among the most frequently referred emission factors are EMEP/EEA and UK DEFRA. Due to the need to assess emissions related to the charging of electric vehicles, it is important to identify the relevant emission factors corresponding to electricity production. The new model for assessing the carbon footprint of transport processes is validated on the basis of transport processes of a company operating in Poland, therefore it was decided to analyse the emission factors related to this area in accordance with the GHG Protocol recommendations for measuring Scope 2 emissions. Hence, the emission factors associated with electricity production in Poland, published by the Institute of Environmental Protection - National Research Institute National Centre for Emissions Management (KOBiZE), were analysed. The detailed scope of emissions within Scope 2 is presented in chapter **2.2**. Specific mission factors are reviewed in detail further in this chapter.

Emission factors published by UK DEFRA and US EPA shows a high level of usability due to their structure and frequency of updates by the above-mentioned credible governmental organisations. Simultaneously, due to the structure of the underlying company data describing the transport processes, the parameter to be assessed by the benchmark can be the distance travelled. A set of indicators published by UK DEFRA is applicable when assessing the carbon footprint resulting from the distance travelled between transport chain participants. Due to limited access to company data on fuel consumption, the set of indicators published by the US EPA is of limited use. The US EPA indicators provide precise information on the energy intensity of individual processes, but can therefore be difficult to adapt to the needs of the calculation model proposed.

EMEP/EEA Air Pollutant Emission Inventory Guidebook

The EMEP/EEA Air Pollutant Emission Inventory Guidebook is a key reference developed jointly by the European Environment Agency (EEA) and the programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP). Guidebook provides detailed methodologies and emission factors for calculating air pollutant emissions from a wide range of anthropogenic sources, including transport (EMEP & EEA, 2024). While primarily designed for air pollutants (e.g., NO_x, PM, SO_2), many of its methodologies and factors are also widely used by organisations and countries in greenhouse gas (GHG) inventories and assessments. The tier system in the EMEP/EEA Air Pollutant Emission Inventory Guidebook comprises a series of hierarchical approaches for estimating emissions. These approaches vary in terms of their complexity, data requirements and accuracy. The Tier approach enables emission estimations to be adapted according to the availability of data, national priorities, and resource capacity. EEA tiers are designed to provide flexibility and scalability in emission quantification, ensuring that countries and organisations with limited basic data can still estimate emission levels (tier 1 reflects low data quality). However, organisations and supply chains with access to more detailed data and greater capacity can apply more advanced and accurate methodologies (Tier 2 and 3 reflect high data quality). The tier structure aligns with the IPCC Good Practice Guidance, supporting transparent, consistent and comparable emission inventories across countries and organisations. The **Fig. 2.10** below shows the logic behind the use of emission factors to assess the carbon footprint within supply chain, resulting from transport processes.

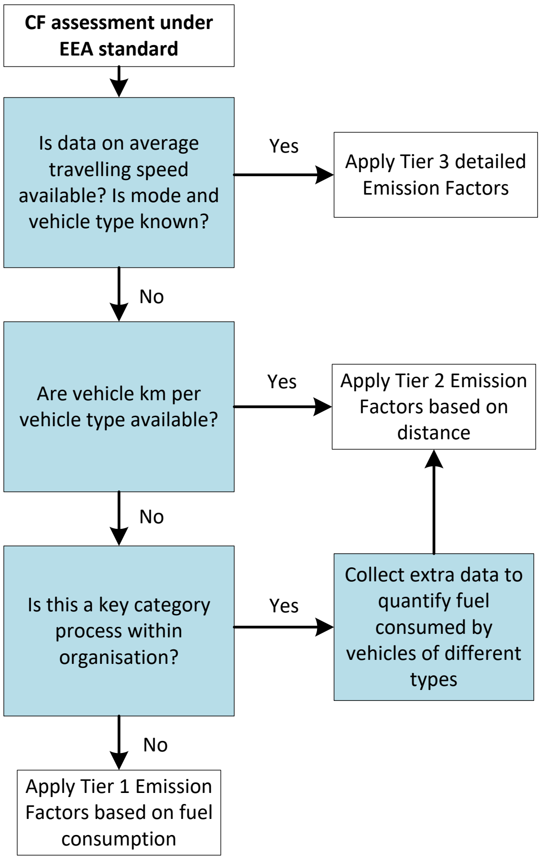


Fig. 2.10 The logic for applying EEA Emissions Factors and Tiers depending on data quality
Source: own elaboration based on EMEP & EEA, (2024).

The fourth step of the EEA's general approach to assessing the carbon footprint of processes within the supply chain indicates the need to further refine the data when the assessed process is a core activity within the supply chain. This element has been applied in the logic of the new approach for measuring and managing transport emissions presented in **chapter 4**.

Tier 1 - The calculation formula for GHG inventory of processes with limited data is presented below (**Formula 5**). Elements of this approach have been incorporated into the logic of calculation models supporting the new method of measuring and managing the carbon footprint of transport processes within sustainable supply chains. The logic is applied in a simplified approach based on low quality data (LQD).

Formula 5 Tier 1 general method for calculating the carbon footprint of transport processes
Source: own elaboration based on EMEP & EEA, (2024).

$$E_i = \sum_j \left(\sum_m \left(FC_{j,m} \times EF_{i,j,m} \right) \right)$$

E_i	Emission of pollutant "I" [g]
$FC_{j,m}$	Fuel consumption of vehicle category "j" using fuel "m" [kg]
$EF_{i,j,m}$	Fuel consumption-specific emission factor of pollutant "I" for vehicle category "j" and fuel "m" [g/kg]

The EEA recommends the use of emissions factors related to fuel combustion and calculate emissions from transport processes in Tier 1, using **Formula 5**. Calculations can be conducted by specifying the fuel type: petrol, diesel, LPG or CNG. Detailed emission factors are presented in **Tab.**

2.13 below. Additional information provided under the EEA Emission Factors, presented in **Tab. 2.13** relates to Non-Methane Volatile Organic Compounds (NMVOC) which are officially defined in EU legislation and international agreements. NMVOCs presents chemical properties and their role in atmospheric photochemical reactions leading to the formation of ground-level ozone (so-called 'Smog'). The detailed impact of NMVOCs, composition and application in the environmental assessment of processes at national level is set out in Directive (EU) 2016/2284 of the European Parliament and of the Council of 14 December 2016 on the reduction of national emissions of certain atmospheric pollutants (EC, 2016).

Tab. 2.13 Key EMEP/EEA emission factors supporting CF assessment of transport processes
Source: own elaboration based on EMEP & EEA, (2024).

Vehicle category	Fuel type	CO_2 emission factor E_i [g/kg fuel]			NMVOC [g/kg fuel]		
		Mean	Minimum	Maximum	Mean	Minimum	Maximum
PC	Petrol	48.36	8.60	338.69	7.75	1.15	176.89
PC	Diesel	2.41	0.52	11.23	0.51	0.02	3.26
PC	LPG	58.22	14.56	139.93	9.43	1.48	20.85
LCV	Petrol	118.70	11.75	356.95	7.42	0.67	53.99
LCV	Diesel	6.81	4.82	21.77	1.23	0.48	2.86
HDV	Diesel	6.10	2.79	13.80	0.90	0.06	7.01
HDV	CNG (Buses)	3.98	2.20	15.12	0.14	0.06	0.39

Tier 2 – This GHG inventory approach is a more detailed and technology-specific approach for estimating emissions from road transport. It is part of the EMEP/EEA air pollutant emission inventory guidebook, which supports national reporting obligations under international agreements such as the UNECE Convention on Long-range Transboundary Air Pollution (CLRTAP). Unlike the simpler Tier 1 method, which uses average emission factors for the entire vehicle fleet, Tier 2 accounts for differences in vehicle types, fuel used, engine size, emission control technology (such as Euro standards), and driving conditions (urban, rural, motorway). By incorporating more granular data, including fleet composition and mileage, Tier 2 provides more accurate and policy-relevant emission estimates. This approach is particularly valuable for countries aiming to assess local air quality impacts or develop targeted transport and environmental policies.
A more detailed classification of vehicles included in the GHG evaluation in Tier 2 is presented in **Tab. 2.14** below. The emission level assessment carried out in Tier 2 also takes into account the European emission classes presented in **Tab. 2.10**. Access to more detailed data allows for a more detailed analysis of emissions and their sources.

Tab. 2.14 EMEP/EEA vehicle classification for assessing transport emissions in the Tier 2 detailed approach
Source: own elaboration based on EMEP & EEA, (2024).

Vehicle Category	Type	European Emissions Standards
Passenger cars	Petrol Mini	Euro 4, Euro 5, Euro 6
Passenger cars	Petrol Small, Medium, Large, SUV-Executive	PRE ECE, ECE 15/00-01, ECE 15/02, ECE 15/03, ECE 15/04, Improved Conventional, Open-Loop, Euro 1 – Euro 6

Vehicle Category	Type	European Emissions Standards
Passenger cars	Diesel Mini	Euro 4 – Euro 6
Passenger cars	Diesel Small, Medium, Large, SUV-Executive	Conventional, Euro 1 – Euro 6
Passenger cars	LPG Mini	Euro 1 – Euro 6
Passenger cars	LPG Small, Medium, Large, SUV-Executive	Conventional, Euro 1 – Euro 6
Passenger cars	Petrol Hybrid	Euro 4 – Euro 6
Passenger cars	Diesel Hybrid	Euro 4 – Euro 6
Passenger cars	Petrol PHEV	Euro 5 – Euro 6
Passenger cars	Diesel PHEV Large	Euro 6
Passenger cars	CNG	Euro 4 – Euro 6
Light commercial vehicles	Petrol (N1-1, N1-2, N1-3)	Euro 1 – Euro 6
Light commercial vehicles	Diesel (N1-1, N1-2, N1-3)	Euro 1 – Euro 6
Heavy-duty vehicles	Diesel Rigid, Articulated	Euro I – Euro VI
Heavy-duty vehicles	Urban CNG	Euro V, Euro VI
Buses	Urban Diesel Buses, Coaches	Euro I – Euro VI
Buses	Urban Diesel Hybrid Buses	Euro V, Euro VI
Mopeds	Petrol 2-stroke < 50 cm^3	Conventional, Euro 1 – Euro 3
Mopeds	Petrol 4-stroke < 50 cm^3	Conventional, Euro 1 – Euro 3
Motorcycles	Petrol 2-stroke 50–250 cm^3	Conventional, Euro 1 – Euro 3
Motorcycles	Petrol 4-stroke 50–250 cm^3	Conventional, Euro 1 – Euro 3
Motorcycles	Petrol 4-stroke 250–750 cm^3	Euro 1 – Euro 5
Motorcycles	Petrol 4-stroke > 750 cm^3	Euro 1 – Euro 5
Micro-cars	Diesel	Conventional, Euro 1 – Euro 5
Quad & ATVs	Petrol	Conventional, Euro 1 – Euro 5

Formula 6 below indicates the method for calculating emissions in the detailed approach. The assessment of the carbon footprint of transport processes in Tier 2 requires the appropriate classification of vehicles in accordance with the emission standards and types specified in **Tab. 2.14**. Tier 2 requires the use of dedicated emission factors for each specific vehicle type, depending on the emission standard and vehicle class. Due to the extensive size of the table containing detailed emission factors used in Tier 2, they have been included in **Appendix 2 - EMEP_EEA_Tier2_Emission_Factors.xlsx**

Formula 6 Tier 2 detailed method for calculating the carbon footprint of transport processes
Source: own elaboration based on EMEP & EEA, (2024).

$$E_{i,j} = \sum_k (N_{j,k} \times M_{j,k} \times EF_{i,j,k})$$

$M_{j,k}$	Total annual distance driven by all vehicles of category "*j*" and technology ""*k* [vehicle/km],
$EF_{i,j,k}$	Technology-specific emission factor of pollutant "I" for vehicle category "j" and technology "k" [g/vehicle-km]
$M_{j,k}$	Average annual distance driven per vehicle of category "j" and technology "k" [km/vehicle],
$N_{j,k}$	Number of vehicles in the nation's fleet of category "*j*" and technology "*k*".

<u>Tier 3</u> - Under the Tier 3 approach, total exhaust emissions from road transport are determined by combining emissions produced during normal engine operation (referred to as "hot emissions" - E_{hot}) with those released while the engine is warming up (known as "cold-start emissions" E_{cold}). In this context, the term 'engine' encompasses both the engine itself and any associated exhaust aftertreatment systems. Differentiating between emissions during stable, fully warmed-up conditions and those during the initial warm-up phase is essential due to the significant variations in emission levels. Pollutant concentrations are often considerably higher during the cold-start phase, necessitating a distinct calculation approach for this period. In summary, the total emissions are obtained using the following formula

Formula 7 Tier 3 detailed method for calculating the carbon footprint of transport processes
Source: own elaboration based on EMEP & EEA, (2024).

$$E_{TOTAL} = E_{HOT} + E_{COLD}$$

E_{TOTAL}	Total emissions "g" of any pollutant for the spatial and temporal resolution of the application.
E_{HOT}	Emissions „g" during stabilised (hot) engine operation.
E_{COLD}	Emissions "g" during transient thermal engine operation (cold start).

However, it should be noted that the Tier 3 approach is too detailed to be incorporated into the new model for assessing emissions and managing transport processes. Tier 3 is applicable when very detailed analyses are required for research or specific reporting purposes.

Summarising, the logic for the assessment of emission levels, emission factors and calculation formulas indicated in Tier 1 and Tier 2 can be exploited in a new model for measuring and managing the carbon footprint of transport processes within sustainable supply chains.

UK DEFRA

The UK Department for Environment, Food & Rural Affairs is responsible for managing national regulations in the United Kingdom in the field of sustainable development. The key areas covered by the UK DEFRA include: Environment, Food and farming, Rural communities, water and marine. The organisation is responsible for counteracting climate change at the national level, including air quality. The environmental standards and regulations developed refer to elements of sustainable development at the economic, social and environmental levels, which is consistent with the ESG approach described in **chapter 1.2**.

UK Defra also provides a set of emissions indicators, which is updated annually and can be downloaded from the organisation's website. Through the provision of accurate emissions indicators, it is possible to assess the carbon footprint of various transport processes, taking into account the parameters of the vehicle fleet and their utilisation level. This approach allows for a very accurate calculation of CO_2 emissions in relation to the transport processes carried out. The general formula for calculating emission levels using UK DEFRA coefficients is presented below.

Formula 8 Simplified formula for assessing emission levels proposed by UK DEFRA
Source: own elaboration based on UK DEFRA (2024)

$$\text{GHG emissions} = \text{activity data x emission conversion factor}$$

Emissions factors provided refers to two types of emissions, Well to Tank (WTT) and Tailpipe. WTT emissions represent the indirect, upstream emissions associated with the extraction, processing, refining, and delivery of fuels or energy to the point of use—but before combustion. For example, in the case of petrol, WTT includes emissions from oil extraction, refining, and distribution to the pump. In electricity, WTT includes emissions from producing and transmitting electricity up to the point of use. These are typically Scope 3 emissions and help provide a full lifecycle view of energy-related impacts.

Tailpipe emissions are the direct emissions released during the combustion of fuels in engines or boilers—usually Scope 1 emissions. This includes gases like CO_2, CH_4, and N_2O that are emitted from the vehicle exhaust or chimney stack during fuel use. Tailpipe emissions exclude any upstream or downstream activities and reflect only what is emitted at the point of use.

Tab. 2.15 below presents the contents of individual tabs of UK DEFRA emission factors.

Tab. 2.15 Description of content of UK Government GHG Conversion Factors for Company Reporting spreadsheet
Source: own elaboration based on UK DEFRA (2024).

Tab name	Description of content
Introduction	General description of the scope of emission factors presented in the sheet. Indication of the version of emission factors, date of publication and approximate date of publication of subsequent emission factors in the following year. The sheet contains basic information on emission scopes, developed on the basis of the logic presented in the GHG Protocol guidelines.
What's new	Outlines changes and updates in the current year’s dataset compared to previous versions. This includes updated emission factors, revised methodologies, corrections from prior years, and changes in global warming potentials (e.g., shift to AR6 GWPs). Helps returning users identify key differences.
Fuels	Contains emission factors for direct combustion of fuels. Covers commonly used fuels such as diesel, petrol, natural gas, LPG, coal, and biomass. Provides factors for CO_2, CH_4, N_2O, and CO_2e emissions per unit of fuel, typically in litres, kWh, or tonnes. Includes breakdowns by combustion technology where relevant.
Bioenergy	

Tab name	Description of content
Refrigerant & other	Contains global warming potential values and emission factors for refrigerants and other industrial gases. Includes factors for refrigerant leakage and GHGs not commonly encountered in fuel combustion, such as HFCs and PFCs.
Passenger vehicles	Provides tailpipe emission factors for owned or leased passenger vehicles, broken down by fuel type (petrol, diesel, hybrid, electric) and vehicle size. Includes g/km factors and lifecycle emissions for Scope 1 reporting.
SECR kWh pass & delivery vehs	Provides emissions per kWh and per kilometre travelled for vehicles relevant to Streamlined Energy and Carbon Reporting (SECR), covering both passenger and delivery vehicles. Factors may include energy consumption rates, especially for electric and hybrid vehicles.
UK electricity	Contains upstream emissions from the generation and supply chain of UK electricity, excluding direct combustion. Complements Scope 2 emissions in the "UK electricity" tab.
UK electricity for EVs	Contains information about electricity production in UK. Emission factors from this tab may be used for CF evaluation of electric vehicles under Scope 2 emissions. In Polish environment, KOBiZe is valid source of information about electricity manufacturing related emissions.
SECR kWh UK electricity for EVs	Offers kWh-based emission factors specifically for electric vehicles under SECR guidelines. Tailored to reflect electricity emissions from vehicle charging activities, both grid average and marginal supply.
Transmission and distribution	This refers to the losses that occur when electricity is transported from the power station to the end user through the grid network. The T&D factor quantifies the additional emissions resulting from these losses, usually expressed in kg CO_2e per kWh delivered. DEFRA includes this within the electricity-related tabs, especially under UK electricity and WTT – UK electricity, allowing users to account for full Scope 2 and 3 emissions if electricity loss is material to their operations. Factoring in T&D is essential for accurate carbon reporting when energy consumption data reflects end-use electricity rather than electricity generated.
Water supply	Lists Scope 3 emissions from mains water usage, measured per cubic metre. Includes factors for water abstraction, treatment, and distribution processes.
Water treatment	Contains Scope 3 emissions from the treatment and discharge of wastewater into public sewer systems. Measured per cubic metre. Best used alongside "Water supply" for full water footprinting.
Material use	Provides embodied emissions for various materials (e.g., metals, plastics, textiles), measured in kg CO_2e per kg of material. Useful for estimating impacts of raw material consumption in products or infrastructure.
Waste disposal	Covers Scope 3 emissions from disposal of different waste streams (general, hazardous, recyclable), across disposal methods like landfill, incineration, recycling, composting.

Tab name	Description of content
Business travel- air	Contains emission factors for air travel, covering upstream impacts of jet fuel production and supply.
Business travel- sea	Upstream emissions for maritime travel fuels used in business travel.
Business travel- land	Contains emission factors for land-based business travel. Applies to both private and public transport options.
Freighting goods	This tab provides Scope 3 emission factors for transporting goods by various modes—road, rail, sea, and air. Emission factors are typically expressed in kg CO_2e per tonne-kilometre, representing the emissions generated from moving one tonne of goods one kilometre. The tab includes distinctions based on the type of vehicle (e.g., HGVs, vans), fuel type (diesel, electric), average payloads, and haul length (e.g., short, medium, long haul). For shipping, vessel type and route also affect emissions. Both direct (tailpipe) and well-to-tank (WTT) emissions are included where applicable. This tab is essential for businesses reporting transport-related emissions in their supply chain or logistics activities.
Conversions	Tab containing additional unit conversion tools. Supports calculations requiring non-standard units or industry-specific inputs.
Fuel properties	This tab provides the physical and chemical characteristics of various fuels used in emissions calculations. It includes data such as gross and net calorific values (energy content per unit mass or volume), density, carbon content, and oxidation factors for fuels like petrol, diesel, natural gas, LPG, coal, and biofuels. These properties are essential for converting fuel quantities (e.g., litres, tonnes) into standard energy units (e.g., kWh, MJ), which in turn are used to apply emission factors accurately. The tab supports users in translating real-world fuel consumption into CO_2e emissions, ensuring consistency with UK national inventory methodologies.
Haul definition	"Haul" refers to the distance category of a journey, primarily used for classifying flights and freight trips. For flights, DEFRA typically defines hauls as follows: Domestic (<785 km), Short-haul (785–3,700 km), and Long-haul (>3,700 km). Emission factors vary by haul due to differences in fuel efficiency, cruise length, and altitude-related impacts. For freight, haul definitions may distinguish between short, medium, and long-distance deliveries by road. These definitions are crucial in selecting the correct emissions factor, as the environmental impact per kilometre can differ significantly by haul type. The definitions are usually included in the footnotes or guidance columns within relevant tabs.

A complete set of up-to-date emission factors introduced into the new CO_2 assessment and management model is available in **Appendix 3 - UK Defra emission factors.xlsx**

PL KOBIZE

The National Centre for Emissions Management (KOBiZE) in Poland is a specialized governmental body operating within the Institute of Environmental Protection – National Research Institute (IOŚ-PIB). Its primary responsibility is to manage, collect, and report data on greenhouse gas emissions and other air pollutants, ensuring compliance with national, EU, and international climate obligations. KOBiZE plays a central role in administering the EU Emissions Trading System (EU ETS) in Poland by overseeing the registration and verification of emissions from industrial installations. Additionally, it supports the Ministry of Climate and Environment in developing environmental policies and prepares Poland's official greenhouse gas emissions inventory submitted to the European Commission and the United Nations. Through its work, KOBiZE promotes transparency and provides public access to emissions data, contributing to Poland's broader climate and air protection efforts. The **Tab. 2**.16 below presents emissions indicators for electricity produced in fuel combustion installations and for end users of electricity, determined using data from the National Database on Greenhouse Gas Emissions and Other Substances.

Tab. 2.16 Emissions indicators in [tonnes/MWh] for end users of electricity
Source: Based on KOBiZE, (2024).

Substance (EN)	[tonnes/MWh]
Carbon dioxide (CO_2)	597,0
Sulfur oxides (SO_x/SO_2)	0,363
Nitrogen oxides (NO_x/NO_2)	0,392
Carbon monoxide (CO)	0,222
Total particulate matter (PM)	0,014

Emissions indicators related to electricity production will be applied in a new model for assessing the emissions level of transport processes. The calculation of emissions associated with the charging of electric vehicles is an important element in assessing the carbon footprint of transport processes. The assessment of emissions associated with the charging of electric vehicles is an important element of the GHG Inventory specified in the GHG Protocol, under Scope 2 emissions. Details of the activities measured under this scope are presented in **chapter 2.2**.

2.4. Compliance of existing management methods with aspects of carbon footprint management of transport processes

The literature review indicated the potential for exploiting elements of existing management methods as a reference point for defining measurement principles, identifying dependencies between supply chain participants, and constraining the creation of transport emissions management methodology. Hence, a further literature analysis had to be executed to precisely identify the key elements of common transport management methods. According to Schermerhorn (2011) "An organisation is a collection of people working together to achieve a common purpose. It is a unique phenomenon that enables its members to perform tasks far beyond the reach of individual accomplishment". It has been observed in the past that the ultimate goals of the management concepts that are widely implemented and applied within existing organisations is to improve the efficiency of selected processes and the organisation's overall performance through management of perceives problems, gathering of various information related to the identified problem and analyses of the alternative courses of actions combined with effective decision making (Mueller, 1972). However, due to the long time in which Mueller's management goals were formulated, such an approach must take into account the results of the latest research. This can be achieved in a number of ways. The literature reviewed indicates that process quality improvement can be achieved through a variety of means. Yumhi et al. (2024), based on the results of desk research, interviews and observations, point to the important role of knowledge transfer systems within an organisation. The Knowledge Management System (KMS) proposed by the researchers, based on MySQL database technology, has the potential to store significant amounts of information, while the use of appropriate programming languages, especially PHP, allows for easier access by creating a user-friendly interface. IT system supported knowledge transfer within an organisation impacts its development despite of its structural changes over the time with a strong(Ren et al., 2024) According to Ren et. al. (2024) research it is strongly depended intra-project relationship between project stakeholders. Research conducted within Spanish vine industry reveals strong connection between sustainability level of organisation and knowledge flow. Research conducted among 202 Spanish wineries reveals strong connection between knowledge management and Sustainable Performance (SP). Thus, it is possible to include elements of emissions management of transport processes in the knowledge base, so that management methods developed within organisation can be applied to future transport operations.

Research based on literature review conducted by Tang et al. (2024) points out better trade-off between performance improvement and energy savings resulting in CF mitigation. The increase of efficiency in this area often leads to the limitation of the emissions of the products and services of the organisation. The increase of the overall effectiveness of the organisation can be observed by the achievement of the goals and objectives of the company in a timely manner. Improving the quality of products or services can be achieved within a "small steps" method, which comes from the Lean Management concept and Kaizen approach(Chen et al., 2024). Management methods focus on employee satisfaction as another key parameter of the organisation, therefore it is another good indicator of the condition of internal and external processes. Employees working within the organisation can provide the best feedback on the quality of the organisation and structural level. A low employee fluctuation rate may indicate a good organisation, but the state of the labour market and external economic conditions must also be taken into account in such an assessment. According to the empirical research based on data from "China's 100 Best Employers Award" conducted by Zhang et al. (2024) employees are willing to work in organisations that reflect not only economic and social aspects but also environmental ones. Environmental awareness is constantly growing among the employees not only in Asia, but in other parts of the world such as Europe and South America which is also reflected in ESG approach that organisations are willing to refer to(De La Torre-Torres et al., 2024). The organisational steps taken by management to reduce the carbon footprint of the entire supply chain is also a critical element of the organisation that employees evaluate. Examples from agricultural supply chains points out importance of management practices impact on strategic planning to align resources and processes with long-term goals to achieve sustainable growth and increase competitiveness(Jumoke Agbelusi et al., 2024). Simultaneously incorporation of proper strategies combined with usage of technologies based on renewable energy sources, even within such specific supply chains reveals benefits on carbon footprint level mitigation. Sustainable development elements reflected in the most popular supply chain management methods also consider risk management as a possible way to mitigate risks that may result not only in loss of assets, resources, infrastructure elements, but also to avoid sudden increase in emissions that would affect the overall level of the organisation's carbon footprint(Pojasek, 2023). Research conducted by Pojasek (2023) underline the importance of incorporation of standards such ISO (Organisation for Standardisation) within supply chain in order to ensure better focused on applicability of standards and legal frameworks requested during the GHG inventory within transportation supply chain. The following **Tab. 2.17** outlines the key management elements and potential impact assessment on the supply chain's carbon footprint.

Tab. 2.17 Key management methods objectives in the context of supply chain carbon footprint management

Source: own elaboration.

Key management methods objectives	References	Assessment of potential influence on supply chain's carbon footprint	Elements to be exploit in the created GHG assessment methodology
Efficiency improvement	(Martyushev et al., 2023; Bais-Moleman et al., 2018; Moyano-Fuentes et al., 2020)	High	Efficient use of means of transport for the transport of defined goods
LCA product management	(Civancik-Uslu et al., 2019a, 2019b; Cordella et al., 2008; Pellengahr et al., 2023)	High	LCA analysis of products in the context of their transport handling. Planning of transport processes in a way that supports mitigation of product-related emissions.
Effectiveness improvement	(Ingrassia et al., 2020; Ren et al., 2024)	High	Striving to increase the efficiency of process realisation in terms of the degree of utilisation of the loading space of means of transport, the route and all elements indicated in the literature review and survey.
Quality Improvement	(Carbone et al., 2003; Kogler and Rauch, 2023)	Medium	Striving to improve the quality of transport processes can contribute to mitigating their carbon footprint. The pursuit of quality

Key management methods objectives	References	Assessment of potential influence on supply chain's carbon footprint	Elements to be exploit in the created GHG assessment methodology
			also applies to transport services provided by third-party service providers (3PL). Emissions generated by external transport operators are classified as Scope 3 emissions in accordance with the GHG Protocol. The new model for measuring and managing the carbon footprint of transport processes can be adapted to the quality policies of transport companies and integrated into existing quality mechanisms.
Waste management	(Abdissa et al., 2022; Arena et al., 2021)	Medium	Reducing emissions associated with post-consumer waste can be an important part of managing a company's carbon footprint. This area is addressed in more detail in PAS 2050, which supports LCA analysis of products with the aim of reducing their carbon footprint. No clear link to transport processes.
Employee Satisfaction	(Yumhi et al., 2024; Zhang et al., 2024)	Low	As with customers, employees may also consider transport processes that are undertaken in a sustainable and low-carbon manner to be more attractive. In this context, the results of the transport chain's emissions assessment can be incorporated

Key management methods objectives	References	Assessment of potential influence on supply chain's carbon footprint	Elements to be exploit in the created GHG assessment methodology
			into internal and external communications, which can contribute to improving employee satisfaction.
Customer Satisfaction	(Shin and Thai, 2016)	Medium	The implementation of low-carbon transport processes can translate into customer satisfaction. In this context, it is possible to adapt a new model of managing transport emissions in order to improve the perception of the company by stakeholders, including end customers.
Adaptability to change	(Singh et al., 2024)	High	The ability to adapt to dynamic changes within the supply chain can be an essential element in the effective evaluation of the level of emissions within the supply chain.
Strategic Planning	(Jumoke Agbelusi et al., 2024; D'Amato and Korhonen, 2021; Tseng and Hung, 2014; Miller et al., 1996)	Medium	The results of the emission assessment and possible ways to mitigate the carbon footprint can be incorporated into the company's strategic planning.
Risk Management	(Pojasek, 2023)	High	Risk management is an important element affecting the resilience of supply chains. Contingency plans prepared for the occurrence of risks should take into account the risk of emissions.

It has been revealed that each management concept focuses on a specific area, so the path to achieving process excellence is slightly different. The management concept of Six Sigma focuses on process improvement by reducing errors and limitation of variation in business processes may also reflect environmental aspects, turning this well-known method into Green Six Sigma (GLSS) approach (Farrukh et al., 2024). Such approach allows companies to manage their emission levels better and to avoid penalties and follow the set emission levels. The Kaizen method similarly focuses on process improvement, but the achievement of process excellence is supported not only by the method of small steps but also by improved understanding of drivers influencing of the efficiency level of supply chain (Moyano-Fuentes et al., 2020). The concept of Lean Management (LM), characteristic for manufacturing and logistics companies, focuses on the determination the ultimate objective of which is to minimise waste (jap. MUDA) and maximise added value of products and services while simultaneously minimising the amount of resources used (Piotrowicz et al., 2023). The principles characteristic of lean management include: taking into account the customer's perspective, value stream mapping, process flow mapping and identification of bottlenecks, along with a pull system introduction to support production in line with current market demand and the pursuit of excellence through the implementation of continuous change in a step-by-step approach, which makes this method capable of significantly improving the efficiency of companies with different business profiles (Bertagnolli, 2022). The Theory of Constraints (TOC) concept, referring to the Continuous Improvement method used in LM, aims to identify and eliminate bottlenecks in organisational processes, leading to the elements of this concept being readily implemented in other management methods. Another very interesting concept is the Agile approach, whose main assumptions indicate the possibility of agile project management, which translates into the ability to quickly adapt the organisation to changing requirements. The concept is most often applied in the service industry (Stachowiak et al., 2013). Agile process management and its characteristic iterative approach can be adopted in the Business Process Reengineering (BPR) concept, the main idea of which is to radically re-engineer essential logistics processes and put them into operation. The choice of the right process design could be made using the iterative approach, during the evaluation of the essential performance indicators proposed in another concept Objectives and Key Results (OKR). Management concepts focused on efficiency and process organisation provide an opportunity for the use of environmental performance indicators in business management. The following Tab. 2.18 identifies the main management methods, elements of which could be used in the created methodology for managing transport emissions

Tab. 2.18 Main management methods elements that may be reflected in transport emissions assessment method

Source: own elaboration.

Process improvement management methods	Environmental aspects	Process excellence	Process failure minimalisation	KPI monitoring	Logistics process adaptivity	User oriented method	Problem solving	Services	Transportation	Production	Warehousing
Six Sigma		x	x		x			x	x	x	x
Theory of Constraints		x		x			x	x	x	x	x
Total Quality Management								x	x	x	x
Lean Management		x	x	x			x			x	x
Agile		x			x	x			x		
Kaizen		x		x							
Management by Objectives				x							
Objective and Key results		x		x							
Corporate Social Responsibility	x			x		x			x		
Business Process Reengineering (BPR)		x	x				x	x		x	
Knowledge Management (KM)						x		x	x	x	x
Design thinking						x	x				

Considering the identified management methods, some of those elements have been pointed out as a potential opportunity to introduce environmental performance indicators. Based on conducted research it was identified that management companies using these methods have the possibility to include the evaluation of the carbon footprint as a primary or supplementary parameter in the assessment of process efficiency. Inclusion of emission-related management methods can support decision making process, maintain sustainability level and increase resilience level of a supply chain. The parameter can also be used not only in performance evaluation, but also in decision-making processes when re-shaping (Business Process Reengineering method) or creating a new processes and when setting targets for the entire organisation and supply chain (CSR method).

Risk management elements within sustainable transport supply chains for better emissions management

Risk management plays a critical role in the context of road process management and its associated emissions, as it enables organisations to proactively identify, assess, and mitigate uncertainties that may hinder environmental performance. Road transport is inherently exposed to a range of risks—operational, regulatory, technological, and environmental—that can significantly influence emission levels and sustainability outcomes. Effective risk management allows for the anticipation of disruptions such as fuel price volatility, changes in environmental regulations, and infrastructure constraints, which directly impact emissions and efficiency. Relevant research has also been carried out on risk mitigation supported by IT tools as part of supply chain quality management (Zimon et al., 2022). Moreover, managing risks related to route planning, vehicle maintenance, and driver behaviour contributes to reducing unnecessary fuel consumption and associated greenhouse gas emissions. Integrating risk management into transport planning enhances decision-making by providing a structured approach to evaluating trade-offs between economic efficiency and environmental impact. It also supports compliance with evolving climate policies, such as those under the European Green Deal, by embedding resilience and adaptability within logistics operations. By quantifying and controlling emission-related risks, organisations can implement more reliable carbon reduction strategies. This is especially important in achieving long-term decarbonisation targets and maintaining competitiveness in a sustainability-driven market. Ultimately, a robust risk management framework ensures that environmental objectives are not compromised by unforeseen operational challenges, promoting both ecological responsibility and economic viability in road transport systems. Simultaneously, supplier selection can also relate to defined risks. Assessing the risks associated with supplier selection can be an important part of the decision-making process of supply chain management (Urbaniak et al., 2022). The selection of a suitable carrier can be performed from the perspective of parameterised risks and used in a multi-criteria analysis. Elements of this solution have been applied in the new CF assessment model, the logic of which is outlined in chapter 4.

A dedicated environmental efficiency indicator may be proposed for all identified elements of the sustainable management concept exploited within supply chains. Regarding risk management, environmental-related risks may be assessed with the support of potential emission levels. Transparency is strongly related to sharing knowledge among stakeholders and basic data availability for evaluation. Social performance level can be assessed with strong support of verification of environmental aspects that can impact local communities and be introduced within organisational values and ethics.

The latest publication by Tsang et al. (2024) examines the impact of the Ukrainian-Russian war on Global Supply Chains (GSCs). Applying the Cumulative Abnormal Return (CAR) methodology, the impact of the war on different companies from Asia, America and Europe was evaluated in terms of their stock market value. The result of the research has underlined the importance of introducing ESG elements within the GSC. Nevertheless, different levels of resistance were observed across various industries.

It has been pointed out that the implementation of appropriate risk management strategies in advance can help to mitigate the consequences of further disruptive events, not only related to war.

The introduction of the concept of Industry 4.0, along with related technologies, is pushing today's SC to become more sustainable in terms of resources used(Chauhan et al., 2022). This can be supported by a concept of IoT, AI and digital twin, but such solutions would require better digitisation of processes and proper understanding of each tool integrated into SC. Research has revealed that the impact of cloud solutions can positively influence the degree of digitalisation of supply chains (Gammelgaard and Nowicka, 2023). This has the effect of minimising the risks associated with a lack of sufficient quantity and quality of data to adequately manage the supply chain.

The objectives of the European Union focused on the decarbonisation of the European economy. To mitigate economy's impact on climate change, recommendations and legislation were issued (European Commission, 2020). The European Green Deal Act aims to create an emission-neutral economy within the European area by 2050. This requires in-depth research on ways to achieve such state and investments dedicated to technological improvement of SSCs. Spatial Durbin model utilised within the research of Kwilinski et al. (2023) led to results that 1% increase in digital performance causes 0.001% increase in ESG index. A more in-depth analysis based on descriptive statistics shows that improving digitalisation within SSCs directly benefits all ESG performance elements - environmental, social and governance. **Tab. 2.19** below presents the main risks and their potential impact on increasing the level of emissions from transport processes.

Tab. 2.19 Key risks that may affect the level of CO_2 emissions resulting from transport processes
Source: own elaboration.

Risk	Reference	Description	Transport process continuity	Impact on transport processes emissions level
Inaccurate or missing transport distance data.	(Md. Rokibul Hasan, 2024)	Low Data quality, ERP or TMS input errors. Entered data can be cross-checked by predictive algorithms to avoid sudden emission increase or errors in emission reporting.	Low. Affects mainly reporting process.	High - emissions may be significantly over or underestimated.
Use of outdated emission factors.	(Li et al., 2025)	Lack of regular updates from DEFRA and other internal or external emission factors sources.	None. Affects only reporting process.	Medium to High - outdated data distorts CF assessment and lead to incorrect reporting.
Inaccurate fuel consumption records for own fleet.	(Tansini et al., 2025)	Telematics failure or manual reporting errors can result in sudden emission increase. Introduction of advanced telemetric equipment in Internal Combustion Engine Vehicles (ICEVs) and Mild Hybrid Electric Vehicles (MHEVs) shows a potential to mitigate the risk.	Medium. Influence both reporting process and operational costs estimations.	High - Scope 1 emissions might be calculated inaccurately.
Change in delivery routing without emissions recalculation.	(Lou et al., 2024)	Changing the route without analysing the most efficient route in terms of emissions.	Medium.	Medium to High - actual emissions are not reflected in decision process.
Lack of integration between TMS and carbon reporting tools.	(Du Plessis et al., 2023)	Failure to use an appropriate tool for collecting information on transport processes in distribution supply chains may result in data loss. Emissions will have to be assessed based on the assumptions, which will affect the level of GHG report accuracy.	Low. Affects mainly reporting process.	Medium. Risk of low GHG report outcome.
War or geopolitical instability.	(Tsang et al., 2024)	Regional conflicts impacts continuity of transport processes within supply chains. War events can influence significantly	High - disruptions, rerouting, blocked transport corridors.	High - longer routes and standby emissions

Risk	Reference	Description	Transport process continuity	Impact on transport processes emissions level
		routes design that would affect in unexpected emission increase.		increase overall transport related carbon footprint.
Poor data availability.	(Shang et al., 2024)	Lack of reporting discipline or manual processes.	Low.	High - carbon data gaps prevent accurate reporting
Low digitalisation of the supply chain.	(Wilson et al., 2024)	Low level of digitalisation influence data availability necessary for further CF assessment. In low data quality situation or limited access to data decision making process can be influenced leading to ineffective management.	High.	Medium to High - delays and inaccuracy in CF reporting, low quality of management and decision making.
Poor quality of distribution supply chains risk management	(Kareem et al., 2024)	Lack of governance, controls, escalation protocols. Can be avoided by proper implementation of Sustainable Enterprise Risk Management (SERM) supported by Systems Thinking (ST) or Systems Dynamics (SD) in transport specific frameworks.	Medium to High.	Medium. A lack of proper risk mitigation procedures may result in an increase in uncontrolled emissions and unreliable CF reporting.

A conducted literature review of the risk management and the impact of risks on emissions levels within the distribution supply chain identified the significance of this area. The collected information on the significance of individual types of risks is incorporated in a new CF assessment model for transport processes. Appropriate criteria indicating the potential level of risk were incorporated into the CF assessment model logic for decision-making and scenario assessment. The relevance of parameters related to risk management assessment was also verified in empirical research conducted among experts. Results of this research are presented in **chapter 3.2**.

3. Parameters influencing changes in emissions from transport process

The literature review presented in **chapter 1** and **chapter 2** identified several areas of sustainable supply chain, each characterized by distinct control parameters that influence both the efficiency of distribution transport processes and associated CO_2 emissions. In **chapter 3.1**, desk research was carried out to identify the key parameters highlighted in the literature. Since these factors determine changes in overall emission levels within distribution systems, their comprehensive identification and classification are essential for building the logic of the proposed CF assessment model. To validate these findings, expert research was conducted to assess the practical significance of the parameters for industry representatives.

Further analysis, presented in **chapter 3.3**, examined vehicle related parameters affecting emission levels. Using anonymized market data, the study identified a specific coefficient for fuel consumption growth linked to vehicle age, which can be integrated into the proposed emission calculation formulas for both heterogeneous and homogeneous fleets.

Chapter 3.4 and **chapter 3.5** focused on cargo units, evaluating the impact of alternative packaging types and reusable packaging solutions on CO_2 emissions and supply chain efficiency.

Chapter 3.6 presented research based on anonymized historical data from a manufacturing company, applying a multi-criteria assessment to transport service selection. This approach incorporated not only cost-related aspects but also quality indicators and emission level differences.

The empirical research confirmed the conclusions drawn from the literature review and provided the foundation for developing the logic of the new CF assessment model presented in **chapter 4**.

3.1. Identification of key control parameters of CO_2 emissions in distribution processes

Emission factors play a crucial role in the modelling of the overall carbon footprint of supply chains. Specific process' control parameters such as vehicle type, fuel quality, load utilisation, routing efficiency, and driving behaviour directly affect fuel consumption and emissions. However, understanding how these factors that can influence emission level is essential for developing certain strategies aimed at reducing CO_2 emissions. Hence, a in depth literature review in terms of key emission factors needs to be conducted.

Research shows that the efficiency of supply chain management methods is closely linked to specific control parameters that determine overall performance. Although effectiveness may be measured through various KPIs, their outcomes are shaped by carefully chosen operational factors. Within transport management, several parameters have been identified as critical to emissions. For example, the average distance has been recognized as a key determinant of greenhouse gas emissions (Luo et al., 2017), while in the context of biofuels, fuel quality plays a decisive role in shaping the carbon footprint of supply chains (Venkataraman and Rao, 2001). Other studies indicate that driving style and road capacity significantly influence fuel consumption in vehicles with combustion engines (Kakouei et al., 2012). Similarly, the implementation of automated toll systems has been shown to reduce emissions on high-speed roads (Pérez-Martínez et al., 2011). The use of electric trucks contributes to a reduction in fossil fuel use and emissions, although their effectiveness depends on route planning and the availability of charging infrastructure, making them best suited for line-haul operations with predictable traffic flows (Zhao et al., 2016). Additional findings reveal that vehicle speed, traffic density, driving dynamics, and urban topography are strongly correlated with fuel consumption, with efficiency improving under certain speed conditions(Zamboni et al., 2015). On a larger scale, national carbon footprints have been linked to traffic density, which in turn is correlated with GDP levels (Crippa et al., 2021).

Extensive literature review identifies several key control parameters shaping emissions in urban logistics, particularly distance travelled, traffic congestion, and the temporal distribution of traffic flows (Rudi et al., 2016). Other influential factors include vehicle load factor, transshipment schedules, and toll systems, each affecting fuel use and related emissions (Moufad and Jawab, 2018; Zamboni et al., 2015). Environmental and infrastructure-related variables, such as road network capacity, topography, and the climatic conditions have also been incorporated into new models for the assessment of emissions. Research further highlights the importance of road grade, vehicle velocity, coolant temperature, and vehicle mass, with driver-controlled choices, such as maintaining moderate speed or selecting routes with lower gradients, that prove effective in reducing consumption (Gao et al., 2019, 2020). Finally, cargo weight, cargo volume, and cargo density have been shown to directly affect energy consumption and emissions (Luo et al., 2017). An extensive research to point out the key emission factors has been conducted by Dubisz et al. (2022). During the brain storming session, experts revealed and important parameters, that in their opinion, influence the overall emission levels. Hence key fleet related parameters have been identified:

- Vehicle type;
- GVM (gross vehicle mass);
- Engine type;
- Truck body type;
- Tires' type and size;
- Age of vehicle;
- Rate of wear and tear on the vehicle.

The importance of identified key process parameters was in-depth investigated in the further expert panel research presented in **chapter 3.2**. The tables below present a review of the literature on essential control parameters that influence changes in transport process emissions.

Tab. 3.1 Key 'Road' category factors influencing level of transport processes emissions
Source: own elaboration.

Factor category	Factor	Reference	Scope of related research
Road	Distance travelled	(Quak et al., 2016)	The research conducted within European FP7 project FREVUE by Quak et al., (2016) was based on the analysis of use of over 100 electric vehicles in large European cities to perform transport tasks. An analysis of operational data, transported goods flow and financial parameters of process indicated a need to review the efficiency of using this type of vehicle, taking into account different user groups. In each user group, the distance travelled was an essential factor influencing the level of emissions achieved.
Road	Distance travelled	(Rudi et al., 2016)	The analysis conducted by Rudi et al., (2016) aimed at improving the efficiency of the transport process, took into account three essential parameters: emission levels, transport operational costs, and improvement of transport time. The analysis conducted for FTL intermodal transport, using multi-criteria analysis, indicated the high significance of the distance parameter as a key factor determining the highest changes in CO_2e levels, operating costs and transit time.
Road	Distance travelled	(Siragusa et al., 2022a)	The application of the LCA method to assess the environmental impact of EV and ICE vehicle use in a real-life case study conducted in Milan, Italy, identified both the boundaries for effective exploitation of electric vehicles for transporting goods in the e-commerce sector and the significance of the distance parameter for both types of the vehicles.
Road	Topography of road network	(Siragusa et al., 2022a)	Siragusa et al., (2022) have proposed a new approach to calculate emissions from e-commerce deliveries, that reflect key factors linked to the increase of the transport processes emissions. Average truck speed, geography elements of the area of operation, including topography and climate. The analyses were carried out using data from electric vehicles. The use of electric vehicles in relation to the identified key parameters influencing emissions level resulted in a reduction of those up to 54%, depending on the specific use case scenario.
Road	Topography of road network	(Moufad, 2018)	Research on urban freight transport (UFT) conducted by Moufad and Jawab (2018) pointed to the important role of this form of transport within the city centres. The researchers indicate the importance of including environmental parameters in the assessment of UFT efficiency, in addition to organisational and financial parameters. The most important parameter for which the final conclusions of the research were defined was the topography of the road network in the city of Fez, where the case study was conducted.

Factor category	Factor	Reference	Scope of related research
Road	Topography of road network	(Gao et al., 2019)	The analysis of Euro 6 emission standard vehicles identified that driving in accordance with eco-driving principles significantly reduces emissions. The frequency of sudden increases in engine RPMs (Rotate per minute) and starting from a stop during the route had the greatest impact on emissions. Changes in RPM were mainly caused by the class of roads, their geography and the layout of the road network. The research identified a strong correlation between the level of emissions and the grade of the road.

Tab. 3.2 Key 'Traffic' category factors influencing level of transport processes emissions
Source: own elaboration.

Factor category	Factor	Reference	Scope of related research
Traffic	Traffic congestions, distribution of traffic over time	(Quak et al., 2016) 16	Research conducted by Quak et al., (2016) indicates the high significance of traffic congestion, especially in transport operations carried out in city centres. Adapting the appropriate type of electric vehicle, from small vans to medium and large vehicles, can help mitigate emissions caused by limited road network capacity.
Traffic	Traffic congestions, distribution of traffic over time	(Siragusa et al., 2022a) 48	Research conducted in Milan, Italy, indicates the impact of traffic congestion on the overall efficiency of both combustion engine vehicles (ICEVs) and electric vehicles (EVs). It is suggested that accurate prediction of traffic intensity changes can support the efficiency of transport processes. This requires the implementation of appropriate management rules within the supply chain. However, a critical factor to consider is the possibility of unpredictable events that may disrupt the continuity of the transport processes and result in the increase of emissions.
Traffic	Traffic restriction	(Pérez-Martínez et al., 2011)	Traffic restrictions analysed in the case of the AP-41 motorway in Spain showed the impact of different toll collection solutions on emissions and road network capacity. The first scenario involved the use of a stop-and-go toll system, the second a free-flow system, and the third involved the use of Electronic Toll Collection (ETC) technology. It was identified that the inclusion of the free-flow option, that does not impose speed reduction, allows for a reduction of CO_2 emissions on the toll section by 92.6% compared to the stop-and-go option. The use of ETC technology, that requires speed reduction on the toll section, indicates a reduction of emissions by only 4% compared to the stop-and-go option. Pérez-Martínez et al. (2011) research results indicate the high importance of traffic restrictions that cause deceleration and acceleration for the change in transport process emissions.
Traffic	Traffic restriction	(Quak et al., 2016)	Research conducted by Quak et al. (2016) indicates the high significance of traffic restrictions. A study involving 100

Factor category	Factor	Reference	Scope of related research
			electric vehicles conducted, among others, in Amsterdam, London, Madrid and Oslo identified that traffic restrictions in strict city centres contribute to an increase in last mile delivery emissions from resulting from ICEVs.
Traffic	Traffic restriction	(Siragusa et al., 2022a)	Siragusa et al. (2022) in the proposed method for assessing emission levels, also point to the need to take into account traffic conditions and related restrictions. When analysing transport processes carried out in areas subject to restrictions, it is suggested that restrictions be taken into account in one of the assessed scenarios in emissions evaluation iterative approach.
Traffic	Traffic density	(Crippa et al., 2021; Zamboni et al., 2015)	The use of Heavy Duty Vehicles (HDV) for transport processes can lead to a sudden increase of transport processes emissions. Accurate knowledge of speed ranges and route planning for HDVs at specific periods allows heavy traffic density periods to be avoided. Research conducted by Zamboni et al. (2015) identified that maintaining predictable speed patterns allows emissions to be managed in a more reliable manner. Simultaneously, an analysis of the European report "GHG emissions of all world countries" (Crippa et al., 2021) presenting global historical emissions related data indicates a correlation between economic development and increase in high traffic density, that if not properly managed, can result in uncontrolled growth of transport emissions and decrease of their level of efficiency.
Traffic	Traffic density	(Andrés and Padilla, 2018)	Andreas and Padila (2018) point to the important element of traffic density in their analysis based on the Stochastic Impact on the Environment by Regression on Population, Affluence and Technology (STIRPAT) model. In their approach, they verify in detail the perspective of changes in transport processes emission levels among all EU Member States in the years 1990-2014. The research conducted is an attempt to assess the effectiveness of the legal regulations introduced in the Transport White Paper, indicated in **Tab. 1.5** in the **chapter 1.1**.
Traffic	Traffic density	(Gao et al., 2019)	Research conducted by Gao et al. (2019) indicates that high congestion on urban road networks affects the fuel consumption dynamics of diesel vehicles. Driving short distances and frequently starting and stopping engine results in a 50% increase in exhaust emissions compared to the same distance without stopping the engine. Sudden changes in speed and acceleration caused by road traffic changes can result in a dynamic increase of emissions. Research also points to the benefits of eco-driving, however, maintaining those principles within urban conditions can be difficult to follow.
Traffic	Speed limitation	(Zamboni et al., 2015)	Research conducted by Zamboni (Zamboni et al., 2015) identified that road infrastructure elements forcing drivers to reduce speed and then accelerate significantly affect

Factor category	Factor	Reference	Scope of related research
			emission levels and their components (NOX). The research was conducted using Heavy Duty Vehicles (HDVs). The research identified an increase in fuel consumption in urban transport on sections of routes where speed limits were in place.
Traffic	Speed limitation	(Gao et al., 2019)	The conclusions drawn from the research by Gao et al. (Gao et al., 2019)(2019) point to the importance of speed limits, in addition to the parameter classified as 'traffic density'. Speed limits has a similar effect on the level of emissions from transport processes. Enforcing sudden speed reductions and acceleration makes it difficult to follow eco-driving rules.

Tab. 3.3 Key 'cargo' category factors influencing level of transport processes emissions
Source: own elaboration.

Factor category	Factor	Reference	Scope of related research
Cargo	Load Factor	(Cheah and Huang, 2022)	Research conducted on China's e-commerce market indicates a trade-off between delivery cost and delivery time. Through choosing the delivery method, customers influence the packaging and efficient utilisation of means of transport. The research conducted among 188 survey participants identified that most respondents are ready to adjust their purchasing decisions to achieve a compromise between cost, delivery time and its carbon footprint resulting in increase of emissions from transport logistics operations.
Cargo	Load Factor	(Luo et al., 2017)	Research conducted by Luo et al. (2017) on parameters affecting passenger transport emission levels is based on comparative analysis. This research indicates that load parameter is one of a few important factors determining the carbon footprint of transport processes. Appropriate cargo management, in this case passengers, may consist of proper route scheduling in relation to the order of pick-up and drop-off points. Thus, it is possible to improve the management of vehicle load efficiency. The conclusions were drawn on the basis of an analysis of the urban transport sector in Shanghai and Tokyo.

Tab. 3.4 Key 'fleet' category factors influencing level of transport processes emissions
Source: own elaboration.

Factor category	Factor	Reference	Scope of related research
Fleet	Vehicle mass	(Grythe et al., 2022)	Research conducted in Norway on the potential for reducing CO_2 emissions used the Norwegian Emission from Road Vehicle Exhaust (NERVE) model. An analysis of data collected from 2009 to 2020 identified a potential reduction in

Factor category	Factor	Reference	Scope of related research
			emissions per kilometre of up to 22% since 2009. This mainly applies to light vehicles, due to the growing popularity of electric vehicles. The NERVE database and the method of continuous data collection on emissions provide a good model for implementation in other regions. The continuous exchange of data provided by NERVE can also contribute to influencing road network capacity and supporting effective transport management.
Fleet	Vehicle mass	(Wang et al., 2023)	Wang et al. (2023) research revealed importance of a fleet parameter by showing how heterogeneous fleets must be managed under traffic restrictions while minimizing emissions. Battery and cargo capacity are identified as key constraints, directly shaping routing efficiency and carbon output. The results underline that effective fleet composition and optimisation are crucial for reducing emissions and adapting to urban logistics restrictions
Fleet	Vehicle type	(Siragusa et al., 2022b)	Research shows differences in environmental and economic performance of electric vehicles (EVs) and internal combustion engine vehicles (ICEVs) in last-mile delivery fleets. Fleet composition based on EVs revealed a direct impact on both operating costs and CO_2 emissions. Although EVs involve higher initial investment, their lower running costs and significantly reduced greenhouse gas emissions demonstrate that fleet decisions strongly influence the sustainability of transport processes.

Tab. 3.5 Key 'fuel' category factors influencing level of transport processes emissions
Source: own elaboration.

Factor category	Factor	Reference	Scope of related research
Fuel	Type of fuel	(Venkataraman and Rao, 2001)	The Research conducted by Venkataraman and Rao (2001) connects to the fuel factor by demonstrating how the type and quality of fuel significantly influence emission levels. Different biofuels wood, and briquettes produced varying amounts of carbon monoxide and particulate matter, highlighting that combustion efficiency depends strongly on fuel properties. In comparison with traditional stoves, improved models reduced pollutant emissions per unit of energy from wood combustion by kW h-1. The findings show that promoting cleaner alternatives, such as biogas, and improving stove design can reduce emissions, underlining the role of fuel selection in managing both environmental and health impacts.
Fuel	Type of fuel	(Thibbotuwawa et al., 2019)	Energy consumption is treated as a core factor influencing Unmanned Aerial Vehicles (UAV) routing efficiency. Although UAVs do not rely on conventional

Factor category	Factor	Reference	Scope of related research
			fuels, their performance depends on the type and amount of energy used, which directly affects fuel consumption in traditional vehicles. By analysing parameters that affect UAV energy demand during delivery missions, the research highlights how energy efficiency functions as a fuel-equivalent factor. Hence a complete comparison with traditional form of last mile delivery could be conducted. UAV electric powered vehicles provides a better environmental performance and support CO_2 mitigation within distribution process.

Detailed review of the literature presented in **Tab. 3.1, Tab. 3.2, Tab. 3.3**., **Tab. 3.4** and **Tab. 3.5** due to the variety of perspectives and research approaches resulted in summary of a key parameters presented in below **Fig. 3.1**.

ROAD	TRAFFIC	CARGO	FLEET	FUEL
• Distance travelled • Topography of road network	• Traffic congestions and distribution of traffic over time • Traffic restrictions • Traffic density • Speed limitations	• Load factor • Transshipment schedule • Cargo volume and density	• Vehicle mass (size) • Number of vehicles • Vehicle type • Vehicle age	• Type of fuel

Fig. 3.1 Key parameters of the transport process affecting its emission level
Source: own elaboration.

The analysis identified five categories of parameters: road, traffic, cargo, fleet, and fuel. Given the scope of influence available to decision-makers when designing transport processes, these parameters were aggregated into three broader areas requiring further examination: Fleet, CO_2 efficiency, and Road. The Fleet category encompasses factors related to vehicles and their payloads. The CO_2 efficiency category includes parameters that directly determine emissions, such as engine performance, vehicle condition, and fuel quality. Road-related parameters act as indirect drivers and cover distance, weather, temperature, terrain, and road types. These categories can be further distinguished as internal and external parameters: internal factors concern the composition of a heterogeneous fleet and its specific emission characteristics, whereas external factors comprise efficiency elements influencing CO_2 emissions, together with road conditions. Detailed information on each parameter group is presented in **Tab. 3.6** below.

Tab. 3.6 Main emission factors and detailed control parameters in each group
Source: own elaboration.

	Main Factor		
	Fleet	CO_2 Efficiency	Road
Control parameters of the factor	• Truck type • GVM • Engine size • Fuel type • Truck body type (i.e. Reefer, curtain-sider, Flatbed, Tanker, lowboy etc.)	• The efficiency of the combustion engine • The degree of wear of the vehicle • Fuel quality	• Distance • Weather conditions • Outer Temperature • Topography of route (Hills on the route)

	Main Factor		
	Fleet	CO_2 Efficiency	Road
	• Tyre type and size • Truck capacity • Cargo weight and volume	• The number of fuel octanes	• Road types

Fleet parameter

To ensure the practical relevance of this parameter, its application under real transport conditions must be specified. Within the first group of control parameters, relating to fleet type, the Gross Vehicle Mass (GVM) of each truck engaged in supply chain operations is considered. Alongside other vehicle-specific characteristics, the physical attributes of the payload must be defined, as the weight and volume of transported goods directly influence energy consumption and, consequently, emission levels. Maximizing vehicle load utilisation is therefore essential, as higher filling rates reduce the number of dispatches required and thereby lower overall emissions.

CO_2 Efficiency

Specific factor influencing emission levels is CO_2 efficiency, defined as the ability of an internal combustion engine to convert fuel into the energy required to move the vehicle. In simplified terms, this can be expressed as the number of litres of fuel consumed per 100 km. Fuel consumption rates were identified in detail for selected vehicle groups by Gross Vehicle Mass (GVM) category, based on surveys conducted with carriers. These results were subsequently compared with manufacturer-reported consumption data and findings from market research. In addition, other control parameters related to CO_2 efficiency, such as fuel quality and octane rating, must also be taken into account during the CF assessment.

Road

The road factor is primarily defined as the total distance to be covered along a given route. This distance, however, is influenced by indirect parameters such as weather conditions and temperature. In addition to the length of the route, factors including terrain, elevation changes, road types, and surface quality exert a significant impact. The interrelationships between the identified fleet parameters are illustrated in **Fig. 3.2**. The purpose of this figure is to highlight the connections among these parameters and to demonstrate their combined influence on the overall carbon footprint of transport processes.

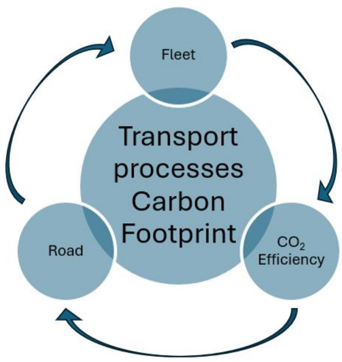


Fig. 3.2 Interconnections between key factors influencing carbon footprint level within Sustainable Supply Chains

Source: own elaboration.

The collected information on essential control parameters is used in the new CF assessment model. Essential parameter categories have been considered in the proposed logic of the model for the model to be useful and consistent with the identified research results.

3.2. Expert research for determination of the significance level of key process parameters

During the literature research, essential parameters with a potential impact on changing the level of transport process emissions were identified and classified in **chapter 3.1.** Based on this research the main types of parameters that may be used in the new management method were selected. However, due to the utilitarian aim of the new model for managing transport process emissions within sustainable supply chains, it was decided to conduct the expert research to verify the significance of the selected parameters from a practical perspective.

Analysing the method of conducting research with experts, it was concluded that in order to guarantee the credibility and reliability of the results obtained, it is necessary to collect a sufficient number of responses from experts. Referring to the Delphi method, which focuses on collective communication with experts in order to determine opinions on a specific topic, 30 responses are considered sufficient to conduct expert research(Hsu and Sandford, 2007). However, the exact number of experts participating in the research may depend on the specific characteristics of the issue being analysed. Brinkmann and Kvale (2015) indicate that a typical expert interview consists of 10-20 experts from a specific field. The results obtained from such a group of respondents can be considered reliable.

Characteristics of the experts involved in the research

According to the reviewed literature, efforts were made to maximise the number of experts participating in the research in order to increase its reliability. A computer-based questionnaire was employed to collect responses from 71 logistics management experts. The respondents came from companies with different business profiles. The NACE classification was used to categorise the responses in order to determine the area of activity of the expert's companies. The NACE classification is the European system for categorizing economic activities to ensure consistent statistical reporting across EU countries(Eurostat, 2008). It groups businesses by their main activity using a hierarchical coding structure. The **Fig. 3.3** below shows the percentage share of experts according to the NACE classification in the conducted Expert Research. The most important category from the point of view of the methodology developed is 'H - Transportation and Storage' due to the dominant nature of transport processes within the companies of 'H' type. The category represents 66,2% (47 experts) of the opinions collected from experts. Other important categories of enterprises from which responses were collected include "A - Agriculture, Forestry and Fishing" (14 experts) and "C – Manufacturing" (7 experts). In case of "A" and "C" categories, transport does not represent the core business activity, however, it is an important element supporting their primary operations. Hence, conclusions regarding the significance of individual parameters affecting the level of emissions from transport processes will allow for cross-verification of answers provided by experts from the most essential category ("H - transportation and storage") from the methodology being developed perspective.

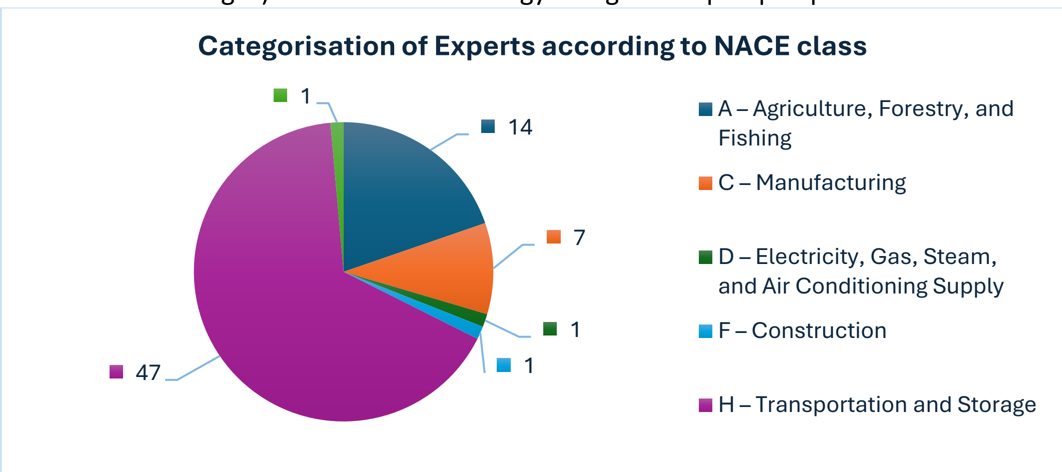


Fig. 3.3 Categorisation of experts according to NACE class
Source: own elaboration.

Subsequently, the size of the experts' organisations was analysed. Scale starting with the first category of 1 to 9 employees was proposed in order to identify small companies. Two further categories indicated small and medium-sized companies (10-49 employees and 50-250 employees). The last of the proposed categories was intended for large enterprises with more than 250 employees. **Fig. 3.4** below shows the distribution of the share of experts by the size of their organisations.

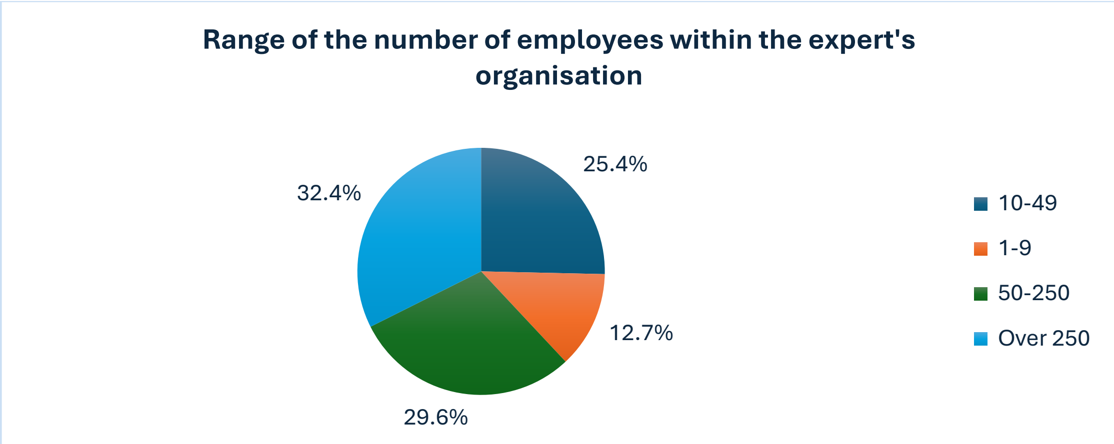


Fig. 3.4 The number of employees within the expert's organisation
Source: own elaboration.

As identified in the Dietz et al., (2018) research, larger organisations demonstrate a greater ability to measure and manage their own carbon footprint. Therefore, the participation of experts from larger organisations legitimises the results obtained in the further part of this research. The significance of individual parameters indicated by the experts has a more utilitarian value from the perspective of establishing a new model for managing the carbon footprint of transport processes within sustainable supply chains. However, it is important to note that the significance of the parameters assessed by the experts may vary depending on the size of the company. Therefore, the size of the experts' companies was analysed in relation to their NACE classification. The results are presented in **Tab. 3.7** below.

Tab. 3.7 Level of employment in experts' organisations by NACE classification
Source: own elaboration.

Employment Range	A – Agriculture, Forestry, and Fishing	C – Manufacturing	D – Electricity, Gas, Steam, and Air Conditioning Supply	F – Construction	H – Transportation and Storage	K – Financial and Insurance Activities
1-9	50.0%	0.0%	0.0%	0.0%	4.3%	0.0%
10-49	21.4%	42.9%	100.0%	100.0%	21.3%	0.0%
50-250	21.4%	42.9%	0.0%	0.0%	31.9%	0.0%
Over 250	7.1%	14.3%	0.0%	0.0%	42.6%	100.0%

Furthermore, the types of loading units used by experts' companies for last mile delivery have been reviewed. The results are presented in **Tab. 3.8** below. Pallets, parcels, and bulk cargo have been identified as the most important basic loading units. However, bulk cargo is used mainly in the agricultural (Class A) and manufacturing (Class C) sectors. Pallets and parcels are important from the perspective of transport supply chain management and were identified as the most important in class H - Transportation and Storage. In this class, experts identified parcels (74.5%) and pallets (14.9%) as the main loading units used in the transport to customers.

Tab. 3.8 Type of primary loading unit in transport to final recipients
Source: own elaboration.

Type of primary loading units	A – Agriculture, Forestry, and Fishing	C – Manufacturing	D – Electricity, Gas, Steam, and Air Conditioning Supply	F – Construction	H – Transportation and Storage	K – Financial and Insurance Activities
Bags	21.4%	0.0%	0.0%	0.0%	0.0%	0.0%
Big Bags	21.4%	14.3%	0.0%	100.0%	2.1%	0.0%
Big boxes	0.0%	0.0%	0.0%	0.0%	4.3%	0.0%
No cargo units, bulk loading	50.0%	28.6%	0.0%	0.0%	2.1%	0.0%
Pallets	0.0%	42.9%	100.0%	0.0%	14.9%	0.0%
Parcels	7.1%	14.3%	0.0%	0.0%	74.5%	100.0%
Cars on a tow truck	0.0%	0.0%	0.0%	0.0%	2.1%	0.0%

Attention was also drawn to the importance of transport operations between locations within the supply chain. Research conducted by Garcia and You, (2015) indicates that transport between key locations within the network also contributes to emissions throughout the supply chain. Therefore, experts were requested to define the type of loading units used in intra-company transport within their organisation's supply chains. The types of loading units are presented in the **Tab. 3.9** table below.

Tab. 3.9 Type of primary cargo units engaged in the transport processes between locations within expert's organisation supply chain
Source: own elaboration.

Type of primary loading units	A – Agriculture, Forestry, and Fishing	C – Manufacturing	D – Electricity, Gas, Steam, and Air Conditioning Supply	F – Construction	H – Transportation and Storage	K – Financial and Insurance Activities
Big Bags	1.4%	0.0%	0.0%	0.0%	2.8%	0.0%
Big boxes	0.0%	1.4%	0.0%	0.0%	1.4%	1.4%
No cargo units, bulk loading	15.5%	4.2%	0.0%	0.0%	4.2%	0.0%
Pallets	1.4%	4.2%	1.4%	0.0%	56.3%	0.0%
Plastic containers	1.4%	0.0%	0.0%	1.4%	0.0%	0.0%
Cars on a tow truck	0.0%	0.0%	0.0%	0.0%	1.4%	0.0%

An analysis of the collected information on loading units indicates that the management method must consider various types of loading units. Due to the diversified nature of loads in real market conditions, the physical parameters of a load, i.e. its weight and volume, need to be convertible into various types of loading units within the method. The new management method for transport process emissions within sustainable supply chains should cover various types of loading units and should not be limited to selected types of loading units.

The experts were asked to indicate the types of vehicles used for transport within their supply chains. The NACE classification was used again to present the responses to consider differences between companies from different sectors. The results are presented in the matrix in **Tab. 3.10**.
The obtained results indicate that in the majority of industry sectors the vehicle classes differ widely in terms of their GVM. Therefore, the carbon footprint management method for transport processes needs to allow for the measurement and management of the carbon footprint of different vehicles within a heterogeneous fleet.

Tab. 3.10 Vehicle class (GVM) used within the expert's supply chain
Source: own elaboration.

Vehicle class (GVM) used within the supply chain	A – Agriculture, Forestry, and Fishing	C – Manufacturing	D – Electricity, Gas, Steam, and Air Conditioning Supply	F – Construction	H – Transportation and Storage	K – Financial and Insurance Activities
Don't know/hard to say		x			x	
From 12 tons to 16 tons	x		x		x	
From 16 tons to 21 tons	x	x	x		x	
From 21 tons to 40 tons	x	x	x		x	
From 7 tons, up to 12 tons	x				x	
Over 3,5 tons, up to 7 tons	x	x		x	x	
Over 40 tons	x	x	x		x	
Up to 3,5 tons	x	x			x	x

It was decided to determine the significance of the essential parameters existing within sustainable transport supply chains. Precise characterisation of the group of experts above, has enabled verification of whether the responses obtained will provide a valuable source of information. The aim of expert research has been conducted to analyse the importance of specific parameters exploit within transport-oriented sustainable supply chains. The study analysed expert evaluations across multiple criteria. A total of 71 expert responses were included in the analysis. The level of agreement among the experts was assessed using Kendall's coefficient of consensus (W). The calculation formula for determining Kendall's coefficient is presented in **Formula 9** below.

Formula 9 Kendall's W - Coefficient of Concordance
Source: own elaboration based on Gibbon (1993).

$$W = \frac{12S}{m^2(n^3 - n)}$$

m Number of experts that took part in the research

n Number of parameters being ranked

S Sum of squared deviations of the total ranks for each item from the mean rank. Calculated according to logic presented in formula:

$$S = \sum_{i=1}^{n} (R_i - \bar{R})^2$$

R_i Total rank of parameter. The sum of all ranks from all experts

$\bar{R}$ The mean of the total ranks of parameters.

The value of the W coefficient indicates the level of concordance among the experts participating in the research. W value of 1 indicates high concordance. A value of 0 indicates no concordance or random responses.

The overall Kendall's W value across all experts and criteria was 0,3588 indicating a moderate level of consensus. To further explore level of consensus, Kendall's W was also calculated within subgroups based on the Economic sector according to NACE classification. Results showed varying levels of concordance:

- H – Transportation and Storage: W = 0,4497
- A – Agriculture, Forestry, and Fishing: W = 0,4076
- C – Manufacturing: W = 0,3701

Obtained results suggest that the highest consistency in expert assessments was found within the transportation sector, which may reflect more homogeneous operational approach or decision-making criteria of parameters influencing changes of emission levels of transport processes.

The responses obtained from experts indicate which of the parameters identified in the literature review are important from a practical perspective. The level of consensus among experts allows to consider the results obtained as reliable and suitable for determining the practical significance of the parameters identified during the analysis of literature, legal regulations and management methods for transport process emissions. Based on the research findings of Tanujaya et al. (2022) the use of a unified 5 level Likert scale allows for better results among experts and facilitates future analysis. It was therefore considered to use this scale in the conducted expert research. The Likert scale was used to determine the significance of individual parameters, where *'1' means insignificant and '5' means very significant* in terms of its impact on changing transport processes emission levels. The **Tab. 3.11** and **Tab. 3.12** below show detailed assessments of parameters identified during expert research.

Tab. 3.11 Significance of parameters on the level of emissions resulting from transport processes. According to expert's position held in company.
Source: own elaboration.

Position held in the company	Truck Type	Engine size	Fuel Type	Truck body type	Tyre type & size	Cargo weight & volume	Fuel Efficiency	Age of the vehicle	Fuel type and its quality	Distance	Weather Conditions	Topography of route	Road types
a) Administrative/Operational staff	2.33	1.67	2.67	2.33	1.33	4.67	2.67	4.33	3.67	4.33	3.33	3.67	2.00
b) Specialist (Junior/Mid/Senior)	3.88	2.35	3.68	2.25	2.43	4.45	3.15	4.43	3.23	4.60	3.65	4.63	3.03
c) Manager (Lower/Senior)	3.84	2.08	3.16	1.92	2.16	4.36	2.64	4.48	3.32	3.52	3.12	4.60	2.92
d) Director/Board Member	4.33	3.33	4.33	3.33	3.00	3.67	3.33	4.67	4.33	3.67	4.00	4.33	3.67

Tab. 3.12 Significance of parameters on the level of emissions resulting from transport processes. According to expert's position held in company.
Source: own elaboration.

Economic sector according to NACE classification	Truck Type	Engine size	Fuel Type	Truck body type	Tyre type & size	Cargo weight & volume	Fuel Efficiency	Age of the vehicle	Fuel type and its quality	Distance	Weather Conditions	Topography of route	Road types
A – Agriculture, Forestry, and Fishing	3.29	2.00	2.79	1.50	3.50	4.21	2.43	4.43	2.79	2.57	3.50	4.57	3.57
C – Manufacturing	4.29	2.43	3.71	2.29	2.71	4.14	3.57	4.14	3.86	4.86	3.29	4.14	2.57
H – Transportation and Storage	3.94	2.30	3.68	2.34	1.87	4.53	3.02	4.53	3.43	4.60	3.53	4.70	2.89

The expert research conducted identified the weight and volume of cargo, the age of vehicles and the topography of routes as significant parameters affecting the level of emissions achieved. This assessment of parameters was provided by experts in NACE categories A, C and H, for the positions of Administrative, Specialist, Manager and Director. It was concluded that there are other parameters affecting the level of transport emissions, such as route distance, truck type and weather conditions. However, these parameters, according to expert's responses, were identified as having a lower impact on the level of transport emissions. The overall significance level of the parameters based on expert responses is presented in the **Tab. 3.13** below. The significance level was determined using the arithmetic mean.

Tab. 3.13 Overall significance of parameters on the level of emissions resulting from transport processes. According to expert's position held in company.
Source: own elaboration.

Parameter	Significancy of parameter
Topography of route	4.56
Age of the vehicle	4.45
Cargo weight & volume	4.39
Distance	4.17
Truck Type	3.82
Fuel Type	3.48
Weather Conditions	3.46
Fuel type and its quality	3.32
Road types	2.97
Fuel Efficiency	2.96
Tyre type & size	2.31
Engine size	2.27
Truck body type	2.18

It was decided to raise a total of 29 additional questions about regarding the supply chains organisation. The five-grade Likert scale was employed. A score 1 indicates an question area that is not relevant or not addressed within the supply chain of the expert's organisation. A score 5 indicates an area that is very important and fully addressed within the supply chain management process of the expert's organisation. The experts' responses are presented in the following charts. The further research was conducted to empirically verify areas not addressed by the current solutions on the market dedicated to carbon footprint management and measurement. The identification of the approach of market companies is essential in determining the substantive scope of a new model for managing transport processes from the perspective of their emissions.

The **Tab. 3.14** below shows the level of significance of the issue in the expert's opinion in the context of improving the sustainability of the supply chain. Table contains a sum of scores given by all experts. In questions 1 to 23, the experts assessed the degree of implementation of the solution in their supply chains or its significance in their subjective assessment. The aim of asking these questions was to determine the level of awareness of stakeholders, experts and managers about the essential elements that determine the level of sustainability of their supply chains. Questions 24 to 29 concerned specific tools and solutions aimed at increasing the level of sustainability in the transport supply chain of experts.

Tab. 3.14 Assessment of the importance of the issue in the opinion of experts or the degree of its implementation within their supply chain
Source: own elaboration.

	Expert's rating				
Question	1	2	3	4	5
Q no. 1 Achieving a better transport processes efficiency through carbon footprint reduction.	4	14	16	23	14
Q no. 2 Adapting supply chain design to reduce the carbon footprint of transport processes.	7	9	21	23	11
Q no. 3 An access to the information on the current CO_2 emissions status of the transport processes.	6	10	19	25	11
Q no. 4 Analysis of existing and planned transport processes from their carbon footprint perspective	6	8	17	28	12
Q no. 5 Assessment of probability of risk occurrence and their impact on the quality of the process and its emission levels	12	25	16	14	4
Q no. 6 Availability of primary data to evaluate the efficiency and environmental performance of transportation processes	4	10	14	27	16
Q no. 7 Concern about conduction of transport processes in a sustainable manner	3	14	13	26	15
Q no. 8 Consider SLA and other internal procedure standards in order to provide transport services in a timely manner	3	13	16	24	15
Q no. 9 Considering customers complaints and implementing actions for transport services improvement	3	6	19	28	15
Q no. 10 Continuous improvement of processes aimed at reduction of the raw resources needed.	4	10	19	26	12
Q no. 11 Continuous increase of competences and support of knowledge sharing of logistic team members to ensure a better quality of transport processes	3	10	20	24	14
Q no. 12 Controlling whether transport processes carried out by subcontractors are consistent with environmental and ethical standards and represented organisation values throughout the entire supply chain	7	10	20	21	13
Q no. 13 Creation of contingency plans for the occurrence of risks that may result in significant emission increase	13	21	22	11	4
Q no. 14 Decision making based on carbon footprint levels estimated for each development scenario.	7	11	16	26	11
Q no. 15 Define ways to mitigate the environmental risk and threats. Minimisation of the probability of their occurrence	15	23	18	9	6
Q no. 16 Definition of the procedures to be followed at the operational and strategic levels in the event of the occurrence of a risk	19	17	17	13	5
Q no. 17 Development of accurate process maps of transport processes to identify the functionality of stakeholders and elements of the process where there is a possibility of risks leading to increased CO_2 emission.	18	21	14	10	8
Q no. 18 Environmental assessments of carbon footprint level of transport processes emissions within the supply chain	5	9	20	22	15
Q no. 19 Identification of alternative ways in which core processes can be executed in case of emergency conditions	17	21	14	12	7

	Expert's rating				
Question	1	2	3	4	5
Q no. 20 Implement solutions that improve transport and delivery services quality thanks to improvement of shipment traceability	2	7	18	27	17
Q no. 21 Implementation of transport emissions management elements into corporate long-term strategies	5	9	9	28	20
Q no. 22 Inclusion of environmental effectiveness parameters in the set of KPIs	5	11	21	23	11
Q no. 23 Involvement in the carbon footprint reduction of transport processes across the supply chain	4	8	17	28	14
Q no. 24 Involvement of stakeholders in the improvement process of the transportation supply chain	6	16	19	22	8
Q no. 25 Involvement of the latest technological solutions to support the reduction of CO_2 emissions of transport processes within supply chain	3	6	19	26	17
Q no. 26 Quick access to the transport-related master data for the stakeholders for further GHG inventory	8	16	15	20	12
Q no. 27 Respect the ethical principles and values of the area of operation of the supply chain	2	7	17	28	17
Q no. 28 The ability of the organisation to self-improve on the basis of complaints and feedback from the stakeholders within the transportation supply chain	4	13	14	21	19
Q no. 29 The implementation of elements of corporate social responsibility within the transport supply chain	4	7	19	24	17

The **Fig. 3.5** below shows the distribution of experts' responses to each question. This allows to verify the differences in the ratings given for each question.

Fig. 3.5 Distribution of importance ratings (Likert scale 1-5)

Source: own elaboration.

Further research, the results of which are presented in **Tab. 3.15**, was conducted to verify the average rating breakdown by industry. This allowed to verify differences in the approach to the significance of individual parameters in the breakdown by companies from whom the experts originate. It has been noticed that the significance of individual parameters is more evenly distributed in companies from category H (Transportation and Storage) than in other NACE categories. Considering that experts from this industry indicated a low degree of implementation of solutions that could support the sustainable development of transport supply chains in questions 24 to 29. It can therefore be assumed that companies in the NACE category H are characterised by high resistance to changes on the level of supply chain parameters. Conversely, the relatively low degree of implementation of solutions that support transport process management in terms of emissions indicates the potential for incorporating such a management concept into organisational decision-making processes. Regardless of industry, experts indicate that companies in NACE classes C, D, F, H and K are willing to increase sustainable development by incorporating innovative technological solutions aimed at reducing CO_2 emissions (Question 1). The exception is class A (Agriculture), where this parameter was rated the lowest (2,57).

Tab. 3.15 Average rating based on responses from experts and their visualisation in heatmap form Source: own elaboration.

Question	NACE business category					
	A	C	D	F	H	K
Involvement of the latest technological solutions to support the reduction of CO_2 emissions of transport processes within supply chain.	2.57	3.57	3.00	4.00	4.02	4.00
Environmental assessments of carbon footprint level of transport processes emissions within the supply chain.	2.57	3.43	4.00	4.00	3.72	3.00
Involvement in the carbon footprint reduction of transport processes across the supply chain	2.36	3.71	4.00	3.00	3.91	3.00
Availability of primary data to evaluate the efficiency and environmental performance of transportation processes	2.57	4.14	5.00	3.00	3.77	4.00
Implementation of transport emissions management elements into corporate long term strategies	2.79	3.86	4.00	1.00	3.96	5.00
Achieving a better transport processes efficiency through carbon footprint reduction.	2.43	4.43	4.00	3.00	3.55	3.00
Analysis of existing and planned transport processes from their carbon footprint perspective	3.14	3.29	3.00	5.00	3.53	4.00
Adapting supply chain design to reduce the carbon footprint of transport processes.	2.86	3.71	5.00	3.00	3.36	3.00
The implementation of elements of corporate social responsibility within the transport supply chain.	2.71	3.43	3.00	3.00	3.89	5.00
Respect the ethical principles and values of the area of operation of the supply chain.	3.00	4.00	4.00	4.00	3.89	3.00
Implement solutions that improve transport and delivery services quality thanks to improvement of shipment traceability.	2.79	4.43	5.00	5.00	3.81	4.00
Consider SLA and other internal procedure standards in order to provide transport services in a timely manner	2.71	4.00	4.00	5.00	3.62	3.00
Continuous increase of competences and support of knowledge sharing of logistic team members to ensure a better quality of transport processes.	2.57	4.29	5.00	2.00	3.68	3.00

Question	NACE business category					
	A	C	D	F	H	K
Considering customers complaints and implementing actions for transport services improvement.	3.14	3.71	4.00	3.00	3.77	5.00
An access to the information on the current CO_2 emissions status of the transport processes.	2.71	3.43	4.00	3.00	3.53	3.00
The ability of the organisation to self-improve on the basis of complaints and feedback from the stakeholders within the transportation supply chain.	2.50	4.29	5.00	4.00	3.70	3.00
Decision making based on carbon footprint levels estimated for each development scenario.	2.64	3.14	4.00	5.00	3.47	5.00
Quick access to the transport-related master data for the stakeholders for further GHG inventory.	2.64	3.86	2.00	4.00	3.23	3.00
Concern about conduction of transport processes in a sustainable manner.	2.86	3.71	2.00	3.00	3.68	5.00
Continuous improvement of processes aimed at reduction of the raw resources needed.	3.00	3.71	4.00	5.00	3.51	3.00
Involvement of stakeholders in the improvement process of the transportation supply chain	2.93	3.43	3.00	5.00	3.09	5.00
Controlling whether transport processes carried out by subcontractors are consistent with environmental and ethical standards and represented organisation values throughout the entire supply chain	3.14	3.43	4.00	1.00	3.38	4.00
Creation of contingency plans for the occurrence of risks that may result in significant emission increase.	2.00	2.86	2.00	2.00	2.77	3.00
Define ways to mitigate the environmental risk and threats. Minimisation of the probability of their occurrence.	2.21	3.00	2.00	3.00	2.57	3.00
Assessment of probability of risk occurrence and their impact on the quality of the process and its emission levels .	2.21	3.00	2.00	2.00	2.70	3.00
Development of accurate process maps of transport processes to identify the functionality of stakeholders and elements of the process where there is a possibility of risks leading to increased CO_2 emissions.	1.79	3.00	2.00	2.00	2.70	5.00
Identification of alternative ways in which core processes can be executed in case of emergency conditions.	2.00	3.71	2.00	4.00	2.62	1.00
Definition of the procedures to be followed at the operational and strategic levels in the event of the occurrence of a risk.	2.00	3.43	2.00	4.00	2.57	2.00
Inclusion of environmental effectiveness parameters in the set of KPIs.	2.64	3.57	3.00	3.00	3.51	4.00

The following **Fig. 3.6, Fig. 3.7, Fig. 3.8, Fig. 3.9, Fig. 3.10** show the percentage results for subsequent questions. An in-depth analysis of the overall results of the expert research allows for a more accurate verification of the application potential of the developed transport process management method, considering their emissions within sustainable supply chains. **Fig. 3.6** below shows the experts' responses in terms of their approach to the general elements related to supply chain management from the perspective of its emissions.

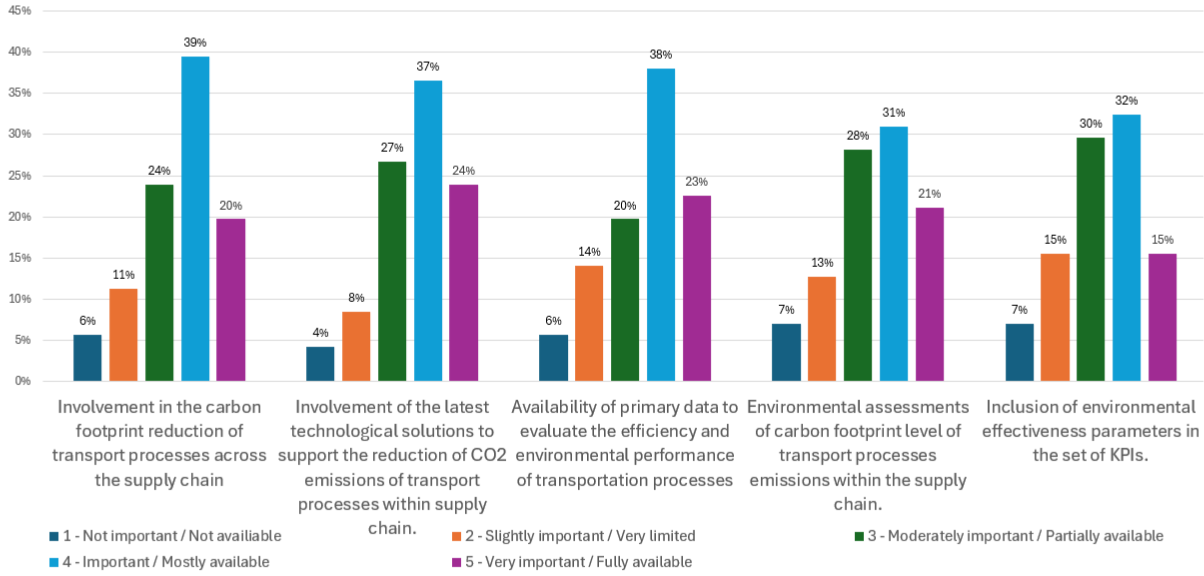


Fig. 3.6 The organisation's approach to carbon footprint management elements - Results of an Expert Research.

Source: own elaboration.

The research indicates that up to 39% of respondents consider it important and 20% consider the involvement in the reduction of emissions resulting from transport processes to be very important. This approach indicates considerable potential for the implementation of dedicated measurement and management solutions in existing organisational structures. A comparable response pattern is observed with regard to the involvement of organisations in the use of modern technologies to support the mitigation and management of the carbon footprint of transport processes within the supply chains. Hence, an association is made with the availability of data necessary for conducting environmental assessments of transport processes. Nevertheless, a total of 21% of respondents indicated that there is very limited or no data available within the supply chain for carbon footprint evaluation. The quality of the data translates into the approach to measuring environmental KPIs, which support the assessment of emissions and enable further inferences. The difference between experts declaring access to the full dataset (23%) and those measuring emissions in a comprehensive manner using KPIs (15%) indicates an application gap. A dedicated method for measuring the carbon footprint and supporting the management process of transport processes, based on the emission levels of individual transport phases, can help to increase the rate of measuring and reporting emissions through KPI toolkits employing available historical data on the ongoing transport processes. **Fig. 3.7** presents the expert responses provided in terms of the adaptability of existing supply chains and the integration of new management solutions focused on emissions mitigation.

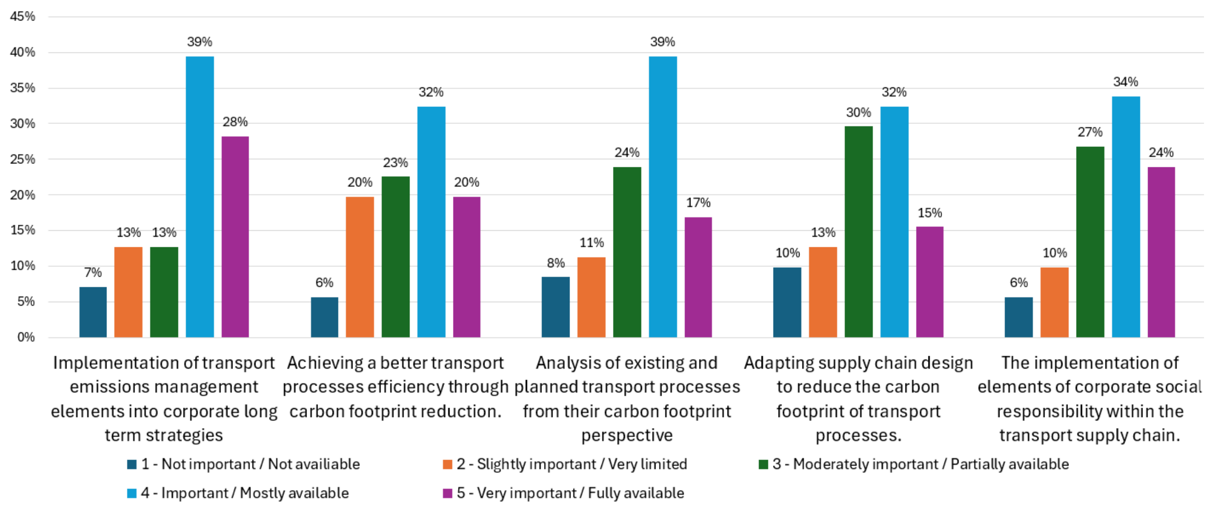


Fig. 3.7 Adaptability of process emissions management within the supply chains - Results of an Expert Research.

Source: own elaboration.

Experts' responses to questions on the feasibility of incorporating transport emissions management elements into the long-term strategies of the organisation 67% indicate as very important and important. This indicates that many of the companies consider the European guidelines in this field, measuring and managing the carbon footprint of transport processes. 33% of the responses indicate the partial availability of emissions management within the supply chains of expert organisations. It suggests a potential for the development of activities by companies in this field. Considering the regulations indicated in **chapter 2.2**, it can be assumed that these companies will need to increase their involvement in carbon footprint measurement and management issues. Experts' answers to further questions indicate a high interest of an expert organisation in the field of carbon footprint management due to the optimisation potential of the transport process. The companies perceive the measurement and mitigation of the carbon footprint as both a cost saving and a chance to build their competitive advantage. An important motivational element, also demonstrated during the literature review, is the desire of organisations to comply with legal requirements and elements of adopted CSR (Corporate and Social Responsibility) programmes. Experts' responses regarding access to and use of information on transport emissions are presented in **Fig. 3.8.**

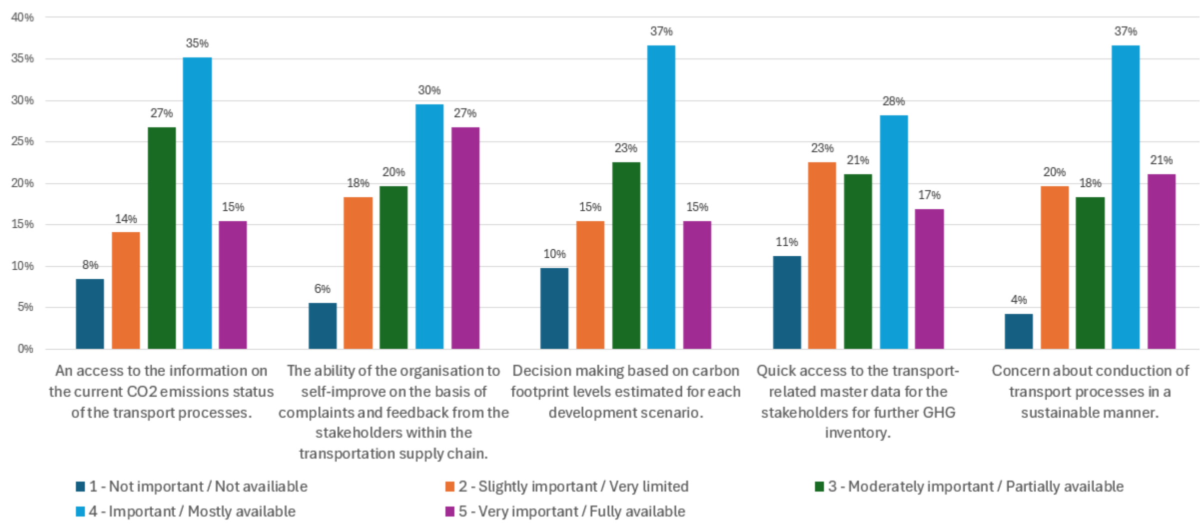


Fig. 3.8 Availability of information on transport process emissions and its application in the transport management process - Results of an Expert Research.

Source: own elaboration.

Responses from experts indicate that only 50% of their companies' supply chains have access to complete information on the level of emissions resulting from transport processes. Considering the legal framework requiring the reporting and measurement of carbon footprint (e.g. the CSRD Directive within EU) among large companies, and in the long term also among medium and small enterprises, there is a need for improvement. Also the expectations of stakeholders identified in the literature review suggest that efforts should be made to increase the availability of information on the level of emissions from transport processes. Furthermore, it was identified that a total of 25% of companies do not take into account the emission levels of individual processes in their management process or only very limited. Simultaneously, companies declare an interest in the execution of transport processes in a sustainable manner. However, the collected results suggest that companies do not interpret this aim correctly or treat it in a limited form. According to only 4% of the experts, the transport processes carried out within their supply chains cannot be defined as carried out in a sustainable manner.

The following questions refer to methods of counteracting the occurrence of risks, which may result in an increase of emissions. The literature research revealed that the resilience of transport supply chains derives from their relevant planning and the identification of essential strategies to support continuous development as well as the deployment of contingency plans in the event of process disruption. Expert responses are presented in **Fig. 3.9** and **Fig. 3.10.**

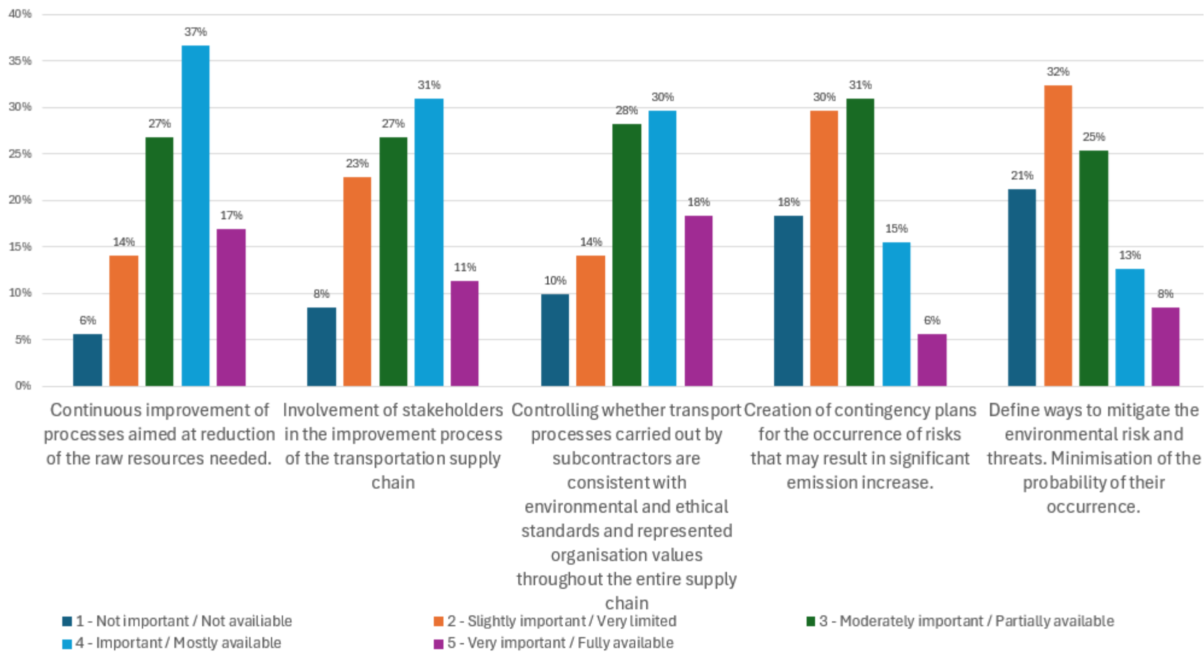


Fig. 3.9 Integration of environmental management of transport processes into corporate strategy and management of emissions of different scopes - Results of an Expert Research.
Source: own elaboration.

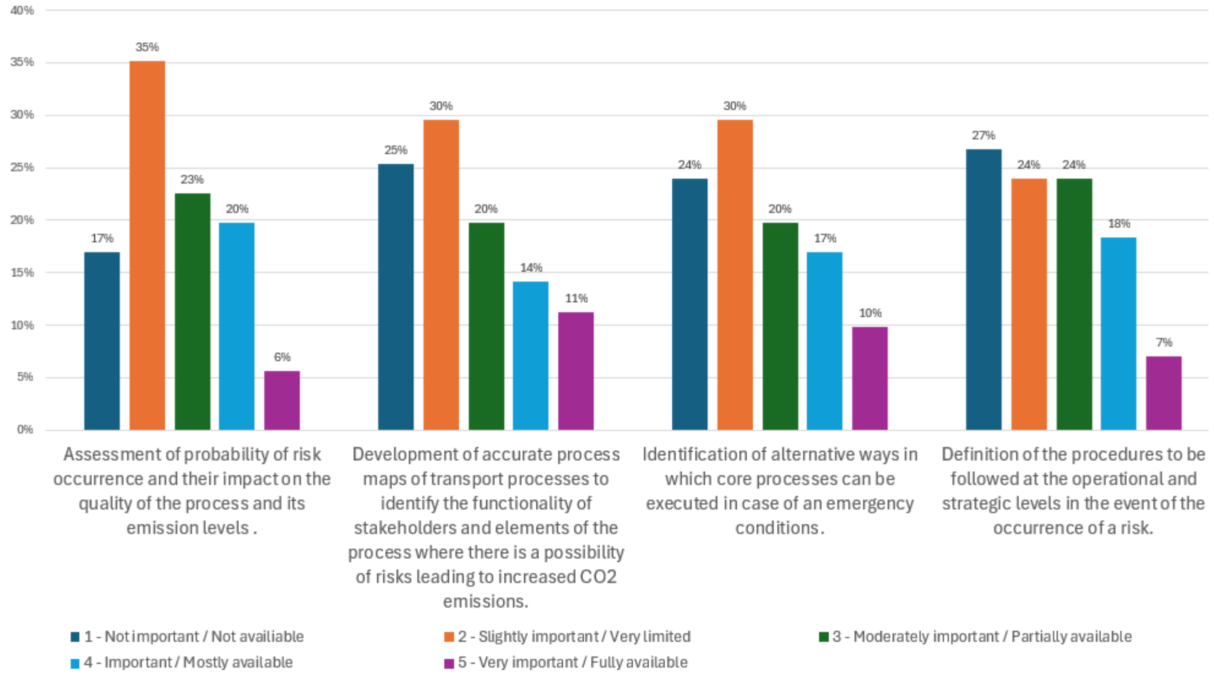


Fig. 3.10 Mitigation planning for risks resulting in increased emissions and defining operational procedures and contingency strategies - Results of an Expert Research.
Source: own elaboration.

The results indicate that companies are considering adopting a continuous development approach. However, they remain closed to stakeholder participation in the execution and implementation of process improvement plans. Among the principles identified in the literature review within sustainable supply chains framework, is transparency. However, 58% of experts did not identify stakeholder involvement as mostly available (Score 4) and fully available (score 5). As a counterpoint, companies point to auditing their subcontractors and checking if the processes they undertake comply with environmental and ethical standards throughout the supply chain. The conducted research identified that up to 18% of companies do not have contingency plans for the occurrence of risks at all (score 1), and 30% are very limited (Score 2). Thus, 52% of companies have not defined how to reduce the carbon footprint of their transport processes in the event of the occurrence of risks. The very high rate has been noted (17% not available, 35% very limited) indicating insufficient assessment of risks in expert organisations. It was also concluded that companies do not map their processes adequately and are therefore unable to define relevant procedures and an alternative form of counteracting the risks that lead to an increase in transport process emissions and a decrease in efficiency.

Conducted research identified that the concept of corporate sustainability is known, but may be misinterpreted by organisations. Organisations aim to improve the efficiency of their processes, by mitigating their carbon footprint. Furthermore, it has been found that companies try to control emissions of various origins, including those arising from the transport activities of their subcontractors, verifying these against environmental and ethical standards. Simultaneously, it was observed that organisations do not assess the significance of risks and the possible consequences of their occurrence. The lack of sufficient process mapping leads to a lack of adequate procedures to support contingency plans and strategies to counteract the increase in transport process emissions. Concurrently, companies are aware that, in addition to stakeholder expectations to measure and manage the carbon footprint of their supply chain processes, the regulatory framework is one of the most important motivators. Expert research indicates the potential application of a new model for measuring and managing the carbon footprint of sustainable supply chains.

3.3. Parameters related to vehicles

The literature review and expert research indicated that the age of vehicles is an important factor influencing changes in emissions from transport processes. The results of the expert research, (presented in **chapter 3.2),** show that the "age of the vehicle" parameter achieved a very high significance coefficient of 4,45 on a 1–5 Likert scale. Considering that the other parameters in the new carbon footprint management method can be directly parameterised and included in the carbon footprint assessment process, the focus was placed on conducting in-depth research on "vehicle age" parameter. Simultaneously conducted practical - commercial project[1] enabled the collection and analysis of actual market data for the company, from which appropriate conclusions could be drawn. Detailed historical operational data from a company in the fast-moving consumer goods (FMCG) industry were collected. The Logistics Department of the company, which outsourced transport services to subcontractors, provided detailed information on vehicle type, Euro emission class, fuel type and average emissions. Detailed parameters, especially regarding average fuel consumption (litres/km), were obtained directly from vehicle owners based on fuel invoices and verified using vehicle telemetry systems where available. Telemetry systems could not be used to verify monthly fuel invoices for vehicles over 11 years old due to a lack of appropriate equipment installed by the vehicle manufacturers.

The analysed vehicles' data carried out transport processes in 13 Polish cities. To determine the size of the town and cities in which transport processes were carried out, a categorisation for small, medium and large class was proposed in accordance with logic presented below in **Tab. 3.16**. Proposed categorisation was based on the number of residents (GUS, 2021).

Tab. 3.16 Classification of cities involved in transport processes according to the number of residents
Source: own elaboration.

Criteria used in city classification:	Population
Small town	fewer than 20 000 residents
Medium city	20 000–100 000 residents
Large city	more than 100 000 residents

The classification of cities proposed in Poland by the Central Statistical Office refers to precise population ranges(GUS, 2014). Small cities are divided into the following classes: I (less than 5,000 inhabitants), II (5,000-10,000 inhabitants) and III (10,000-20,000 inhabitants). Medium-sized cities include classes IV (20,000-50,000 inhabitants) and class V (50,000-100,000 inhabitants). Large cities are described by class VI (100,000-200,000 inhabitants) and class VII (over 200,000 inhabitants). Verification of the data obtained in the context of the types of cities in which transport processes were conducted by transport operators will help to verify in which classes and types of cities the further results of the operational research conducted can be applied. The **Tab. 3.17** below shows how individual cities were classified and allocated to the appropriate predefined class. The analysis was conducted using data from 11 voivodeships, including both lowland and mountainous areas, thus covering most of Poland's territory. This also validates the average fuel consumption values due to the diverse topographical parameters in areas where transport processes were undertaken.

[1] A commercial project conducted by the Łukasiewicz Research Network - Poznań Institute of Technology in 2022 for a company in the FMCG sector. Project scope: Analysis of the subcontractor-carrier supply chain structure including cost and non-cost parameters. Project manager: Damian Dubisz.

Tab. 3.17 Classification of cities engaged into research
Source: own elaboration.

City/ Town name	Population [residents]	Voivodeship	City size classification	GUS city class
Łódź	650 066	Łódź	Large	VII class
Jelenia Góra	76 090	Lower Silesian	Medium	V class
Legnica	96 970	Lower Silesian	Medium	V class
Szczecin	396 654	West Pomeranian	Large	VII class
Gliwice	171 307	Silesian	Large	VI class
Poznań	518 274	Greater Poland	Large	VII class
Rzeszów	209 924	Subcarpathian	Large	VII class
Wrocław	642 228	Lower Silesian	Large	VII class
Gdańsk	487 834	Pomeranian	Large	VII class
Grudziądz	95 045	Kuyavian-Pomeranian	Medium	V class
Lublin	330 000	Lublin	Large	VII class
Kraków	800 653	Lesser Poland	Large	VII class
Białystok	297 585	Podlaskie	Large	VII class

Tab. 3.18 below presents detailed data from 34 vehicles conducting transport operations of food products. Depending on the GVM of the vehicles, the routes undertaken included linehaul transport between key points within the supply chain (vehicles with GVM above 3 500 kg) or last mile transport for vehicles with GVM up to 3,500 kg. The table presents detailed information on the truck's brand, the type of city in which the vehicle operated, Gross Vehicle Mass (GVM), fuel type, vehicle age, EURO emission class and average fuel consumption.

Tab. 3.18 Detailed parameters of the age of vehicles participating in the operational research
Source: own elaboration.

Truck ID	Anonymized vehicle brand	City of operations size classification	Gross Vehicle Mass (GVM)	Truck's engine size	Fuel type	Vehicle's age	Euro class	Average fuel consumption
[Id]	[Letter code]	[Class]	[kg]	[cm3]	[type]	[years]	[Class]	[litres/100 km]
Truck 1	D	Medium	3 500	2 179	Diesel	1	Euro 5	8.50
Truck 2	A	Large	3 500	2 179	Diesel	4	Euro 6	18.00
Truck 3	H	Large	18 000	6 700	Diesel	8	Euro 5	28.00
Truck 4	H	Large	40 000	12 000	Diesel	7	Euro 6	30.00
Truck 5	A	Medium	3 500	2 998	Diesel	7	Euro 5	18
Truck 6	D	Medium	3 500	3 000	Diesel	13	Euro 3	18
Truck 7	A	Large	3 500	3 000	Diesel	12	Euro 4	16
Truck 8	F	Large	11 990	6 470	Diesel	6	Euro 6	22.50
Truck 9	H	Large	11 990	6 450	Diesel	8	Euro 5	23.00
Truck 10	F	Large	11 998	7 698	Diesel	7	Euro 6	22
Truck 11	G	Medium	19 000	6 693	Diesel	11	Euro 5	25
Truck 12	A	Medium	3 500	2 179	Diesel	5	Euro 5	18.00
Truck 13	A	Large	3 500	2 798	Diesel	16	Euro 3	16
Truck 14	A	Large	3 500	2 998	Diesel	1	Euro 6	16
Truck 15	A	Large	3 500	2 287	Diesel	9	Euro 4	16
Truck 16	A	Large	3 500	2 287	Diesel	11	Euro 5	16

Truck ID	Anonymized vehicle brand	City of operations size classification	Gross Vehicle Mass (GVM)	Truck's engine size	Fuel type	Vehicle's age	Euro class	Average fuel consumption
[Id]	[Letter code]	[Class]	[kg]	[cm3]	[type]	[years]	[Class]	[litres/100 km]
Truck 17	H	Large	11 990	6 871	Diesel	15	Euro 4	23
Truck 18	H	Large	11 990	6 871	Diesel	20	Euro 3	23
Truck 19	H	Medium	11 990	6 871	Diesel	6	Euro 5	26
Truck 21	G	Medium	18 000	12 000	Diesel	5	Euro 6	31
Truck 22	G	Medium	18 000	12 000	Diesel	7	Euro 6	31
Truck 23	D	Large	18 000	12 419	Diesel	5	Euro 5	31
Truck 24	A	Large	3 500	2 300	Diesel	10	Euro 4	16
Truck 25	H	Large	11 990	4 300	Diesel	20	Euro 3	23
Truck 26	H	Large	17 990	6 700	Diesel	11	Euro 5	27
Truck 27	F	Large	17 990	6 700	Diesel	16	Euro 4	27
Truck 28	A	Large	3 500	3 000	Diesel	4	Euro 6	16.5
Truck 29	F	Large	11 990	5 132	Diesel	6	Euro 6	22.5
Truck 30	F	Large	11 990	5 132	Diesel	10	Euro 5	23
Truck 31	H	Large	15 000	6 870	Diesel	11	Euro 5	24
Truck 32	A	Medium	3 500	2 287	Diesel	6	Euro 5	15
Truck 33	A	Large	15 000	6 871	Diesel	20	Euro 3	21
Truck 34	H	Large	18 000	6 871	Diesel	12	Euro 5	28

In order to effectively use the data collected from the FMCG distribution company, it was necessary to obtain and analyse actual market data on the combustion of new vehicles. The information collected allowed to build a reference point for fuel consumption trends in vehicles with higher consumption levels and longer exploitation periods.

To properly analyse the collected data, the fuel consumption declared by vehicle manufacturers was verified based on the new trucks catalogue cards of Iveco, Scania, Volvo, Renault, Volkswagen, Mitsubishi, Mercedes, DAF and MAN conversion trucks. The collected information was verified by experts from the company's Logistics Department on the basis of the data provided for the research and subjected to expert correction of the average fuel consumption level of +/- 3% depending on the vehicle. The reference fuel consumption values are presented in **Tab. 3.19**.

Tab. 3.19 Fuel consumption and GVM parameters of a new conversion trucks

Source: own elaboration.

Vehicle for cargo space conversion (Anonymized vehicle brand)	Fuel type	Engine capacity [cm3]	Fuel consumption (L/100 km)	Gross Vehicle Mass (GVM)	Emission standard
A	Diesel	2287 cm³	16.9	3 500	Euro 6
A	Diesel	3000 cm³	20.8	7 200	Euro 6
A	Diesel	3908 cm³	24.7	18 000	Euro 6
A	Diesel	3908 cm³	23.4	16 000	Euro 6
A	Diesel	8700 cm³	23.4	18 000	Euro 6
A	Diesel	8700 cm³	31.2	40 000	Euro 6
B	Diesel	12700 cm³	30	40 000	Euro 6
C	Diesel	16100 cm³	31.2	40 000	Euro 6

Vehicle for cargo space conversion (Anonymized vehicle brand)	Fuel type	Engine capacity [cm3]	Fuel consumption (L/100 km)	Gross Vehicle Mass (GVM)	Emission standard
D	Diesel	12777 cm³	30	40 000	Euro 6
E	Diesel	1968 cm³	15.6	3 500	Euro 6
F	Diesel	3000 cm³	14.3	3 500	Euro 6
F	Diesel	3000 cm³	18.2	7 500	Euro 6
F	Diesel	3000 cm³	19.5	8 500	Euro 6
F	Diesel	5100 cm³	18.2	12 000	Euro 6
F	Diesel	5100 cm³	20.8	16 000	Euro 6
F	Diesel	7700 cm³	24.7	18 000	Euro 6
F	Diesel	12800 cm³	28.8	40 000	Euro 6
G	Diesel	4700 cm³	18.2	7 500	Euro 6
G	Diesel	4700 cm³	20.8	10 000	Euro 6
G	Diesel	4700 cm³	19.5	12 000	Euro 6
G	Diesel	4700 cm³	22.1	14 000	Euro 6
G	Diesel	4700 cm³	26	18 000	Euro 6
G	Diesel	10800 cm³	33.6	40 000	Euro 6
G	Diesel	12900 cm³	32.4	40 000	Euro 6
H	Diesel	1968 cm³	15.6	3 500	Euro 6
H	Diesel	1968 cm³	16.25	7 500	Euro 6
H	Diesel	6871 cm³	17.55	12 000	Euro 6
H	Diesel	6871 cm³	22.1	16 000	Euro 6
H	Diesel	6871 cm³	23.4	18 000	Euro 6
H	Diesel	12500 cm³	32.4	40 000	Euro 6

Based on the collected data presented in **Tab. 3.19**, the average fuel consumption was determined for each GVM class. The average values for new vehicles according to their weight are presented in **Tab. 3.20** below.

Tab. 3.20 Average fuel consumption of new vehicles according to GVM
Source: own elaboration.

Gross Vehicle Mass (GVM)	3500	7200	7500	8500	10000	12000	14000	16000	18000	40000
Average Fuel consumption [l/100km]	15.60	20.80	17.55	19.50	20.80	19.34	22.10	22.10	24.44	31.20

The data outlined in **Tab. 3.20** is also visualised in the **Fig. 3.11** below. The increase in fuel consumption for 7 200 kg vehicles may suggest that the engine power is not well matched to the vehicle weight. It has been noticed that vehicles with a GVW of 7 200 kg often use the same engines as vehicles in the GVW category up to 3 500 kg. As a result, the technical parameters of the vehicles do not meet the power requirements. However, in order to fully diagnose the causes of this anomaly in fuel consumption for vehicles with a GVW of 7 200 kg, more in-depth research needs to be conducted. Further increases in the GVW of vehicles coincide with a steady increase in fuel consumption.

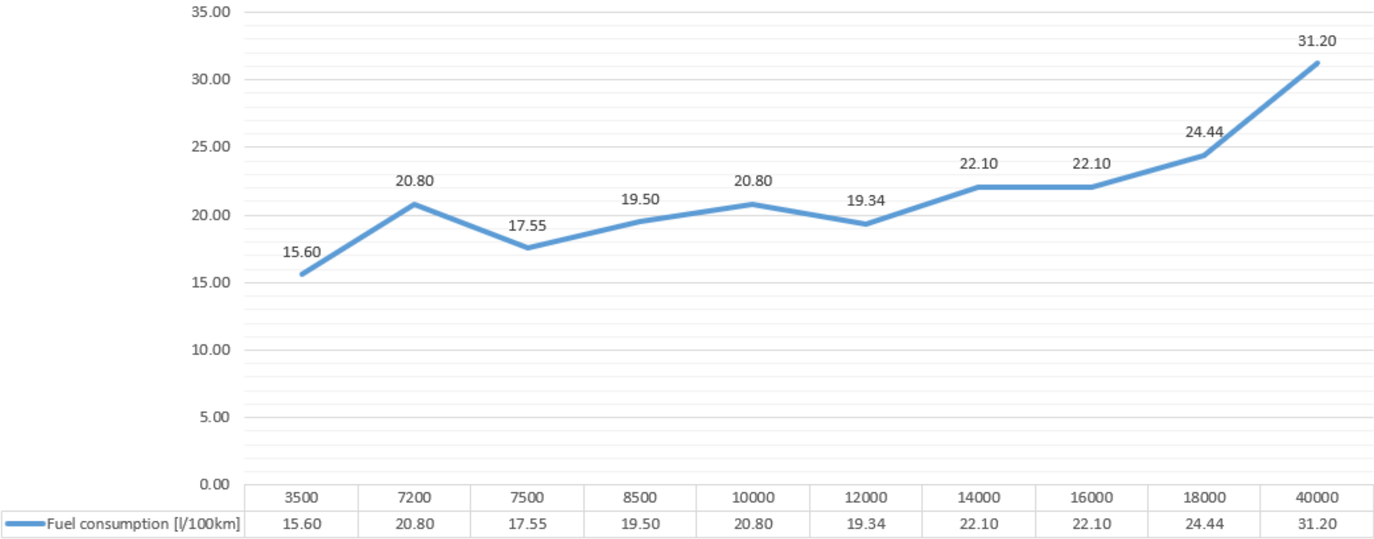


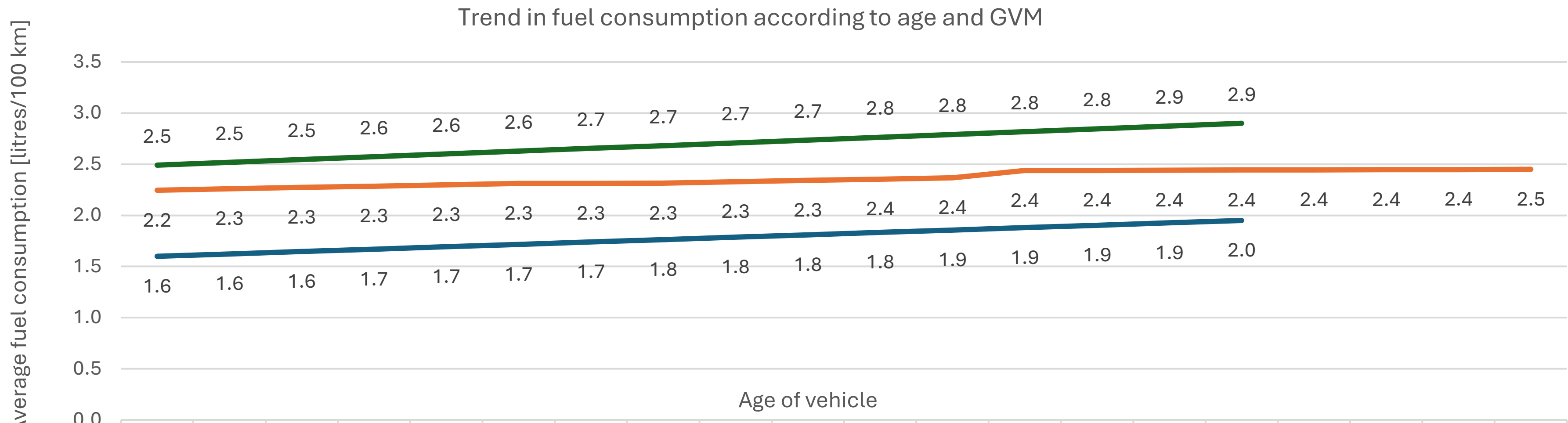
Fig. 3.11 Average fuel consumption of a new conversion trucks according to their gross vehicle mass (GVM)
Source: own elaboration.

Additional verification of engine capacity in relation to vehicle GVM indicates that for the 7,200 kg category, engine capacities in the first range occur. However, this range is most commonly represented by vehicles with a mass of up to 3 500 kg. **Tab. 3.21** also shows clearly that engine capacity increases with vehicle weight and corresponds to requirements in real market conditions.

Tab. 3.21 Engine capacity ranges according to Gross Vehicle Mass of new conversion trucks
Source: own elaboration.

	Gross Vehicle Mass (GVM) category									
Engine capacity category	3500	7200	7500	8500	10000	12000	14000	16000	18000	40000
1 000 - 2 000 cm3	2	0	1	0	0	0	0	0	0	0
2 000 - 3 000 cm3	1	0	0	0	0	0	0	0	0	0
3 000 - 4 000 cm3	1	1	1	1	0	1	0	1	1	0
4 000 - 5 000 cm3	0	0	1	0	1	1	1	0	1	0
5 000 - 6 000 cm3	0	0	0	0	0	1	0	1	0	0
6 000 - 7 000 cm3	0	0	0	0	0	1	0	1	1	0
7 000 - 8 000 cm3	0	0	0	0	0	0	0	0	1	0
8 000 - 9 000 cm3	0	0	0	0	0	0	0	0	1	1
10 000 - 11 000 cm3	0	0	0	0	0	0	0	0	0	1
12 000 - 13 000 cm3	0	0	0	0	0	0	0	0	0	5
16 000 - 17 000 cm3	0	0	0	0	0	0	0	0	0	1

Due to the availability of operational data on fuel consumption, the focus was placed on three basic vehicle types according to their weight (GVM category). Category I includes vehicles up to 3 500 kg, category II includes vehicles up to 12 000 kg, and category III includes vehicles up to 18 000 kg. The oldest vehicles in class up to 3 500 kg and up to 18 000 kg were 16 years old, which made it possible to determine the trend in fuel consumption according to age up to that year of operation. The oldest vehicles with a GVM of up to 12 000 kg were 20 years old. Hence it was possible to determine the level of fuel consumption changes up to 20 year of operation. The information gathered, combined with data on fuel consumption by new vehicles, made it possible to determine the trend line for fuel consumption growth. The dynamics of the changes are shown in the **Fig. 3.12** below.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
GVM 3 500	1.6	1.6	1.6	1.7	1.7	1.7	1.7	1.8	1.8	1.8	1.8	1.9	1.9	1.9	1.9	2.0				
GVM 12 000	2.2	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.5
GVM 18 000	2.5	2.5	2.5	2.6	2.6	2.6	2.7	2.7	2.7	2.7	2.8	2.8	2.8	2.8	2.9	2.9				

Fig. 3.12 Survey – based trend in fuel consumption increases with the age of vehicles and GVM considering also fuel consumption of new vehicles
Source: own elaboration.

The data collected on the fuel consumption of individual vehicle groups made it possible to determine the year-on-year fuel consumption growth rates. The rate can be used in a new model for assessing the carbon footprint of transport processes within sustainable supply chains. Referring to the fuel consumption values for vehicles with GVM classes I, II and III presented in **Fig. 3.12**, individual fuel consumption growth factors were calculated for the identified fuel consumption trend. The factors have been calculated according to the below logic described in following **Formula 10**.

Formula 10 The calculation logic of the average yearly increase in fuel consumption
Source: own elaboration based on own research.

$$\bar{I}_a = \frac{\sum_{i=1}^{k} Ii}{k}$$

$\bar{I}_a$	Average yearly fuel consumption increase indicator per each GVM truck class.
$\sum_{i=1}^{k}$	Total truck's fuel consumption.
Ii	Fuel consumption increase of each truck.
k	Number of trucks.

The $\bar{I}_a$ factors values are presented in **Tab 3.22** below.

Tab. 3.22 Fuel consumption growth rated according to GVM
Source: own elaboration.

GVM	Fuel consumption year - to – year $\bar{I}_a$ factor value
3500	1,31%
12000	0,46%
18000	1,01%

The research led to the suggestion of a new way of calculating the carbon footprint of transport processes. Research outcome creates a foundation for further assessment of the carbon footprint of transport processes new model. The proposed method enables emissions to be calculated in a practical manner, initially for groups of vehicles sharing the same characteristics (GVM and age), and subsequently for the entire heterogeneous fleet. These calculations rely on a key parameter identified in the literature review: the distance travelled by each vehicle class (defined by the same GVM and age). The distance must be calculated following the logic outlined in the **Formula 11** below.

Formula 11 Logic for distance calculation for further heterogeneous CF level assessment
Source: own elaboration based on own research.

$$R_\alpha = \sum_{i=1}^{k} R_i$$

R_α	The total amount of kilometres travelled by the group of trucks with the same age and GVM parameter.
R_i	Total distance of truck in kilometres.
k	Number of trucks within the same GVM class and age.

Formula 12 Logic for assessing the emission level of a homogeneous fleet
Source: own elaboration based on own research.

$$Homogeneous\ \ fleet\ \ emissions\,[kg\ CO_2e]\ = \mathrm{R}_{\alpha} * \left(\frac{\overline{FC}_{\alpha}}{100}\right) * \left((\bar{I}_a * V) + 1\right) * F_C$$

Fcf	Fuel conversion factor - UK DEFRA conversion factors chart for liquid or gaseous fuels combustion.
$a -$	GVM class.
R_{α}	the total amount of kilometres travelled on the route by group of trucks with the same Vα and a parameter.
$\overline{FC}_{\alpha}$	Average fuel consumption [litres/100km] per each GVM class.
$\bar{I}_a$–	Yearly average increase of fuel consumption indicator per each GVM class described as α type.
V_{α}	Vehicle's age (years in operation per each α type).

Formula 13 The logic for assessing the emission level of a heterogeneous fleet
Source: own elaboration based on own research.

$$\begin{matrix} Heterogeneous \\ Fleet \\ Emission \\ [kg\ CO_2e] \end{matrix} = \sum_{a=1}^{n}\left[\mathrm{R}_{\alpha} * \left(\frac{\overline{FC}_{\alpha}}{100}\right) * \left((\bar{I}_a * V) + 1\right) * F_{cf}\right]$$

Fcf	Fuel conversion factor - UK DEFRA conversion factors chart for liquid or gaseous fuels combustion.
a	GVM class.
R_{α}	the total amount of kilometres travelled on the route by group of trucks with the same V_{α} and a parameter.
$\overline{FC}_{\alpha}$	Average fuel consumption [litres/100km] per each GVM class.
$\bar{I}_a$–	Yearly increase of fuel consumption indicator per each GVM class described as α type.
V_{α}	vehicle's age (years in operation per each α type).

The calculation formulas obtained as a result of the research, taking into account various parameters of heterogeneous and homogeneous fleets, are included in the new model for managing and measuring the carbon footprint of transport processes. The consideration of all relevant fleet parameters, such as GVM, age and fuel type, is an important element in assessing the level of transport emissions and allows the analyses to maintain their actual dimension.

3.4. Parameters related to loading units

During the literature research presented in **chapters 1 and 1.1** it was identified that the type of packaging has an impact on the efficiency of transport processes. The appropriate use of available cargo space affects the level of process execution efficiency and the transport utilisation index. Simultaneously, in relation to the NCN research programme BIOLOG[2], the impact of the selection of alternative types of collective packaging on the level of emissions achieved was revealed. In order to verify impact of loading unit parameters the own research was conducted on the basis of data from a company handling post-production furniture wood biomass flows.

The case study research was conducted using basic data of a manufacturing company in the furniture industry. The information on the company's internal flows included in the data allowed to estimate the overall level of post-production waste. Anonymized basic data of a company involved in the production of wooden furniture was used in the simulation. For this purpose, actual production data of 25379 indexes was used for further calculations within scenarios. Gathered data describes production volumes for 2021. It has been observed that during the production process about 20% of production waste is turned into wood biomass. Based on the indicators developed, the level of production waste was estimated by product group. The processed waste feeds into the reversed supply chain of wood biomass. Once the waste material is obtained and loaded onto the trucks is transferred to proper processing centres. The general functional scope of the reverse supply chain is presented in the **Fig. 3.13** below.

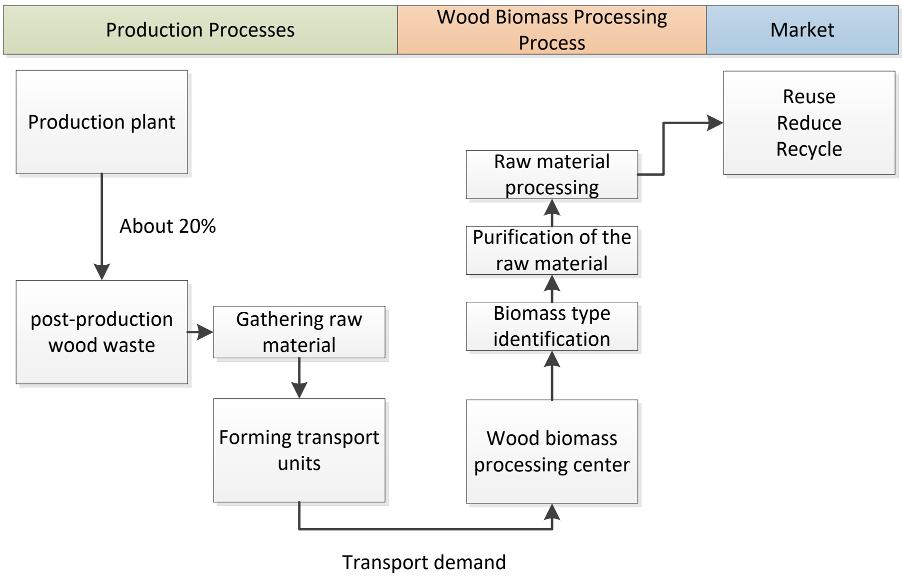


Fig. 3.13 Simplified process of post-production biomass handling in the analysed case
Source: own elaboration.

The reverse supply chain consists of three key segments: Production Processes, Wood Biomass Processing, and Market. The primary entity within this chain is the production facility, which generates post-production wood biomass. As illustrated in **Fig. 3.13**, approximately 20% of production output results in post-production waste—a notably high figure that necessitates efficient raw material management. Within the production facility, biomass is grouped into logistic units before transport. However, the current logistics model lacks standardized transport units, making it difficult to assess and categorize the logistics configurations. Consequently, only 40-ton trucks with a capacity of up to 33 pallets are utilized. The wood biomass processing centre is another critical actor in the reverse supply chain. Located 134 kilometres from the production site, any additional transport runs

[2] National Science Centre [Narodowe Centrum Nauki] – grant number DEC-2020/39/I/HS4/03533. Researcher: Damian Dubisz.

significantly increase the emissions associated with the supply chain. The processing centre is responsible for identifying biomass types, sorting and removing contaminants, purifying the material, and preparing it for its final use based on its type and utility. The final component of the supply chain is the market, which dictates the method of processing the recovered biomass. The entire reverse supply chain operates according to the 3R principles—Reduce, Reuse, Recycle—and aligns with circular economy concepts as discussed by Krstić et al. (2022) and Stahel (2016) To assess the environmental impact of implementing standardized packaging for wood biomass, a literature review identified six packaging types, listed in **Tab. 3.23**. These packaging types were incorporated into simulation scenarios to evaluate their effect on emissions within the reverse supply chain. Each packaging type was analysed based on core parameters, including width, depth, and height. Special attention was given to weight, volume, and vehicle loading efficiency, as these factors directly influence transport utilisation and the overall environmental performance of the reverse wood biomass supply chain.

Tab. 3.23 Packaging types implemented for wood biomass handling in alternative distribution scenarios.
Source: own elaboration.

Packaging type	Packaging capacity		Packaging specification				
	Maximum weight [kg]	Maximum cbm [litres]	Packaging weight [kg]	Packaging cbm [m3]	width [cm]	depth [cm]	height [cm]
Big Bag A	1 000.00	480.00	30.63	0.48	1.11	0.71	0.61
Big Bag B	1 000.00	250.00	14.38	0.26	0.74	0.54	0.64
Big Bag C	1 000.00	820.00	41.90	0.83	1.11	0.91	0.82
Cage Container A	1 000.00	960.00	26.20	0.96	1.20	0.80	1.00
Cage Container B	1 000.00	760.00	24.20	0.77	1.20	0.80	0.80
Cage Container C folding window	1 000.00	1 152.00	32.90	1.15	1.20	0.80	1.20

The efficiency of the logistic units implemented to handle the raw material, indicated in Table 1, was demonstrated through further simulation of alternative handling methods. Six scenarios were created and the result of each scenario was compared with the current model. In this way, a number of outcome parameters were demonstrated on the basis of which the level of efficiency was verified. The level of savings resulting from a reduction in the number of means of transport, the number of kilometres was indicated on this basis. It also showed a number of control parameters that were modelled for simulation in alternative operating scenarios. Means of transport characteristic is presented in **Tab. 3.24.**

Tab. 3.24 Means of transport specification
Source: own elaboration.

Gross Vehicle Weight	40 000 kg
Vehicle weight capacity [kg]	25 000
Vehicle volume capcaity [m3]	91
Emission factor [kgCO_2/km]*	0.633
Distance from Production Plant to Wood Biomass Processing Centre [km]	134

** According to emission factors provided by UK DEFRA (2024).*

The specifications of the logistic units used for handling post production wood biomass are detailed in **Tab. 3.23**. The efficiency of each solution was evaluated through simulations using alternative types of logistics units. To enable a meaningful comparison, four scenarios were developed, each incorporating one of the six logistics unit types. The results were compared based on emissivity levels, expressed in $kgCO_2e$. In addition to the number of trucks required for transport, the total carbon emissions were calculated and are presented in **Tab. 3.24**.

Obtained emission level for each alternative scenario were estimated using a standardized CF assessment approach. The evaluation was based on carbon footprint calculations in accordance with the GHG Protocol and ISO 14064 standards (Crippa et al., 2021). Emissions were calculated using established emission factor datasets, with the UK DEFRA Emission Factors database serving as the primary source. This dataset was selected for its reliable emission factors across various transport modes, accounting for gross vehicle mass (GVM) and cargo space utilisation. The final simulation results are summarized in **Tab. 3.25**.

Tab. 3.25 Emission efficiency evaluation for each packaging type dedicated to wood biomass handling.

Source: own elaboration.

	Amount of packaging units per its type [Pcs]					
Month	Big Bag A	Big Bag B	Big Bag C	Cage Container A	Cage Container B	Cage Container C folding window
January	1 442	2 870	907	714	864	570
February	763	1 520	480	378	458	302
March	697	1 387	439	345	418	276
April	1 753	3 490	1 103	868	1 051	693
May	3 304	6 576	2 079	1 636	1 980	1 306
June	1 750	3 483	1 101	867	1 049	692
July	3 077	6 124	1 937	1 524	1 844	1 216
August	1 637	3 258	1 030	811	981	647
September	821	1 634	517	407	492	325
October	624	1 241	392	309	374	247
November	667	1 327	420	330	400	264
December	337	671	212	167	202	133

	Number of routes of 40 tonnes GVM trucks according to packaging unite type [Routes]					
Month	Big Bag A	Big Bag B	Big Bag C	Cage Container A	Cage Container B	Cage Container C folding window
January	7.62	8.06	8.26	7.53	7.29	7.22
February	4.03	4.27	4.37	3.99	3.86	3.82
March	3.68	3.90	3.99	3.64	3.53	3.49
April	9.26	9.81	10.04	9.16	8.87	8.77
May	17.45	18.48	18.93	17.26	16.71	16.54
June	9.24	9.79	10.02	9.14	8.85	8.76
July	16.26	17.21	17.63	16.08	15.56	15.40
August	8.65	9.16	9.38	8.55	8.28	8.19
September	4.34	4.59	4.70	4.29	4.15	4.11
October	3.29	3.49	3.57	3.26	3.15	3.12

November	3.52	3.73	3.82	3.48	3.37	3.34
December	1.78	1.89	1.93	1.76	1.70	1.69

	Carbon footprint of transport processes - Production plant to Wood biomass processing centre [$kgCO_2e$]					
Month	Big Bag A	Big Bag B	Big Bag C	Cage Container A	Cage Container B	Cage Container C folding window
January	646	684	700	638	618	612
February	342	362	371	338	327	324
March	312	330	338	309	299	296
April	785	831	851	776	752	744
May	1 479	1 566	1 604	1 463	1 416	1 402
June	783	830	850	775	750	742
July	1 378	1 459	1 494	1 363	1 319	1 305
August	733	776	795	725	702	694
September	368	389	399	364	352	348
October	279	296	303	276	267	265
November	299	316	324	295	286	283
December	151	160	164	149	145	143

Overall carbon footprint [$kgCO_2e$]	7 554	7 999	8 191	7 471	7 233	7 157

The simulation results demonstrated that modifying the type of logistics units used for handling wood biomass can significantly enhance the efficiency of transportation processes and mitigate their carbon footprint. The number of transport vehicles required was presented with decimal values to reflect monthly fluctuations and highlight instances where 40-ton trucks were underutilized. The findings suggest that adopting alternative packaging solutions can reduce the frequency of linehaul transports between the production facility and the wood biomass processing centre. These changes led to a reduction in the total distance travelled, thereby improving transport efficiency. Additionally, the results allow for a direct comparison of the supply chain's carbon emissions based on different types of transport packaging. Among the tested options, the Cage Container C with a folding window achieved the lowest emissivity level, while the Big Bag Type C resulted in the highest emissions, expressed in $kgCO_2e$. Depending on the packaging type used, the annual demand for transport vehicles varied by up to 12 trucks, underscoring the significant impact of logistics unit selection on both operational and environmental performance.

Cargo space utilisation efficiency is an important parameter in the new model of measuring and managing the carbon footprint of transport processes. A detailed approach uses the vehicle load factor parameter, which is indirectly derived from selecting the most efficient types of collective packaging. Vehicle filling efficiency is important due to the emission factor structure presented by UK DEFRA (see **chapter 2.3**), in which the emissions indicator value varies according to the level of vehicle filling.

3.5. Reusable packaging impact on transport emissions

Literature review identified the loading unit as an important element of the supply chain affecting its efficiency(Dubisz et al., 2023; Gavazzi et al., 2022; Pålsson, 2018). Research conducted in the area of food packaging transport indicates that reusable packaging has a significant impact on emissions(Accorsi et al., 2020). Research conducted by Baruffaldi et al. (2019) shows that the use of reusable packaging reduced transport costs by 11.7%. Simultaneously, in addition to reducing costs, it was possible to mitigate CO_2 emissions by 9.2%. This was achieved through the use of Reusable Plastic Crates (RPCs) dedicated to vegetables in intermodal transport. Hence, it was concluded that it is important to verify the validity of implementing reusable packaging elements within supply chains due to their impact on changing the level of emissions from transport processes. Therefore, own research was conducted based on historical data[3].

The supply chain of the analysed manufacturing company includes two main production centres and six local branches, which handle last-mile distribution. The production centres are responsible solely for manufacturing and loading linehaul trucks that deliver goods to the local branches. From a sustainable supply chain perspective, this model appears inefficient. The extensive internal network, involving multiple local branches, increases energy consumption in both transportation and storage operations. Nevertheless, due to the nature of the company's primary customers derived mainly from the automotive sector and the critical need to ensure the availability of spare parts and uninterrupted production processes, maintaining the current supply chain structure remains necessary. To carry out transportation tasks, the company uses standardized euro-class pallets, ensuring consistency in basic logistics units. However, the production components shipped from the two centres are packed in various types of multipacks, complicating the return of reusable packaging to the appropriate distribution centre. A schematic representation of the goods flow between production plants, distribution centres, and local branches is shown in **Fig. 3.14** below.

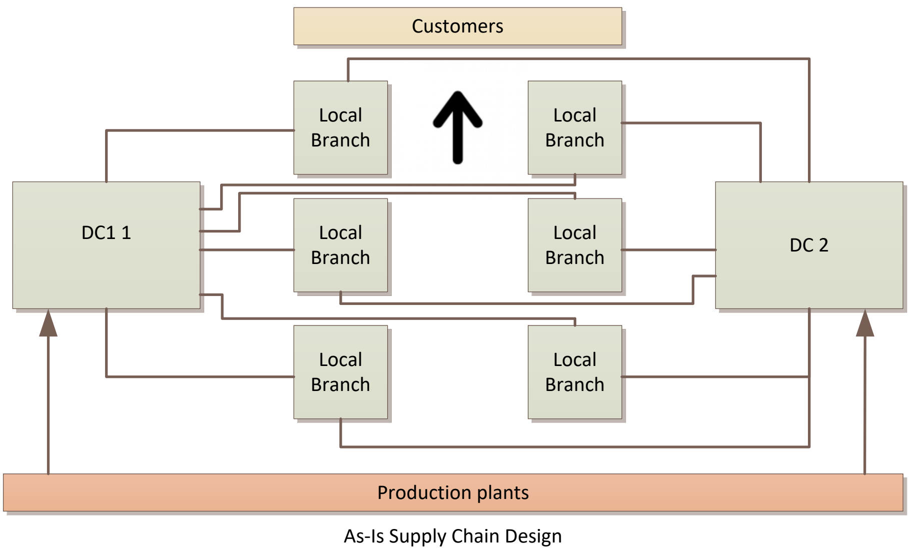


Fig. 3.14 Current logistics model based on various reusable packaging solutions

Source: own elaboration.

Currently 12 types of reusable packaging are utilized within the supply chain. However, the lack of standardisation in loading units requires each local branch to return empty packaging to its respective distribution centre of origin. This return process is based on the packaging's point of origin rather than proximity, leading to increased energy consumption, higher carbon emissions, and

[3] Based on historical data of a company from a chemistry distribution sector gathered during the commercial project conducted by the Łukasiewicz Research Network - Poznań Institute of Technology in 2023 Project scope: Improving the efficiency of the liquid product supply chain. Project manager: Damian Dubisz.

elevated return logistics costs. A comprehensive list of the packaging types currently in use within the internal supply chain is provided in **Tab. 3.26.**

Tab. 3.26 Loading units used currently within the internal distribution chain
Source: own elaboration.

Logistics unit type code	Total goods volume [m3]	Number of packages [pcs]	Distribution Centre of origin
NF	0.22	5	Distribution Centre 1
NG	1.31	55	Distribution Centre 1
NH	0.28	74	Distribution Centre 1
NM	4.34	183	Distribution Centre 1
NN	352.80	283	Distribution Centre 1
NP	1.33	645	Distribution Centre 1
NR	0.20	28	Distribution Centre 2
NS	0.97	41	Distribution Centre 2
NU	0.05	7	Distribution Centre 2
NX	3.37	1421	Distribution Centre 2
NZ	0.23	8	Distribution Centre 2
SA	6845.37	6339	Distribution Centre 2

The current logistics model, shaped by demand and production cycles, exhibits noticeable seasonality, as illustrated in **Fig. 3.15**. The highest distribution flows in terms of cargo weight occur between February and March, while peak volumes are observed in September and November. These demand patterns directly influence the required capacity and availability of transport resources.

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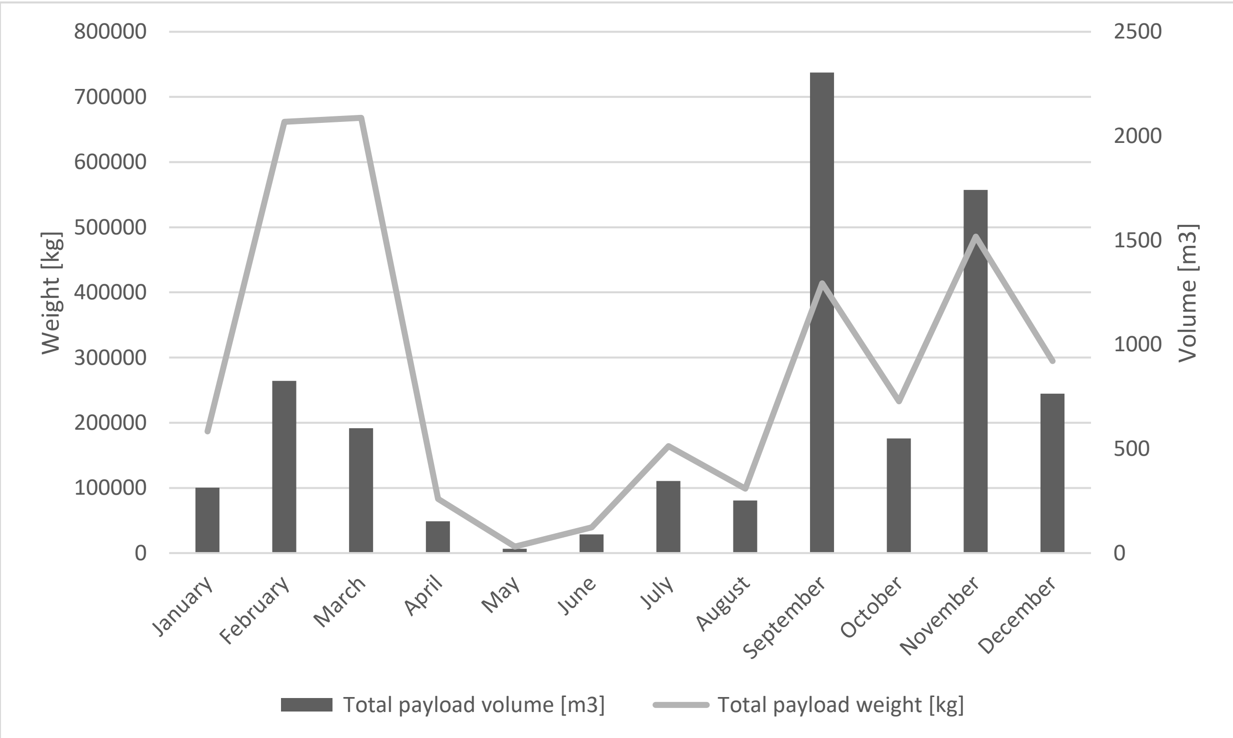

Fig. 3.15 Seasonality of goods flow within internal supply chain processes
Source: own elaboration.

According to the requirement of returning reusable packaging to the originating distribution centre, dedicated transport vehicles must be allocated for this purpose. Analysis of the data revealed that Distribution Centre 1 handles only 4.997% of the total goods flow to local branches, while

Distribution Centre 2 accounts for a dominant 95.003%. This imbalance indicates that return transport vehicles to the distribution centres are significantly underutilized. Nevertheless, for technological reasons tied to production processes that rely on reusable packaging, it is not feasible to reduce the frequency of return trips to less than once per month. The number of units primarily used for distribution tasks, shown in **Tab. 3.27 was** based on the dimensions of all packaging types involved in the supply chain. This data was then used to estimate the number of return transports from local branches to each distribution centre, as detailed in **Tab. 3.29**. As observed in **Tab. 3.27** which outlines the usage volumes of individual packaging types, the highest demand is associated with the SA, NX, and NP packaging types. In contrast, demand for the remaining packaging types is minimal. These findings suggest that narrowing the range of reusable packaging in use could improve efficiency within the supply chain.

Tab. 3.27 Number of renewable packages and its types engaged within supply chain
Source: own elaboration.

Logistics unit type code	Total goods volume [m3]	Number of packages [pcs]
NF	0.22	5
NG	1.31	55
NH	0.28	74
NM	4.34	183
NN	352.80	283
NP	1.33	645
NR	0.20	28
NS	0.97	41
NU	0.05	7
NX	3.37	1421
NZ	0.23	8
SA	6845.37	6339

Detailed information on the volume of goods transported between the Distribution Centres and Local Branches is provided in **Tab. 3.26** and **Tab. 3.27**. While the values are expressed in terms of shipment volume, the calculation of required transport vehicles also considered the maximum load capacity of vehicles with a Gross Vehicle Mass (GVM) of up to 40 tons.

Tab. 3.28 Goods flow between Distribution Centre 1 and local branches. Reverse flow and packaging types included
Source: own elaboration.

Month	Goods volume per packaging type [m^3]						Estimated number of vehicles	Estimated number of returning vehicles
	NF	NG	NH	NM	NN	NP		
January	0.20	1.31	0.07		5.92	0.07	1	1
February			0.10	4.11	149.35	0.55	2	1
March			0.10	0.23	41.13	0.61	2	1
April						0.01	1	1
October			0.01				1	1
December	0.02				156.40	0.08	2	1
Grand Total	0.22	1.31	0.28	4.34	352.80	1.33	9	6

Distribution Centre 1 has relatively small role in managing goods flow within the internal supply chain, the number of return trips does not exceed one vehicle. The transported volume alone does not warrant these return shipments; they are driven solely by the need to return reusable packaging. A summary of the return shipment flows is provided in **Tab. 3.29.**

Although Distribution Centre 2 handles approximately 95% of the total goods flow, the number of return vehicles does not increase proportionally when compared to DC1. This discrepancy suggests that the return shipments to DC1 could be further optimised to improve overall transport efficiency.

Tab. 3.29 Goods flow between Distribution Centre 2 and local branches. Reverse flow and packaging type included

Source: own elaboration.

Month	Goods volume per packaging type [m^3]						Estimated number of vehicles	Estimated number of returning vehicles
	NR	NS	NU	NX	NZ	SA		
January		0.03	0.05	0.18		254.21	8	2
February	0.20	0.57		0.91	0.05	415.59	26	3
March		0.11		2.24	0.15	165.02	26	3
April				0.00		117.97	4	1
May						91.02	2	1
June						191.90	3	1
July						501.24	7	2
August						320.75	5	1
September						2160.10	29	3
October						533.05	9	1
November						1542.95	21	3
December		0.27		0.04	0.03	551.56	12	2
Grand Total	0.20	0.97	0.05	3.37	0.23	6845.37	152	23

In accordance with the methodologies established by the IPCC and UK DEFRA standards, the carbon footprint of the current logistics model has been calculated and will be compared with the proposed optimised model in the following section.

Implementation of a Standardized Universal Logistics Units within the Supply Chain

In the proposed to-be model of the supply chain, the introduction of standardized reusable packaging is recommended. This strategy eliminates the need to return packaging to its original distribution centre. As a result, the total number of shipments across the supply chain can be reduced by 3.16%. All returnable packaging will be redirected exclusively to Distribution Centre 2 (DC2), and the volume of returned units can be accommodated using the vehicles already operating within DC2’s reverse logistics flow. The revised supply chain design is illustrated in **Fig. 3.16**.

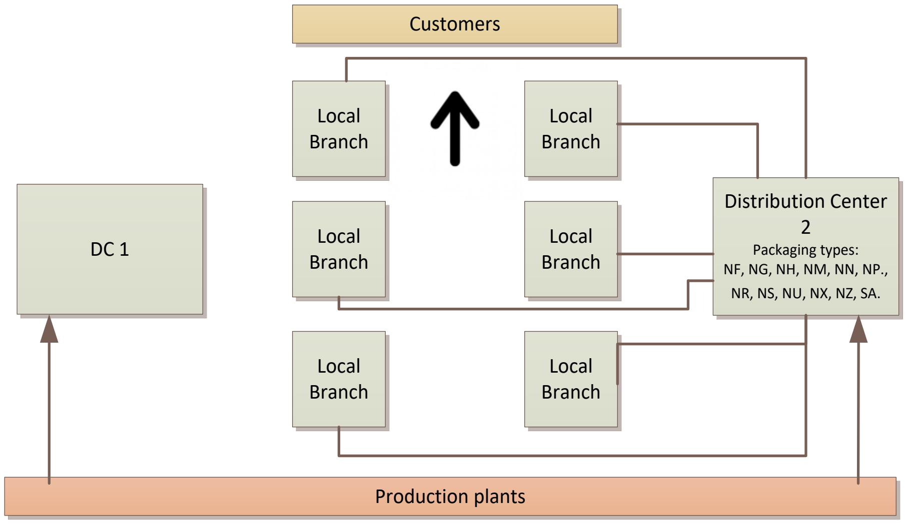

Fig. 3.16 Mutual interconnections within supply chain based on standardized types of packaging
Source: own elaboration.

The assessment of carbon footprint levels under different scenarios

To assess the significance of the differences between the proposed models, their environmental performance within the supply chains was examined. Beyond variations in the number of transports, which directly influence cost efficiency, the carbon footprint of both models was estimated and expressed in kilograms of CO_2e. Subsequent emission calculations for the supply chains were carried out using the emission factors presented in **Tab. 3.30.**

Tab. 3.30 Emission factors used for CF assessment within presented supply chain
Source: own elaboration based on UK DEFRA (2024).

Truck [GVM]	Distance unit	Average laden			
		Total kg CO_2e per unit	kg CO_2e of CO_2 per unit	kg CO_2e of CH_4 per unit	kg CO_2e of N_2O per unit
40 tonns lorry	km	0.92391	0.90772	0.00013	0.01606

Logic and results of the conducted calculations are presented in **Tab. 3.31** below. The environmental performance assessment focuses on the total distance travelled by 40-ton GVM vehicles within the supply chain, both before and after the implementation of standardized packaging.

Tab. 3.31 Environmental assessment of as is and to-be supply chain model.
Source: own elaboration.

Phase 1. Non-standardized reusable packaging within supply chain				
Month	Distribution Centre 1		Distribution Centre 2	
	Estimated number of vehicles	Estimated number of returning vehicles	Estimated number of vehicles	Estimated number of returning vehicles
January	1	1	8	2
February	2	1	26	3
March	2	1	26	3
April	1	1	4	1
May	0	0	2	1
June	0	0	3	1
July	0	0	7	2
August	0	0	5	1
September	0	0	29	3
October	1	1	9	1
November	0	0	21	3
December	2	1	12	2
Total routes	9	6	152	23
Average route distance [km]	425		320	
Total kg CO_2e per DC	5889,92625		51738,96	
Total kg CO_2e in SC	57628,88625			
Phase 2. Implementation of standardized reusable packaging within supply chain				
Month	Distribution Centre 1		Distribution Centre 2	
	Estimated number of vehicles	Estimated number of returning vehicles	Estimated number of vehicles	Estimated number of returning vehicles
January	1	0	8	2
February	2	0	26	3
March	2	0	26	3
April	1	0	4	1
May	0	0	2	1
June	0	0	3	1
July	0	0	7	2
August	0	0	5	1
September	0	0	29	3
October	1	0	9	1
November	0	0	21	3
December	2	0	12	2
Total routes	9	0	152	23
Average route distance [km]	425		320	
Total kg CO_2e per DC	3533.95		51738.96	
Total kg CO_2e in SC	55272.91			

In the optimised supply chain model, a reduction in carbon emissions of 2 355.97 kg CO_2e was achieved. This outcome highlights the potential for significant environmental benefits through incorporation of reusable packaging within reverse logistics. It is important to emphasize that such reductions could be even more substantial in other industrial sectors not addressed in this study. The adoption of standardised reusable transport packaging facilitates the restructuring of reverse logistics operations, directly affecting greenhouse gas emissions. Specifically, the reduction in transport frequency leads to improved cost efficiency. However, the primary indicator of environmental impact remains the calculated CO_2 equivalent emissions. Even marginal changes in the standardisation of transport packaging within internal distribution networks can substantially enhance operational efficiency and reduce total vehicle kilometres travelled. Further research is recommended to assess the environmental impact associated with the production processes and life span of reusable transport units. Continued investigation into supply chain emissions should adopt a Life Cycle Assessment (LCA) framework to comprehensively evaluate sustainability performance. Results of this research are essential for understanding the full environmental implications of supply chain activities, particularly in relation to reverse logistics functions, including recycling, reuse, and remanufacturing. Integrating life cycle perspectives is vital to accurately quantify and improve the sustainability of supply chains.

3.6. The use of multi-criteria analysis in the management of carbon footprint of transport process in a supply chain

Further research was conducted on the essential elements of the new management method to management and measurement of the carbon footprint of transport processes was conducted towards the adaptation of the Multi Criteria Decision Making (MCDM) matrix. For this purpose, the justification for the selection of the appropriate FTL full truckload and LTL palletised transport type was empirically verified. Environmental parameters, costs and fleet availability were taken into account to reflect the significance of the parameters reported by the actual market company. These three parameters were identified by experts during an execution of a project - a logistics audit carried out for business partner of Łukasiewicz Research Network - Poznań Institute of Technology[4]. The research was conducted using historical data from a paper industry company. The main area of the company's activity is the production of cardboard packaging. It serves both international and domestic customers. It is part of a larger European group, which operates throughout Europe. The Polish branch employs about 350 people. Research on the operational alignment of service levels, with reference to three essential parameters, was conducted on a sample route carried out in Poland.

The initial assessment of process efficiency primarily focuses on cost considerations. The literature review indicates that organisational success often hinges on the selection of appropriate parameters for supply chain participants. To achieve the most effective supply chain configuration, choosing the correct service level—either Full Truck Load (FTL) or Less Than Truck Load (LTL)—is equally important. However, offer selection should not be based solely on cost, and various additional factors must also be taken into account.

An analysis of transport operator offers was conducted, incorporating several non-cost criteria, including:

- Types of vehicles available,
- Vehicle weight classified by gross vehicle mass (GVM),
- Availability and quantity of transport resources,
- Average emissions per vehicle in the fleet (measured in kgCO_2e/km),
- Unit transport costs,
- Geographic markets served,
- Type of service level offered (FTL or LTL).

The operational research examined ten offers from transport operators who confirmed their capacity to provide continuous service for the sender's transportation needs. Each carrier was requested to submit pricing for both FTL and LTL options. Loading and unloading locations were identified using postal codes. To evaluate the attractiveness of each carrier's offer, a sample route from Świecie to Rzeszów was selected, with additional unloading points planned along the way. The route is illustrated in **Fig. 3.17**.

[4] A commercial project conducted by the Łukasiewicz Research Network - Poznań Institute of Technology in 2023 for a company in the cardboard and paper industry sector. Project scope: Verification of alternative organisational scenarios for transport processes, considering LTL and FTL transport as well as non-cost parameters of transport process execution. Project manager: Damian Dubisz.

Fig. 3.17 Route employed in the operational research to apply the MCDM matrix
Source: own elaboration.

Carrier's FTL and LTL offers

The submitted offers from carriers were reviewed for consistency and completeness. This involved evaluating the level of freight information provided, particularly regarding the detailed postal codes for departure and destination locations. For each carrier, the gross vehicle weight (GVW) of the analysed vehicle group was identified, and the declared fleet availability was recorded. Using this data, vehicle emissions were estimated with reference to emission matrices published by the UK Department for Environment, Food and Rural Affairs (DEFRA), applying an average vehicle load factor. Subsequently, information was collected on the markets each operator served and the scope of services offered. It was noted that not all carriers provided both Full Truck Load (FTL) and Less Than Truck Load (LTL) options. Additional non-cost-related details from the submitted offers are presented in **Tab. 3.32.**

Tab. 3.32 Transport Operators' Offers: Key Performance Metrics
Source: own elaboration.

Carrier No.	GVM of vehicles [kg]	Vehicles in Fleet	Average emissions of heterogenous fleet [kgCO_2e/km]	Supported markets	Mode of transport
Carrier no. 1	40 000	6	0.74	All EE countries	FTL
Carrier no. 2	32 000	11	0.72	All EE countries	FTL
Carrier no. 3	32 000	13	0.75	All EE countries	FTL; LTL
Carrier no. 4	32 000	7	0.78	All EE countries	FTL; LTL
Carrier no. 5	32 000	2	0.77	All EE countries	LTL
Carrier no. 6	32 000	7	0.74	All EE countries	LTL
Carrier no. 7	40 000	13	0.72	All EE countries	FTL
Carrier no. 8	40 000	6	0.71	All EE countries	LTL
Carrier no. 9	40 000	9	0.74	All EE countries	FTL; LTL
Carrier no. 10	40 000	11	0.73	All EE countries	LTL

Analysis of the attractiveness of the offers

To assess the attractiveness of the offers, it was decided to carry out a cost simulation for a theoretical freight route between Świecie in the Kujawsko-Pomorskie Voivodeship, Poland, and

Rzeszow in the Podkarpackie Voivodeship, Poland. An additional five unloading points were planned along the route. A visualisation of the route is shown in **Fig. 3.17**. The shortest route was adopted according to the available network of motorways, expressways, and national roads. The means of transport defined in Table 1 were engaged in the assessment. For the purpose of further simulation, Table 2 provides details of the locations of the subsequent delivery points. The order of the points along the route, the name of the town, and the number of kilometres between locations are indicated. For each point, the number of load units to be unloaded was determined.

Tab. 3.33 Details of the Swiecie-Rzeszow route assessed

Source: own elaboration.

Route points	Town name	Postcode	Distance [kms]	Pallets [pcs]
Start of route	Świecie	86-100	–	–
Drop off point 1	Włocławek	87-800	167	5
Drop off point 2	Łódź	90-024	274	12
Drop off point 3	Radom	26-600	439	1
Drop off point 4	Kielce	25-001	520	7
Drop off point 5	Tarnów	33-100	630	1
End of route	Rzeszów	35-001	717	7

Simulation of FTL full truckload transport costs based on the submitted offers from the carriers, a cost simulation was conducted for the specified route.

Tab. 3.34 presents the simulated FTL transportation costs for each carrier. The calculations include not only the base freight rate but also the total estimated transport cost, accounting for additional expenses related to extra unloading points along the route.

Tab. 3.34 Full truck load (FTL) Transportation Rates

Source: own elaboration.

Route points	Cost parameters							
	Carrier No. 1		Carrier No. 2		Carrier No. 3		Carrier No. 7	
	Extra drop off point costs	Main freight rate	Extra drop off point costs	Main freight rate	Extra drop off point costs	Main freight rate	Extra drop off point costs	Main freight rate
Start of route	–	–	–	–	–	–	–	–
Drop off point 1	€ 50.00		€ 50.00		€ 50.00		€ 50.00	
Drop off point 2	€ 50.00		€ 50.00		€ 50.00		€ 50.00	
Drop off point 3	€ 50.00		€ 50.00		€ 50.00		€ 50.00	
Drop off point 4	€ 50.00		€ 50.00		€ 50.00		€ 50.00	
Drop off point 5	€ 50.00		€ 50.00		€ 50.00		€ 50.00	
End of route	–	€ 268.39	–	€ 533.34	–	€ 573.34	–	€ 595.56
In total		€ 518.39		€ 783.34		€ 823.34		€ 845.56

Simulation of LTL transport costs

Based on the submitted transport service offers, the costs of LTL pallet transport for the planned route were estimated. Of the ten transport operators analysed, only four offer LTL services. The results of the LTL transport cost simulation are presented in Tab. 3.35. In calculating total LTL costs, actual pricing was used, including surcharges related to the number of pallets transported. Unlike FTL services, LTL does not follow a single fixed rate per shipment; instead, the total cost is composed of several individual charges. For reference, the FTL transport cost simulation results remain presented in **Tab. 3.34.**

Tab. 3.35 Less-than-truckload (LTL) Transportation Rates
Source: own elaboration.

Route points	Location/ name	Number km	Number pallets	Costs							
				Carrier 3		Carrier 5		Carrier 6		Carrier 9	
				Rate per pallet	LTL cost	Rate per pallet	LTL cost	Rate per pallet	LTL cost	Rate per pallet	LTL cost
Start of route	Świecie	–		–	–	–	–	–	–	–	–
Drop off point 1	Włocławek	167	5	€ 21.89	€ 109.43	€ 24.52	€ 122.59	€ 20.48	€ 102.40	€ 22.65	€ 113.27
Drop off point 2	Łódź	274	12	€ 23.10	€ 277.22	€ 26.65	€ 133.25	€ 20.48	€ 102.40	€ 23.22	€ 116.11
Drop off point 3	Radom	439	1	€ 29.49	€ 29.49	€ 36.51	€ 182.56	€ 20.48	€ 102.40	€ 30.96	€ 154.80
Drop off point 4	Kielce	520	7	€ 31.22	€ 218.53	€ 34.65	€ 173.23	€ 20.48	€ 102.40	€ 32.74	€ 163.71
Drop off point 5	Tarnów	630	1	€ 31.31	€ 31.31	€ 37.31	€ 186.55	€ 20.48	€ 102.40	€ 35.87	€ 179.35
End of route	Rzeszów	717	7	€ 31.22	€ 218.53	€ 37.31	€ 186.55	€ 20.48	€ 102.40	€ 35.87	€ 179.35
Total [plts]/[costs]			33	–	€ 884.52	–	€ 984.72	–	€ 614.40	–	€ 906.58

The choice of the optimal transport service from among the offers submitted by operators was carried out using a multi-criteria analysis. The proposed evaluation model incorporates several control parameters that shape the final outcome, including transport costs, vehicle emission characteristics, availability of transport resources, and delivery lead time. A defined weight of each parameter was reflected in the assessment. Appropriate weight was assigned to the individual parameters presented in **Tab 3.36** and **Tab. 3.37**. The outcomes of the multi-criteria analysis for FTL carrier selection are presented in **Tab. 3.36.** The results for LTL carrier selection are shown in **Tab. 3.37**. The assessment of parameters was conducted using a three-point scale, where 1 represents the lowest value and 3 the highest and most significant. The selection of parameters was based on the company's needs, which formed the foundation for developing the carrier evaluation model. In line with the literature, parameter choice should be aligned with the requirements of the supply chain (Camargo Pérez et al., 2015). Within an urban transport chain, the number of parameters may be expanded and assigned different weights if required. In this study, however, the evaluation was limited to three parameters in accordance with the company's specific context. The number of assessed parameters as well as the scale range can be adjusted depending on organisational needs, though excessively large scales may reduce the influence of individual parameters on the final outcome. The scales applied here were established in consultation with the company and provided the basis for the research on carrier offer evaluation.

Tab. 3.36 Results of the multi-criteria analysis for the selection of an FTL carrier
Source: own elaboration.

Carrier ID	Total cost [EUR]	No. of available vehicle [no.]	Delivery lead time [hrs]	Avg. emissivity of fleet vehicles [kgCO_2e/km]	Value of parameter				Evaluation of parameter				Result
					Costs	Fleet availability	Delivery lead time	Environmental parameter	The cost parameter	The fleet availa-bility parameter	The lead time parameter	The environmen-tal parameter	
Carrier no. 1	€ 518.39	5	24	0.74	3	2	3	2	1.00	0.42	1.0	0.67	8.17
Carrier no. 2	€ 783.34	10	24	0.72	3	2	3	2	0.66	0.83	1.0	1.00	8.65
Carrier no. 3	€ 823.34	12	48	0.75	3	2	3	2	0.63	1.00	0.5	0.50	6.39
Carrier no. 7	€ 845.56	12	36	0.72	3	2	3	2	0.61	1.00	0.7	1.00	7.84

Tab. 3.37 Results of the multi-criteria analysis for LTL carrier selection
Source: own elaboration.

Carrier ID	Total cost [EUR]	No. of available vehicle [no.]	Delivery lead time [hrs]	Avg. emissivity of fleet vehicles [kgCO2e/km]	Value of parameter				Evaluation of parameter				Result
					Costs	Fleet availability	Delivery lead time	Environmental parameter	The cost parameter	The fleet availa-bility parameter	The lead time parameter	The environmen-	
Recommended carrier 5	€ 984.72	1	24	600	3	2	3	2	0.62	0.08	1.0	0.50	6.04
Recommended carrier 6	€ 614.40	6	48	300	3	2	3	2	1.00	0.50	0.5	1.00	7.50
Recommended carrier 3	€ 884.52	12	24	300	3	2	3	2	0.69	1.00	1.0	1.00	9.08
Recommended carrier 9	€ 906.58	8	36	300	3	2	3	2	0.68	0.67	0.7	1.00	7.37

To examine how the introduction of an LTL pallet service affects transport costs, simulations were performed comparing FTL and LTL operations for scenarios with six, four, and two unloading points along the designated route (**Fig. 3.17**). For the purpose of ensuring comparability, a total shipment volume of thirty-three pallets was assumed. Since the analysis required a comparison of FTL and LTL offers, adjustments to the route and the corresponding number of kilometres were made. The modified routes, which served as the basis for subsequent simulations, are presented in **Tab. 3.38**.

Tab. 3.38 Transport logistics parameters for the adopted unloading points
Source: own elaboration.

Route steps		Postcode	Number [km]	Number pallets [pcs]
6 drop off points				
Start of route	Świecie	86-100	–	–
Drop off point 1	Włocławek	87-800	167	5
Drop off point 2	Łódź	90-024	274	12
Drop off point 3	Radom	26-600	439	1
Drop off point 4	Kielce	25-001	520	7
Drop off point 5	Tarnów	33-100	630	1

Route steps		Postcode	Number [km]	Number pallets [pcs]
End of route	Rzeszów	35-001	717	7
4 drop off points				
Start	Świecie	86-100	–	–
Drop off point 1	Włocławek	87-800	167	7
Drop off point 2	Łódź	90-024	274	14
Drop off point 3	Radom	26-600	439	3
Stop	Rzeszów	35-001	717	9
2 drop off points				
Start	Świecie	86-100	–	–
Drop off point 1	Włocławek	87-800	167	16
Stop	Rzeszów	35-001	717	17

The outcomes of the simulation, comparing FTL and LTL transport costs based on the assumed number of unloading points and total distance, are presented in **Tab. 3.39**

Tab. 3.39 Simulation results of FTL versus LTL transport cost comparison for the assumed number of unloading points
Source: own elaboration.

Mode of transport				FTL ave. costs	LTL ave. costs	Ratio
FTL		LTL				
6 drop off points						
Carrier 1	€ 518.39	€ 884.52	Carrier 3	€ 742.66	€ 847.56	14.12%
Carrier 2	€ 783.34	€ 984.72	Carrier 5			
Carrier 3	€ 823.34	€ 614.40	Carrier 6			
Carrier 7	€ 845.56	€ 906.58	Carrier 9			
4 drop off points				FTL ave. costs	LTL ave. costs	Ratio
Carrier 1	€ 418.39	€ 849.03	Carrier 3	€ 642.66	€ 820.99	27.75%
Carrier 2	€ 683.34	€ 926.19	Carrier 5			
Carrier 3	€ 723.34	€ 675.84	Carrier 6			
Carrier 7	€ 745.56	€ 832.91	Carrier 9			
2 drop off points				FTL ave. costs	LTL ave. costs	Ratio
Carrier 1	€ 318.39	€ 877.25	Carrier 3	€ 542.66	€ 837.91	54.41%
Carrier 2	€ 583.34	€ 1 026.55	Carrier 5			
Carrier 3	€ 623.34	€ 675.84	Carrier 6			
Carrier 7	€ 645.56	€ 772.01	Carrier 9			

The research revealed that full truckload (FTL) transport services were comparable in cost to less-than-truckload (LTL) services when six delivery points were considered. As highlighted in Vega et al.'s (2021) research, the efficiency of different service types depends on the parameters considered during the decision-making process. In the current operational research, FTL transport was found to be more cost-effective in most cases. However, this result assumes that the vehicle is fully loaded at the start of its route.

The research demonstrated that full truckload (FTL) services were cost-comparable to less-than-truckload (LTL) services when six delivery points were considered. As noted by Vega et al. (2021), the efficiency of transport service types depends strongly on the parameters applied in the decision-making process. In the present analysis, FTL transport proved more cost-effective in most scenarios, though this outcome assumes full vehicle utilisation at the start of the route. The proposed multi-criteria analysis method for evaluating transport modes can be effectively adapted into a model for measuring and managing the carbon footprint of logistics processes. A key strength of this approach lies in its ability to incorporate non-cost factors, such as environmental impact, alongside traditional cost-based considerations. While FTL is generally the most economical option under full capacity utilisation, LTL services may offer advantages in cases with a high number of closely located delivery points. The operational results, based on historical company data, showed that LTL was 14.12% more expensive with six delivery points, 27.75% with four, and 54.41% with two, indicating that FTL gains cost efficiency as delivery points decrease. These findings confirm the complex relationship between delivery network structure and transport costs, underlining the need to assess each scenario individually by accounting not only for cost, but also for environmental and operational parameters such as emissions, fleet availability, and delivery lead time.

The study revealed that the optimal configuration of a supply chain and the selection of transport operators should not be determined solely by cost considerations. At the same time, environmental criteria cannot be the only factors guiding these decisions. Other important aspects, such as emissions generated by transport processes and fleet availability, also play a decisive role. Effective management of transport supply chains therefore requires balancing cost efficiency with environmental performance in carrier selection. In this context, the use of multi-criteria decision-making (MCDM) tools provides valuable support by enabling the simultaneous consideration of economic, environmental, and operational parameters.

4. A new model for transport processes emissions management

The logic of the new model for measuring and managing transport emissions is based directly on the internationally recognised standards of the GHG Protocol, ISO 14 064 and utilises emission factors published by UK DEFRA for estimating Scope 1 and Scope 3 emissions caused by transport operations undertaken by Internal Combustion Engine (ICE) vehicles and KOBiZE emission factors for determining emissions resulting from charging electric vehicle (EV) under Scope 2. It has to be considered before enrolment of CF assessment to provide a dedicated emission factors for each country. The KOBiZE emission factor set is dedicated to the Polish energetic mix, hence composition of emissions may vary in other countries. The essential steps included in the assessment methodology are directly derived from the GHG Protocol CF assessment recommendations presented in **chapter 1.1, Fig. 2.5**. Subsequently, the coverage of all essential elements indicated in the standards and norms in the basic steps guarantees their compatibility with existing guidelines and international frameworks. The logic of the model is based on five primary steps presented in **Fig. 4.1** below.

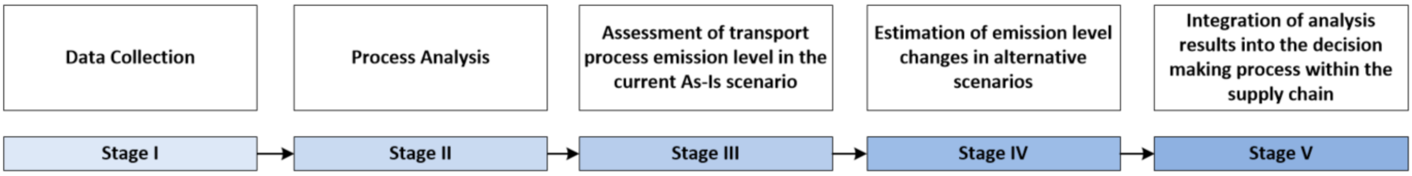

Fig. 4.1 Five key steps of a new model for managing CO_2 emissions within distribution supply chains
Source: own elaboration.

Based on the variant structure of the new model for assessing the carbon footprint of transport processes, a detailed logical diagram has been prepared. The CF assessment begins with diagram A, which contains details of Stage I and Stage II. These are mainly focused on data collection and realisation of process analysis. Afterward, depending on the quality of the collected data, a computational approach is selected in the model. If high-detail data has been obtained, the High Data Quality Assessment is selected. Detailed Approach presented has been presented in diagram. However, in case of the limited data quality, then the simplified approach must be chosen. The Simplified Approach is presented in diagram C. Afterwards, the current level of carbon footprint is assessed and presented in the As-Is scenario. The next step is to implement changes in order to obtain alternative transport flow scenarios CF results. The way to obtain results for alternative scenarios are presented in diagram D. Based on Multi Criteria Decision Making (MCDM) approach, the most optimal to-be scenario may be pointed out and choose for implementation in actual sustainable supply chain. The composition of model logic elements is presented in **Fig. 4.2**

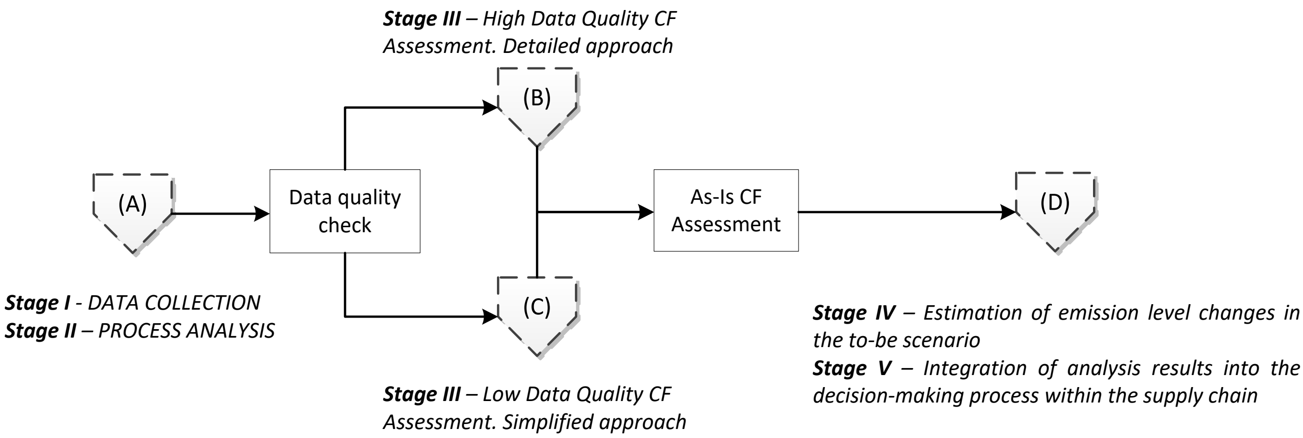

Fig. 4.2 Roadmap for the detailed diagrams of the CF transport process assessment map
Source: own elaboration.

The **Tab. 4.1** provides information about the differences between the LDQ and the HDQ models. Each model offers a different level of CF assessment quality, depending on the scope of input data.

Tab. 4.1 Comparison of input and result parameters in HDQ and LDQ Cf assessment models.
Source: own elaboration.

		Low Data Quality CF Assessment model (LDQ)	High Data Quality CF Assessment Model (HDQ)
Input parameters	Age of the vehicle	Yes	Yes
	Gross Vehicle Weight (GVW)	Yes	Yes
	Fuel type	Yes	Yes
	Distance travelled	Yes	Yes
	Vehicle body type	Yes	Yes
	Identification of the distribution process participants within entire supply chain	No	Yes
	Transported goods parameters	No	Yes
	Specific pick-up, and goods drop-off location parameters	No	Yes
	CF assessment based on detailed information about goods flow between location within supply chain	No	Yes
Result parameters	Calculation of overall emission level under Scope 1, 2, 3	Yes	Yes
	Determination of the emission level of the various types of means of transport	Yes	Yes
	Determination of the emission level per load unit and carrier	No	Yes
	Calculation of the emission factor corresponding to the specifics of transported goods [$kgCO_2e/kg$]	No	Yes
	Calculation of emission level per location within entire distribution supply chain	No	Yes
	Calculation of emission level per specific commodity group and SKU	No	Yes
	Identification of CO_2 emissions per vehicle groups	Yes	Yes
	Identification of CO_2 emission per specific vehicle	Yes *	Yes
	Identification of cost parameters of transport processes	Yes	No
	Compliance with the GHG Protocol and ISO 14 064:2018 standard	Yes	Yes

** Depending on the use of the LDQ model. To calculate this result parameter, the emission level must be assessed for a single vehicle, not for a group of vehicles.*

The following diagrams show in detail the logic of application and the scope of calculation models in the detailed and simplified approaches. **Fig. 4.3** below shows element A containing details of Stage I and Stage II.

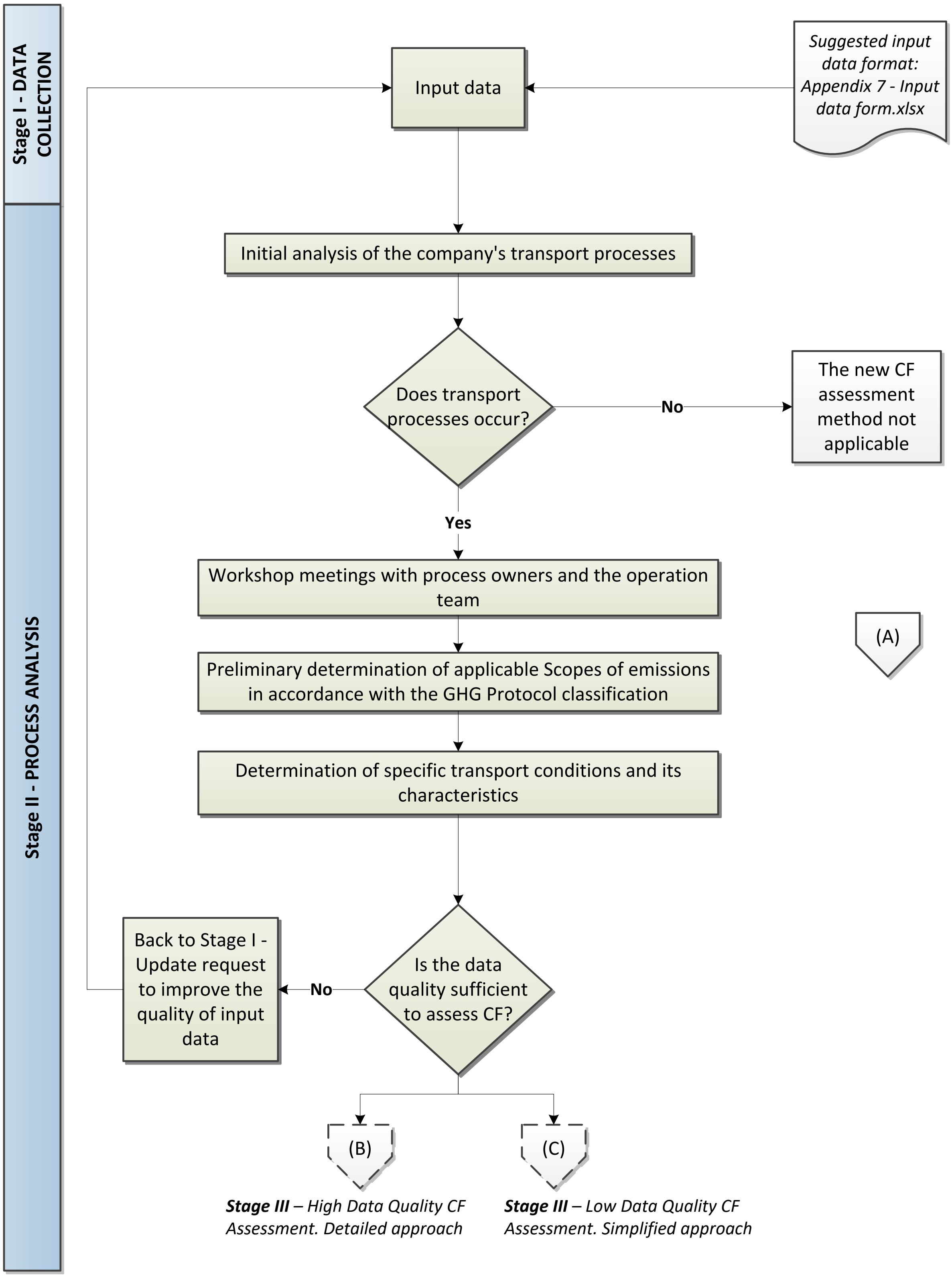

Fig. 4.3 Part A. Initial steps of "data collection" (Stage I) and "process analysis" (Stage II) in a new model for measuring and managing transport emissions
Source: own elaboration.

Regarding the assessment logic defined in the GHG Protocol (**chapter 1.1**), it is necessary to determine the initial level of data detail available for the carbon footprint assessment of transport processes within sustainable supply chains. **Fig. 4.3** above illustrates the initial steps required to begin assessing the carbon footprint of transport processes. **Fig. 4.4** below shows how to interpret the information obtained after the data collection stage. The first important phase in the analysis of the collected data and the identification of essential information on how the process is executed is data screening. In accordance with the GHG Protocol recommendations, the allocation of emissions to individual Scopes (1, 2 and 3, upstream and downstream) must be preliminarily determined at this phase of the CF evaluation. The subsequent step is to ascertain whether detailed data is available, or the evaluation will have to be conducted in more general terms. The next essential step is to identify the mode of transport in order to determine further evaluation parameters and indicate possible future management strategies concerning transport processes. Depending on the quality of the data provided for assessment, it is recommended to choose between a simplified or general evaluation of the carbon footprint of transport processes. However, it should be concerned that the identified processes must already be assigned to individual scope of emission at this stage, in accordance with the nomenclature specified in the GHG Protocol (**described in chapter 2.2**). The following **Fig. 4.4** shows basic steps of the developed method for measuring and managing the carbon footprint of transport processes in a sustainable supply chain. The **Fig. 4.4** shows the steps towards defining the mode of transport and the initial adoption of an appropriate calculation approach. At this stage, data screening should be conducted and the scopes within which emissions will be measured should be preliminarily defined. It is vital to emphasise that correct identification of the quality of basic data is a key stage that must be taken into account, as it determines subsequent actions in the CF evaluation and further decision-making related to the CF assessment outcome. To support the evaluation of data quality, a dedicated checklist has been proposed. The data quality level can be assessed using the checklist provided in **Appendix 4 - Data quality checklist.xlsx**

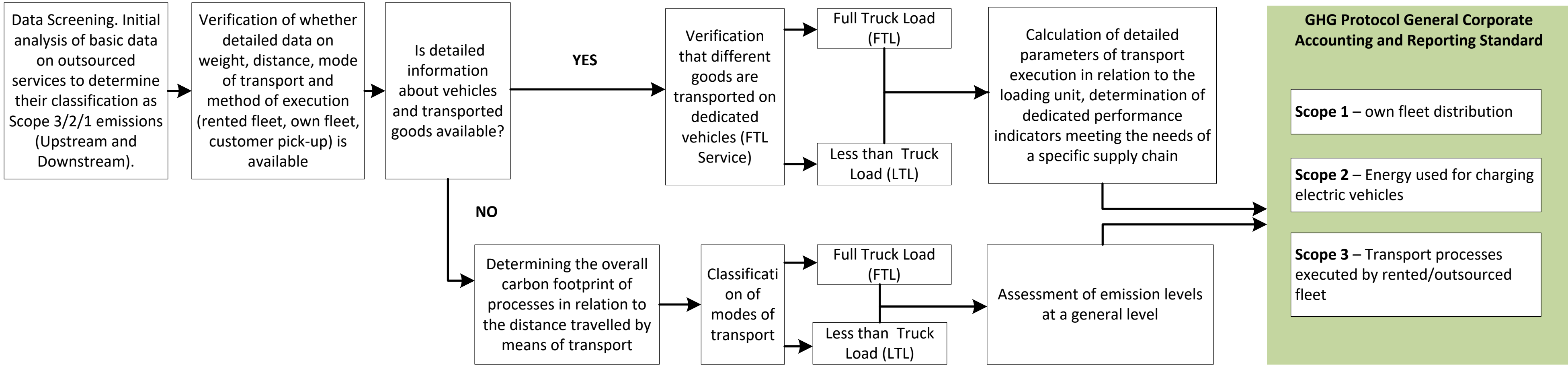

Fig. 4.4 Interpretation of the data collected in Stages I and II

Source: own elaboration.

Regardless of the quality of data and the amount of detailed information about vehicles and transported goods, it is necessary to verify the mode of transport. In each case, a distinction must be made between full truckload (FTL) and less than truckload (LTL) transport. The assessment of the carbon footprint level must refer to the selected mode of transport. Regardless of the chosen assessment path, emissions must be classified according to the adopted GHG Protocol Scopes classification.

As a result of conducted literature research, analysis of available management methods and verification of existing methods for measuring the carbon footprint of logistics processes, as well as through the identification of the significance of individual parameters affecting the level of emissions from transport processes and the results of expert research, it was concluded that the level of detail of the available basic process data requires the implementation of an appropriate assessment approach. Based on the analyses conducted of the GHG Protocol, ISO 14 064 and the UK DEFRA emission factors, it was identified that the foundation of a reliable assessment of transport processes emissions is taking into account the fuel-based and distance-based approaches. Due to the significance of both approaches, it was decided to include them in both calculation models supporting the assessment of transport process emissions and to incorporate the evaluation results into the further decision-making process of a new model for managing transport process emissions within sustainable supply chains. The logic for selecting the appropriate calculation approach and tool is shown in the **Fig. 4.5** below.

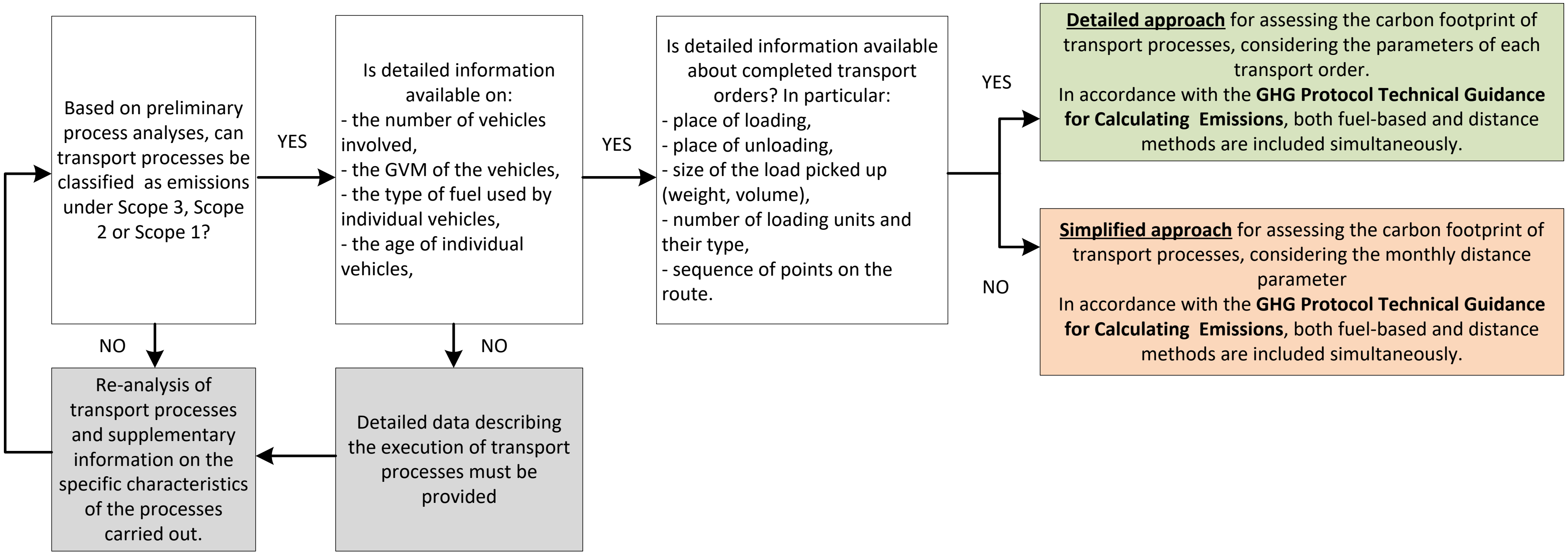

Fig. 4.5 Selection of a calculation approach depending on the quality of transport processes data - Data quality assessment

Source: own elaboration.

The first step involves a preliminary analysis of transport processes in order to assign the corresponding emissions to individual scopes defined in **chapter 2.2,** based on the recommendations and principles outlined in ISO 14064 and the GHG Protocol. However, if it is not possible to determine the assignment of specific processes, a re-analysis of the processes must be carried out (Stage II) and the basic information defining the characteristics of the processes and their assignment must be supplemented (Stage I). Furthermore, the basic parameters must be determined, such as the number of vehicles involved in transport operations, the gross weight of individual vehicle and the type of fuel used by each. Another important factor is the age of each vehicle involved in transport operations. However, if detailed data are not available, it is necessary to make another attempt to obtain general transport process data determining the conditions of transport execution. Once additional data are received, it is necessary to re-verify the process and reassign the identified transport processes to individual scopes 1, scopes 2 and scopes 3 according to GHG protocol and ISO 14064 classification. The next phase of selecting an approach method for assessing the level of emissions from transport processes within sustainable supply chains is verification of a data quality level. If accurate information about individual transport orders can be identified, such as the place of loading, place of unloading, weight and volume of the transported cargo, number of loading units (big boxes, euro pallets, industrial pallets etc.) as well as the sequence of deliveries on each transport route, it is possible to apply the detailed approach (High Data Quality). However, in the case of limited data on transport processes, such as the number of vehicles, vehicle types, vehicle age and total mileage, it is possible to use a simplified approach (Low Data Quality). Simplified solution also allows to determine additionally the unit cost per kilometre travelled. Therefore, the use of a simplified model allows for additional cost verification of detailed analyses conducted in the High Data Quality model. Therefore, it can be assumed that the Simplified Approach may supplement the cost parameters for calculations performed in the Detailed Approach. The procedure for assessing emission levels in each variant is presented in **Fig. 4.6** and **Fig. 4.7** below. Each of the emission assessment variants is possible to perform using dedicated calculation models. For low data quality, it is recommended to use the calculation model provided in **Appendix 8 - Low data quality CF assessment.xlsx**. For High Data Quality, it is recommended to use the calculation model provided in **Appendix *7* - High data quality CF assessment.xlsx**. **Fig. 4.6** below presents the elements of detailed approach for High Data Quality CF assessment.

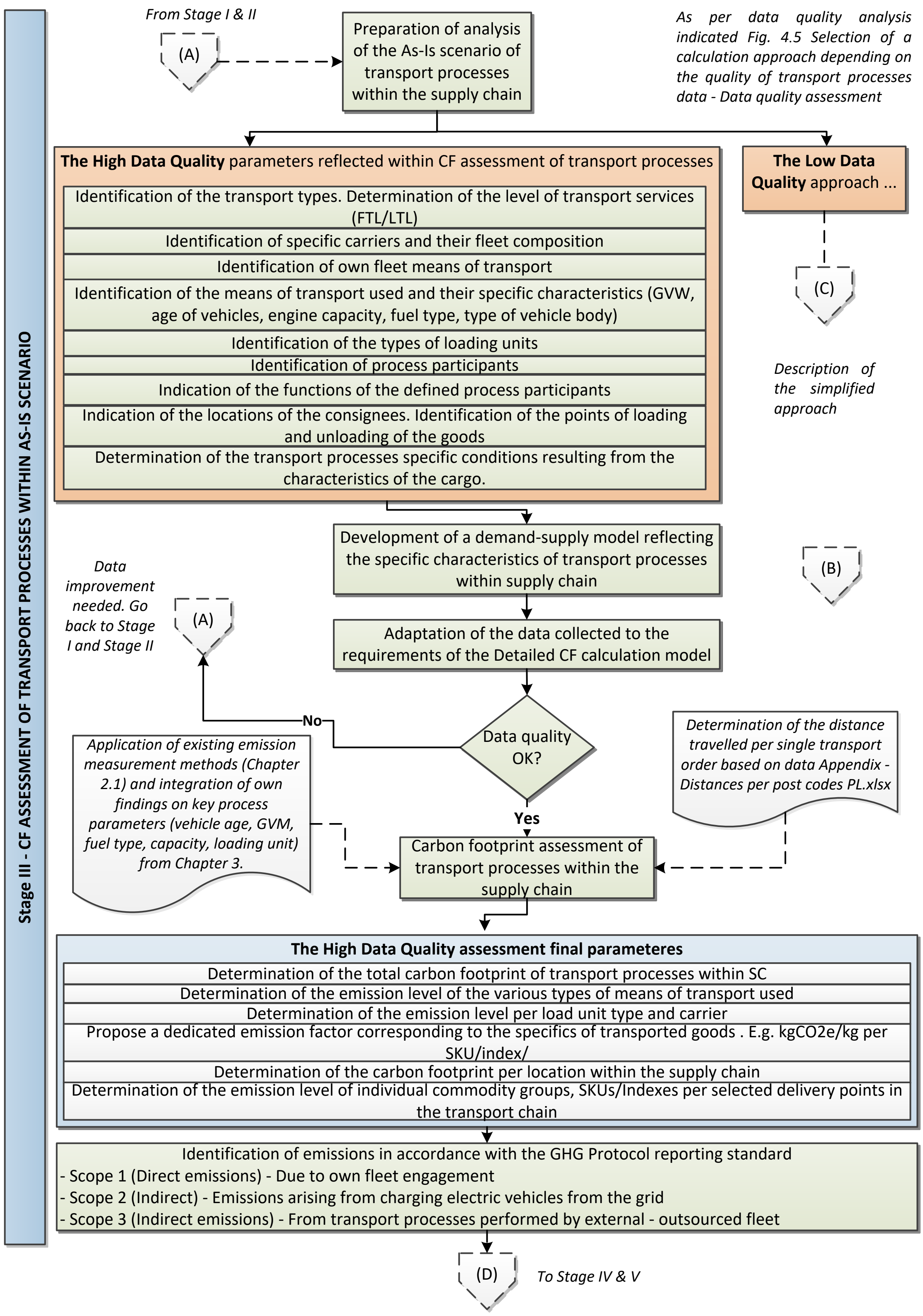

Fig. 4.6 Part B. Stage III – High Data Quality Assessment within a new model for measuring and managing transport emissions

Source: own elaboration.

The following **Fig. 4.7** presents the elements of simplified approach for the Low Data Quality CF assessment.

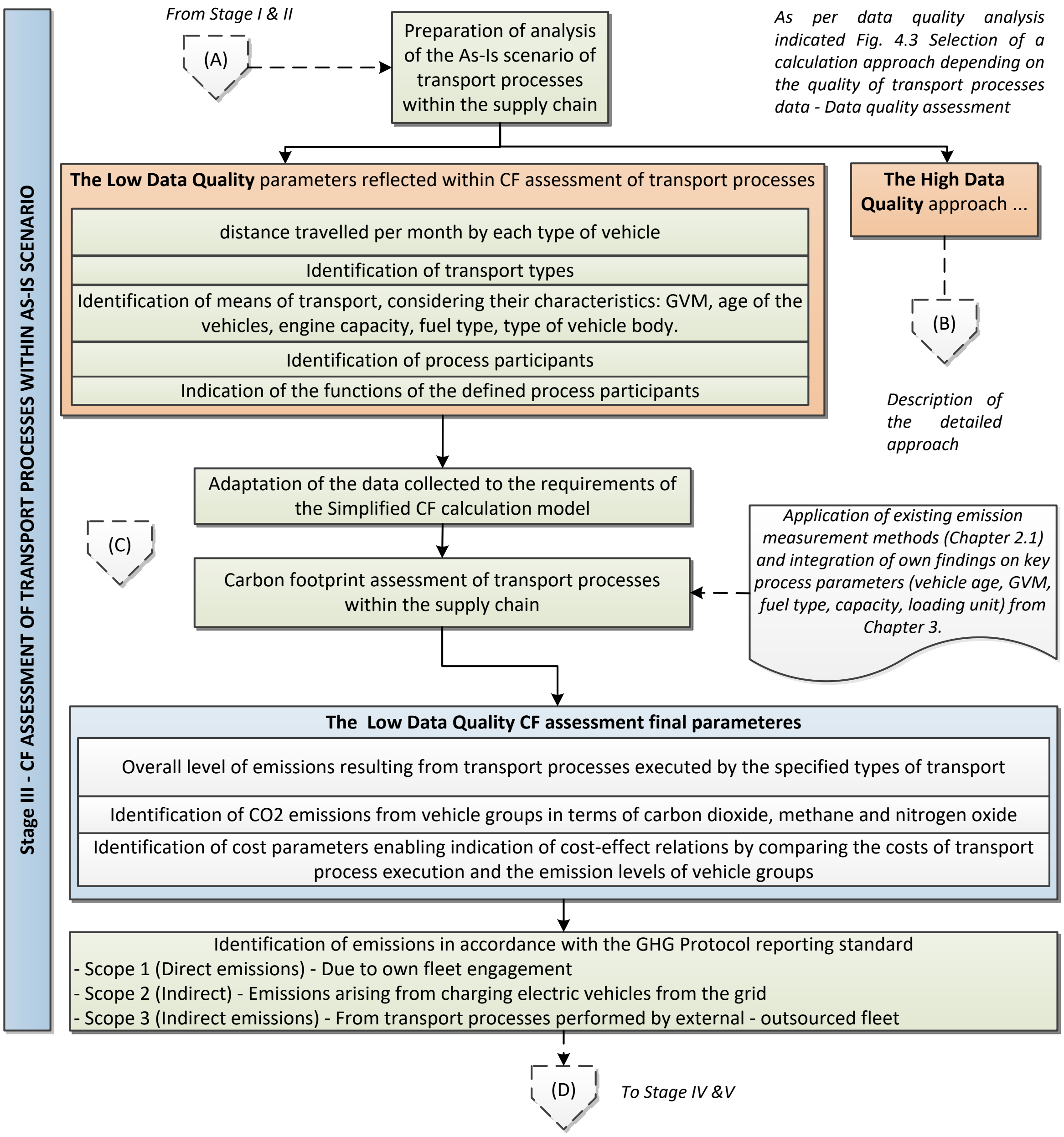

Fig. 4.7 Part C. Stage III – Low Data Quality Assessment within a new model for measuring and managing transport emissions
Source: own elaboration.

In the third step of the assessment of transport processes emissions using the proposed calculation models, the As-Is scenario is analysed. In the next step, once changes have been made to the transport process execution scenarios, it will be possible to conduct a simulation in the To-Be scenarios using the same calculation models, depending on the quality of the available data. As indicated in **Fig. 4.8**, the proposed method involves changes to parameters in alternative scenarios of transport process execution. Following the introduction of changes, it is necessary to re-evaluate emission levels using both calculation models. Consequently, it is possible to carry out several iterations presented in sperate scenarios. The collected information should be compared with the results of the 'As-Is' scenario to demonstrate the trend of changes and the impact of changed parameters on the values of specific emission indicators.

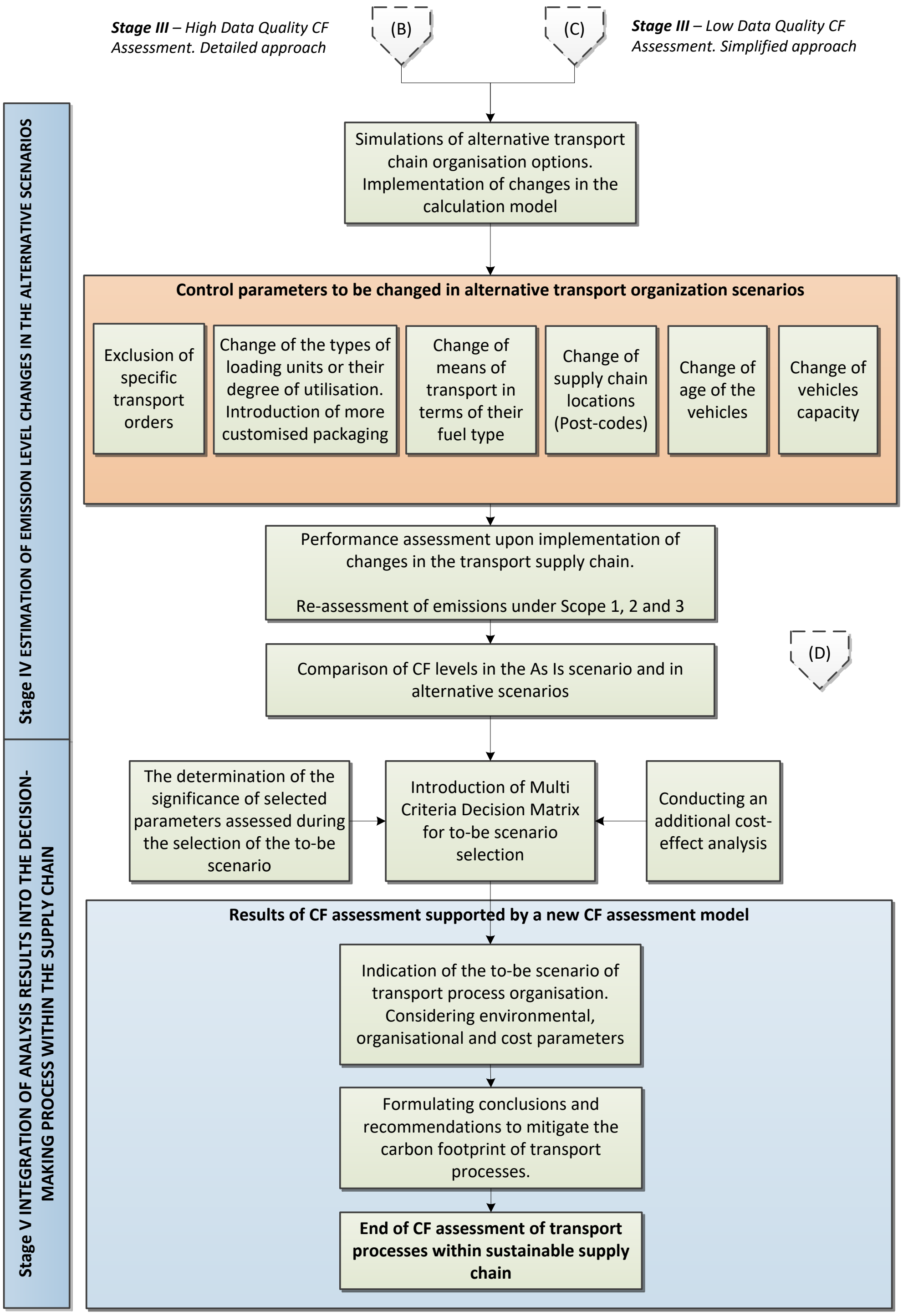

Fig. 4.8 Part D. Stage IV and Stage V for emission changes in To Be scenario. Integration of CF assessment results into SC management process

Source: own elaboration.

Regardless of the calculation approach chosen, the five main stages of the new transport process management method include: Data Collection, Process Analysis, Assessment of Emission Levels in the As-Is scenario, Assessment of Emission Levels in the To-Be scenario (**Fig. 4.1**). Nevertheless, the final stage of the new model of managing transport processes from the perspective of their emission levels involves the inclusion of the results obtained in the decision-making process aimed at minimising the emission levels of transport processes. It can consider simultaneously the cost parameters of transport process execution thanks to the result parameters calculated within simplified assessment approach. The logic of both assessment approaches is presented in the following chapters.

4.1. Detailed approach supported by High Data Quality calculation model

The functioning of the detailed calculation model depends on the input of detailed basic data. The tabs that need to be completed are marked in green in **Tab. 4.2** described as ‘reserved for entering basic data’. The structure of the data necessary to feed the calculation model and perform a detailed assessment of the emission level is defined below. s identified in the adopted methodology for estimating the carbon footprint of transport processes in supply chains dedicated to the transport of batteries for electric vehicles, it is necessary to determine the appropriate structure of the input data. Presented below data structure refers to calculation model provided in **Appendix *7* - High data quality CF assessment.xlsx.** The main tabs in the Detailed model are shown in **Fig. 4.9** below.

SKUs	Transport orders As Is	Vehicles As Is	Goods Flow As Is	Customers	UK Defra EF

Fig. 4.9 Tabs within the spreadsheet relating to the proposed basic data structure used for the emissivity evaluation
Source: own elaboration.

“SKUs” tab

In the following section, the structure of the file describes the details of the data contained within the following columns of the sheet. The separate tab helps to organise detailed information on the products in the supply chain. The key information is the index number referring to the specific type of product. The following columns contain information that indicates the full name assigned to the index. The next column contains a description, which is optional information. Important information could be the assignment of an index to a relevant assortment group, which enables the identification of the emission level of individual commodity groups in further evaluation steps.
The following columns contain key information relating to the specific characteristics of the index, including its physical form, which is essential for determining the emissivity of individual commodities. it is important to specify the units.

	A	B	C	D	E	F	G	H	I	J
1	Index code	Name of the index	Description	Group	Unit of Measurement [UM]	Amount [UM]	Amount of UM per pallet	Weight per single UM [kgs]	Volume per single UM [m3]	Volume per single UM [litres]
2										
3										
4										
5										
6										

Fig. 4.10 Layout of the tab “SKUs” in the spreadsheet
Source: own elaboration.

Tab “Transport orders As Is”

The next tab contains detailed information describing the identified transports for which the emissivity has to be determined. The important information in the first column is the unique number of the transport order. Among the most important information to be defined in this tab is the precise specification of the place of loading and unloading. This information is crucial for indicating the overall emissivity of transport processes. The code for the place of loading and unloading should be consistent with the "Customer/Location ID" given on the "Customers" tab. If specific vehicles are being assessed for emissivity, their identification numbers (Registration plates, internal identification code etc.) should also be available. If such information is not available, information describing the type of transport is necessary.

	A	B	C	D	E	F	G	H	I
1	Transport ID	Date of transport odrder	Loading place (code)	Delivery place (code)	Type of carrier (own fleet, external logistics operator etc.)	Carrier code	Vehicle ID	Amount [plts]	Amount [kgs]
2									
3									
4									
5									

Fig. 4.11 Layout of the tab "Transport orders As Is" in the spreadsheet
Source: own elaboration.

Tab "Vehicles"

The tab "Vehicles" contains information describing the means of transport used to carry the batteries of electric vehicles. If it becomes essential to determine the emissivity of specific means of transport dedicated to the transportation of batteries, it will be necessary to supplement the columns containing specific vehicle identification numbers. It is important that the "Vehicle ID" number matches the numbers entered in the same column in the "Transport orders" tab.

	A	B	C	D	E	F	G	H	I	J	K
1	Vehicle ID	Vehicle reg. plate	Vehicle type code	Vehicle type	Capacity [plts]	Capacity [kgs]	Capacity [m3]	Capacity [litres]	GVM (Gross Vehicle Mass) [t]	Fuel type	Age of the vehicle [years]
2											
3											
4											
5											

Fig. 4.12 Layout of the tab "Vehicles" in the spreadsheet of the tab "Transport orders" in the spreadsheet
Source: own elaboration.

Tab "Goods flow"

The "Goods flow" tab provides information about the flow directions of goods within the entire supply chain. To enable the determination of the emissivity of individual indexes, groups of indexes, as well as to indicate the emissivity of individual participants in the supply chain, the completion of this table may be essential. The information provided, which defines the batch sizes being transported within the supply chain, will allow the calculation of specific emission factors, such as $kgCO_2e/kg_{(SKU)}$, $kgCO_2e/m^3_{(SKU)}$ etc.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	Index code	Goods description	Type of flow	Collection code - Customer/ Location ID	Collection Post Code	Delivery code - Customer/ Location ID	Delivery Post Code	Date (DD-MM-YYYY)	Amount [pcs]	Amount [plts]	Amount [kgs]	Amount [m3]	Amount [litres]	Value [currency]	Transport ID	Vehicle reg plate
2																
3																
4																
5																
6																

Fig. 4.13 Layout of the tab "Goods flow" in the spreadsheet
Source: own elaboration.

Tab "Customers"

The last tab "Customers" contains information about the participants of the supply chain. Each of the customers, suppliers and own locations should be identified and properly characterized in the table. In addition to address data, it is necessary to indicate a unique identification number (Customer/Location ID) in order to enable the linking of information from the "Goods flows" and "Transport orders" tabs. Providing correct information about the location of supply chain participants directly affects the quality of the CF assessment. On this basis, the distance between each participant of the supply chain will be determined using the distance matrix presented on **Fig. 4.16**.

	A	B	C	D	E	F	G	H
1	Customer/ Location ID	Type of localisation	Name	Post code	City	Street	Latitude	Longitude
2								
3								
4								
5								

Fig. 4.14 Layout of the tab "Customers" in the spreadsheet of the tab "Goods flow" in the spreadsheet
Source: own elaboration.

Structuring data in a specific format guarantees that a carbon footprint assessment can be carried out in a detailed model. The method of using primary company data in carbon footprint assessment is described in detail in the **chapter 5** dedicated to model validation. The complete scope of the input data can be found in the dedicated template available in **Appendix 5 - Input data form.xlsx**

General logic of the detailed CF assessment approach

The High Data Quality Model enables users to begin analysis by entering essential data related to transported products (SKUs), transport orders, loading units, and the locations of both recipients and key supply chain's locations. All relevant process data should be completed within the defined input tabs. Subsequently, by defining the weight and volume characteristics of packaging in the "Scenarios" and "SKUs" tabs, users can simulate outcomes under a To-Be scenario. The As-Is baseline scenario is documented in a separate tab, "KPI As-Is", which provides a detailed assessment of the transport process's carbon footprint. The To-Be scenario, reflecting proposed changes, is detailed in the "KPI To-Be" tab and includes key process parameters. A comparative analysis of the As-Is and To-Be scenarios is presented in the "As-Is & To-Be Comparison" tab.

The assessment of the level of changes in the carbon footprint should be carried out using a scenario approach. The results obtained in each scenario should be compared with the parameters in the As-Is scenario in order to point out the change trends. Each scenario should be assessed in a separate file. The results should be stored for further detailed analysis if necessary.

The logic of the Detailed Model for Assessing Transport Process Emissions has been defined in the following **Fig. 4.15**.

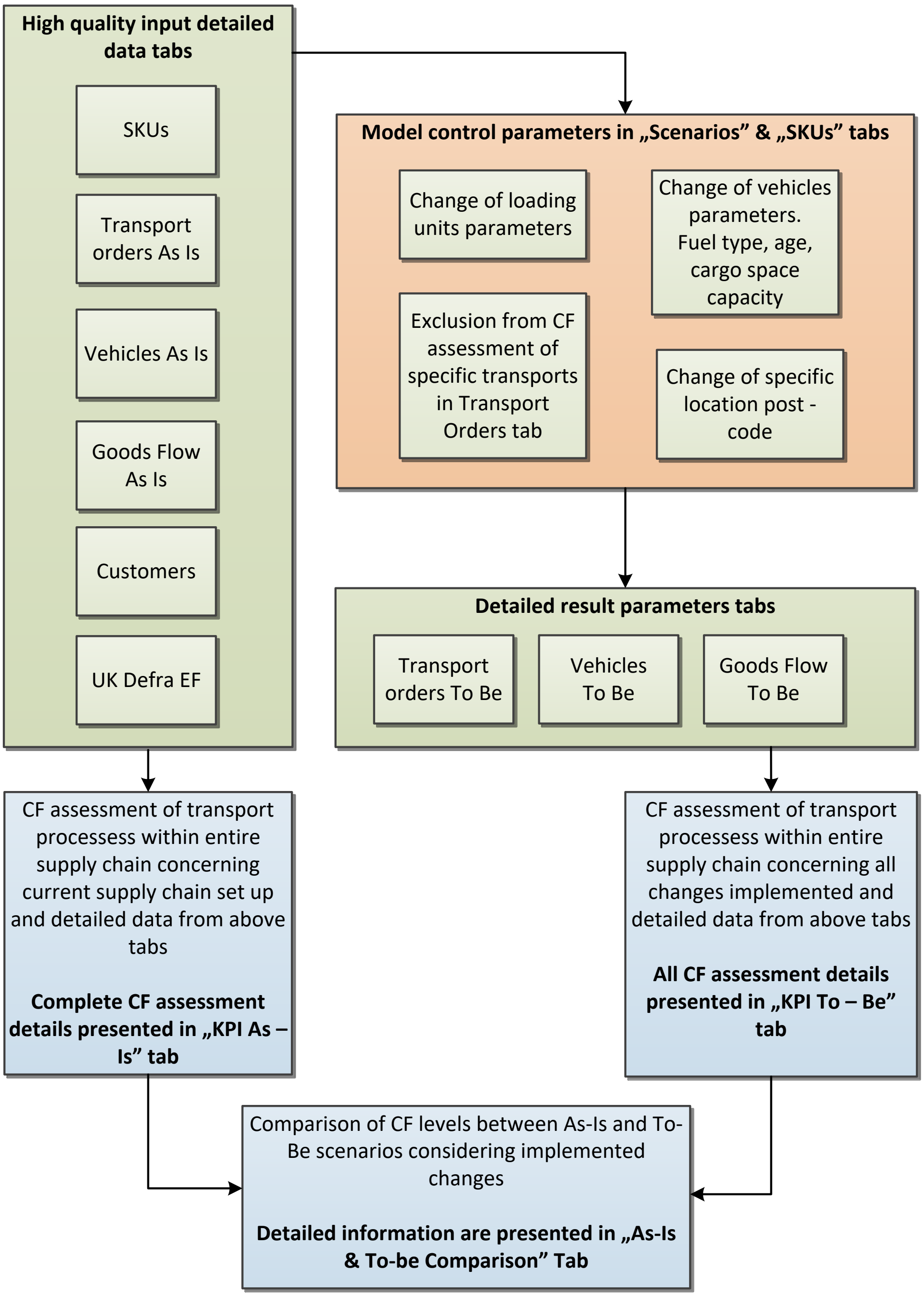

Fig. 4.15 Simplified logic of CF assessment applied in High Data Quality Model
Source: own elaboration.

Estimating distances between loading and unloading points within the supply chain using HDQ calculation model

The assessment of the carbon footprint of transport processes, carried out in a detailed approach, refers to the specific parameters of the transported goods and the transport routes. With regard to the defined location dictionaries of collection and delivery points, it is possible to dynamically determine the distance at the level of each transport route.

Distance estimation in the High Data Quality Model is based on a distance matrix. In the current detailed calculation approach, it is possible to measure the distance between any postcodes in Poland for individual transport orders. Based on official data from Poczta Polska, all postcodes existing in

Poland were identified (Poczta-Polska, 2025). It was found that there are 20 466 codes. It was found that the total number of combinations when indicating distances would be 418 857 156 (20 466 * 20 466). Such an amount of data in the distance matrix would result in a decrease in its usability. Therefore, for cities with more than 200 000 inhabitants, it was decided to limit the combination of postcodes to 4 digits (instead of 5 digits in the full postcode). The high density of postcodes in the centres of larger cities does not translate into an increase in distance. This resulted in a significant reduction in the number of combinations, which fell to 97 634 161 (9 881*9 881). The matrix was developed using ArcGIS Pro with the Network Analyst add-on version 3.4.3. **Appendix 6 - Distance matrix PL.xlsx** presents the assignment of individual postcodes to the code in the distance matrix. The full distance matrix between the selected codes is presented in a detailed calculation tool, in the file **Appendix 7 - High data quality CF assessment.xlsx** in the 'Distances' tab. The analysis of the matrix quality conducted during the dynamic determination of distances between the addresses of goods collection and delivery identified an error margin of up to 5 km. This deviation is within the accepted tolerance limit and allows for quick and dynamic verification of distances at the level of individual transport orders, based on defined dictionaries of locations of collection points, warehouses, cross-docks and recipients. **Fig. 4**.16 below shows a general overview of the distance matrix used for dynamic distance estimation in the Detailed Approach to Carbon Footprint Assessment using High Data Quality.

Post code - 5 digits	Post code - 4 digits	Post code - 3 digits	Code in distance matrix
55-081	55-08	55-0	3253
55-300	55-30	55-3	3475
55-311	55-31	55-3	3364
55-320	55-32	55-3	3585
55-340	55-34	55-3	3363
56-100	56-10	56-1	3808
56-160	56-16	56-1	3919
56-200	56-20	56-2	4251
56-209	56-20	56-2	4140
56-215	56-21	56-2	4250
57-215	57-21	57-2	2587
57-300	57-30	57-3	2476
57-313	57-31	57-3	2365
57-314	57-31	57-3	2364
57-315	57-31	57-3	2476
57-320	57-32	57-3	2364
57-322	57-32	57-3	2475
57-330	57-33	57-3	2364
57-340	57-34	57-3	2363
57-343	57-34	57-3	2362

Code From/To	1054	1055	1059	1060	1061	1062	1063	1064
1054	0	11	64	71	91	103	112	12
1055	12	0	60	67	87	99	108	12
1059	65	60	0	14	22	35	46	5
1060	71	67	14	0	10	23	35	4
1061	91	87	22	10	0	12	24	3
1062	103	99	35	23	12	0	14	2
1063	113	108	46	35	24	14	0	1
1064	126	122	57	46	35	25	19	0
1065	137	133	68	57	46	36	29	1
1066	175	171	97	87	76	65	59	3
1067	180	176	102	92	81	71	64	4
1068	194	189	116	106	99	88	77	5
1069	200	196	127	112	106	95	89	6
1070	209	205	135	121	114	104	97	7
1071	215	211	146	127	127	116	110	8
1072	225	221	156	137	137	126	119	9
1073	235	231	166	147	147	136	130	10
1074	253	248	183	164	165	157	147	12
1075	295	290	194	175	176	167	153	13
1076	307	309	197	178	179	171	161	13

Fig. 4.16 Distance matrix for dynamic estimation of distances between points specified in transport orders

Source: own elaboration.

Detailed assessment approach. High Quality Data calculation model structure

The main element of the detailed approach is the first tab, 'Instruction'. The user can relatively easily go through the entire process of feeding data into the calculation model, generating results in the As-Is model, introducing changes to scenarios and verifying the trend of changes based on the evaluation of results in the To-Be model. To do this, it is necessary to go through the 10 steps described in the 'Instruction' tab and presented on **Fig. 4.17** below.

Navigation in the High Data Quality CF assessment model and the suggested order of using the sheets embedded			
Evaluation model input data	Go to	Step 1	Specify vehicle types and define their parameters
	Go to	Step 2	Specify index types
	Go to	Step 3	Enter information about completed transport orders
	Go to	Step 4	Enter information about the flow of goods within the supply chain
	Go to	Step 5	Enter recipient information
Result parameters As-Is Scenario	Go to	Step 6	Check the emission level in the current transport model (as-is)
Model controll parameters	Go to	Step 7	Set scenarios controll parameters for alternative arrangement of transport flows in the (to-be) model
		Step 8	Evaluate the emission level of the to-be model. Consider changes selected in the scenarios
Result parameters To-Be Scenario	Go to	Step 9	Check the emission level in the transport model after changing the parameters specified in the (to-be) scenarios
	Go to	Step 10	Check the optimization potential of transport flows as a result of changes introduced in the scenarios (Comparison of results of as-is and to-be models)

Fig. 4.17 View of the main user panel of HDQ CF assessment model
Source: own elaboration.

The detailed scope of data necessary to complete the calculation model is presented subsequent tabs presented in **Fig. 4.9**. Below is a description of the steps necessary to carry out a detailed assessment of transport process emissions using the High data Quality Model.

Step 1 – Determination of vehicle parameters. The identification of relevant vehicle parameters such as GVM, fuel type, capacity expressed in load units and age is an essential element developed during the literature review and expert research conducted. Therefore, the precise identification of parameters describing the specific characteristics of vehicles is an essential element of a detailed assessment of the level of emissions from transport processes.
Step 2 - Determination of the specific characteristics of the transported products in terms of weight, volume and assignment to specific product groups. Such detailed information allows to conduct the assessment of emission levels for each product group separately and enable the creation of dedicated emission indicators.
Step 3 - Specification of detailed information regarding transport orders. Indication of the place of collection of goods, and indication of the sequence of delivery points on the route. Assignment of the size of the transported load to the order and definition of the quantity of products delivered to each delivery point. Assignment of a specific vehicle to a specific transport order.
Step 4 - Information about the flow of goods from the loading point to the unloading point. Detailed information about the structure of individual customer orders allows for the re-planning of transport orders in alternative to-be scenarios.
Step 5 - Defining the recipient dictionary. Specifying the point code, location, country, city and postcode. Assigning functions to individual participants in the supply chain.
Step 6 - Analysis of emissions levels in the current as-is model. The information presented in this tab is calculated on the basis of the input data. The emissions indicator values presented in this tab serve as a reference point for subsequent to-be scenarios, taking into account the changes introduced in the scenarios in step 7.
Step 7 - Implementing changes to the location (postcodes) of individual loading and unloading points defined in Step 5. Implementing changes to the age of individual vehicles and excluding selected transports from the assessment of transport process emissions. Changes to the parameters of logistics units must be entered manually in the 'SKUs' tab.

Step 8 - Command to execute a macro that calculates the carbon footprint in the to-be scenario, taking into account the changes made to the control parameters. The calculation process is performed automatically, and after its completion, a message confirming the correct recalculation of the model is displayed.
Step 9 - Navigation to the tab presenting detailed parameters in the calculated to-be scenario. Possibility to analyse individual parameters of the transport process, taking into account the emission level of a specific point, vehicle, product group and carrier.
Step 10 - Navigation to the tab presenting a comparison of the as-is scenario and the calculated to-be scenario. Identification of trends in relation to the baseline scenario. Possibility to assess the impact of changes introduced in the scenario on the achieved emission level.

The High Quality Data Model consists of a series of sheets. For ease of use, each group has been marked with a different colour to facilitate navigation between sheets. The **Tab. 4.2** below specifies the general functionality of each tab.

Tab. 4.2 Definition of the functionality of individual tabs in the Detailed Approach calculation model for assessing the carbon footprint of transport processes
Source: own elaboration.

Tab	General function
Instruction	presents navigation in the calculation model and the suggested order for completing and using the sheets embedded in the model
SKUs, Transport orders As Is, Vehicles As Is, Goods Flow As Is, Customers, UK Defra EF, Emission EF	Reserved for entering basic data
KPI As - Is, KPI To-Be, As-Is & To-be Comparison	Designed for displaying calculated emission level data
Transport Orders To Be, Vehicles To-Be, Goods Flow To Be, Distances	Contains data calculated by the model, taking into account the changes indicated in the 'Scenarios' tab. From the user's point of view, these are supplementary tabs from which no data is read.
Scenario	A tab where it is possible to implement changes determining the manner of transport process execution

A more detailed description of each tab is provided below:

- The sheet SKUs contains information about the codes of materials in circulation. In addition to the code information, the tab also includes a field specifying its precise name, product group, unit of measure and parameters enabling the determination of its physical form.
- The sheet Transport orders As Is contains information on the correct transport order number, the type of carrier (external/internal) and its name-symbol, which is used in the analytical part of the sheet to assign the emissions level and calculate the environmental performance of the transports carried out.

- The sheet Vehicles As Is contains detailed information on the means of transport used to carry out transport within the supply chain. An important piece of information is the vehicle registration number, which allows the emissions of the orders executed to be assigned.
- The sheet Goods Flow As Is contains information about deliveries made from individual locations. In addition to information about the size of deliveries, each index is assigned the appropriate record document, which allows information about the size of the outgoing volume to be linked to transport orders.
- The sheet Customers contains a set of the most important information about the recipients defined in the logistics model.
- The sheet UK Defra EF contains Emission Factors structured as published by UK DEFRA, while sheet Emission EF contains Emission Factors transformed for the purposes of the transport emissions assessment tool.
- The sheet KPI As - Is presents graphical data related to the current environmental performance of the supply chain.
- The sheet KPI To-Be presents graphical data related to the environmental performance of the supply chain that should be achieved.
- The sheet As-Is & To-be Comparison contains a comparison of AS-IS KPIs with TO-BE KPIs, showing the trend of changes in the target model.
- The sheet Scenario contains modules that allow you to change the control parameters in transport supply chains, the results of which are presented in the tab KPI To-Be.
- The sheet Transport Orders To Be presents transport orders optimised by the developed calculation model.
- The sheet Vehicles To-Be presents the emissions of transport processes simulated by the calculation model.
- The sheet Goods Flow To Be presents flows together with the results of the calculation model.
- The sheet Distances contains a matrix showing the distances between individual collection points and delivery points.

The method of presenting the results of the carbon footprint assessment of transport processes within distribution supply chains is shown in **Fig. 4.18** below. The presentation of the results allows for a comparison of the CF assessment results between the As-Is and To-Be scenarios. Thereby, after making changes to the scenario, it is possible to verify the trend of changes and indicate the detailed value of the decrease or increase in emissions. Precise KPI, emission values by vehicle, location and product group are available in the tabs 'KPI As - Is' and 'KPI To – Be' tabs. The detailed HDQ model can be found in **Appendix 7 - High data quality CF assessment.xlsx.**

AS IS	
TOTAL ROAD TRANSPORT EMISSIONS	339 738 kgCO2e
AVERAGE ROAD TRANSPORT EMISSION PER ROUTE	371 kgCO2e
AVERAGE EMISSIONS PER MEAN OF TRANSPORT	16 987 kgCO2e
TOTAL WEIGHT OF TRANSPOTED GOODS	43 929 060 kg
TOTAL DISTANCE	364 274 km

TO - BE	
TOTAL ROAD TRANSPORT EMISSIONS	324 324 kgCO2e
AVERAGE ROAD TRANSPORT EMISSION PER ROUTE	354 kgCO2e
AVERAGE EMISSIONS PER MEAN OF TRANSPORT	16 216 kgCO2e
TOTAL WEIGHT OF TRANSPOTED GOODS	43 929 060 kg
TOTAL DISTANCE	364 274 km

Trend of changes in the To-Be Scenario		
TOTAL ROAD TRANSPORT EMISSIONS	Trend	Increase / Decrease
-15 414 kgCO2e	decrease of emissions	-4.54%
AVERAGE ROAD TRANSPORT EMISSIONS	Trend	Increase / Decrease
-16.88 kgCO2e	decrease of emissions	-4.55%
AVERAGE EMMISIONS PER MEAN OF TRANSPORT	Trend	Increase / Decrease
-771 kgCO2e	decrease of emissions	-4.54%
TOTAL WEIGHT OF TRANSPOTED GOODS	Trend	Increase / Decrease
0.00 kg	no change	0.0%
TOTAL DISTANCE	Trend	Increase / Decrease
0.00 km	no change	0.00%

AS IS	
AVERAGE EMISSIONS INDICATOR FOR ALL PRODUCT GROUPS kgCO2e/m3	AVERAGE EMISSIONS INDICATOR FOR ALL PRODUCT GROUPS kgCO2e/kg
5.68 kgCO2e	0.00773 kgCO2e

TO - BE	
AVERAGE EMISSIONS INDICATOR FOR ALL PRODUCT GROUPS kgCO2e/m3	AVERAGE EMISSIONS INDICATOR FOR ALL PRODUCT GROUPS kgCO2e/kg
5.68 kgCO2e	0.00773 kgCO2e

Trend of changes in the To-Be Scenario	
AVERAGE EMISSIONS INDICATOR FOR ALL PRODUCT GROUPS kgCO2e/m3	AVERAGE EMISSIONS INDICATOR FOR ALL PRODUCT GROUPS kgCO2e/kg
0 kgCO2e	0 kgCO2e
Reduction / Increase [%]	Reduction / Increase [%]

Fig. 4.18 View of the panel with a general comparison of results between the As-Is and To-Be scenarios in 'As-Is & To-be Comparison' tab

Source: own elaboration.

4.2. Simplified assessment approach - Low Quality Data calculation model

The logic defined in **chapter 4** of the new model for managing transport process emissions requires compliance with the measurement guidelines identified during the literature review and standards analysis. The indication of specific scopes and types of emissions, as specified in **chapter 2.2** points to the need to use a dedicated tool to assess emission levels under conditions of limited data. For simplified CF assessment, it is possible to use the Low Quality Data calculation tool that supports the assessment of emission levels without taking into account the specific characteristics of products, product groups, and individual transport orders.

Conducting an assessment of emission levels in accordance with the defined scopes 1, 2 and 3 under the GHG Protocol guidelines requires consideration of a number of vehicle parameters and conditions of transport process execution. In the event that low-quality data, it is possible to conduct an assessment of transport process emission levels using a simplified approach. The simplified approach refers mainly to the parameters of distance, vehicle type, GVM and fuel.

In addition to transport process emission parameters, the LDQ model allows the determination of cost parameters. Therefore, the use of a simplified model can complement the assessment of emission levels conducted in HDQ model with cost parameters. The presentation of cost parameters may be essential for decision-making using a multi-criteria matrix. The Low Data Quality CF assessment model can be seen in the **Appendix 8 - Low data quality CF assessment.xlsx.** Below **Fig. 4.19** shows a general overview of the LDQ model.

Simplified Approach - Low Data Quality - Estimating the level of emissions from a heterogeneous fleet		Units		Group of own vehicles 1
Vehicle type	*Vehicle*	*[pcs.]*	*Select*	DMC 3,5 t. Vehicle 1
	DMC	*[kg]*		3500
	Engine capacity	*[cm3]*		2287cm3
	Type of fuel	*[type]*		Diesel
	Vehicle age [years]	*[years].*	*Select*	1
	Combustion standard	*[type]*		Euro 6
	Lift	*[type]*	*Select*	No
	Truck body type	*[type]*	*Select*	Isothermal without cooling unit
	Cooling unit type	*[type]*	*Select*	
	Load-Lok thermal divider	*[type]*	*Select*	
	Fan with thermostat	*[type]*	*Select*	No
Input data	km travelled per vehicle	*[km/month].*	*Type in*	8000
	Daily number of operating hours of the cooling unit	*[hours].*	*Select*	
	Month	*[name of the month].*	*Select*	March
	Method of financing	*[type]*	*Select*	leasing
	Expected depreciation period **or** estimated usage period when	*[months].*	*Select*	60
Leasing	Initial payment [%]	*[%]*	*Select*	30
	Final redemption [%]	*[%]*	*Select*	16
	Annual interest rate [%]	*[%]*	*Type in*	11%
	Monthly interest rate [%]	*[%]*		0.92%
	Debt – after deduction of payment	[illegible]		186 967.90 zł

Fig. 4.19 Design of the main panel and part of input parameters within Low Data Quality CF assessment model

Source: own elaboration.

The columns on the left, marked with blue line, define individual parameters entered by users or calculated by the model. Each row contains additional information about the type of parameter and how it is defined. Columns with the heading 'Group of own vehicles' are used to enter information for different groups of vehicles, which allows for the heterogeneous type of the vehicle fleet for which CF has to be assessed. Cells coloured with yellow points values that has to be typed in by user or selected from the drop down list. The following section presents the types of parameters and their range more detailed.

Simplified approach – Input data structure, CF and costs assessment logic

Precise definition of the logic applied within the calculation model requires specification of individual parameters, their significance and impact on the assessed emission level. The developed calculation model is implemented in an Excel spreadsheet and, using appropriate formulas, enables estimation of the emission level of transport processes, considering numerous variable fleet parameters and actual transport conditions.

Table following **Tab. 4.3** provides a detailed description of the "Vehicle type" category parameters included in the LDQ calculation model supporting CF assessment of distribution transport processes.

Tab. 4.3 Description of the "Vehicle type" category parameters included within the LDQ model
Source: own elaboration.

Parameter description	Unit
Vehicle - Once the appropriate vehicle has been selected in the 'Vehicle' row, the relevant market parameters assigned to the specific vehicle model are automatically matched. The information includes the type of fuel (Diesiel, benzin, Electric, LPG/CNG), the purchase price of the vehicle, the cost of conversion if an isothermal body is required, the cost of additional equipment such as a cooling unit, fans, internal thermal dividers. In addition to cost parameters, technical parameters of the vehicle are also obtained when selecting a specific vehicle model, such as engine size, load capacity (expressed in EPAL pallet spaces), average fuel consumption (litres/100 km), as well as information related to the local vehicle tax in the place of registration of the vehicle, in the municipality in Poland. The last parameter is the number of wheels, which is subsequently converted into their purchase and replacement costs. This parameter is used in the following parameter category to determine the maintenance costs of the vehicle.	[pcs]
Gross Vehicle Mass (GVM) - The vehicle weight parameter is automatically displayed after selecting the appropriate vehicle. The weight value affects a number of factors such as vehicle insurance, driver's salary, taxes, environmental parameters and emission levels. GVM is an essential parameter for selecting the relevant emission factor specified in Greenhouse gas reporting: conversion factors, published by the United Kingdom Department for Environment, Food & Rural Affairs (UK DEFRA).	[kg]
Engine capacity - impacts insurance cost only	[cm3]
Fuel type - impacts the selection of further emission factor specified in Greenhouse gas reporting: conversion factors, published by the United Kingdom Department for Environment, Food & Rural Affairs (UK DEFRA). The level of unit emissions and the composition of the carbon footprint may differ depending on the type of fuel indicated.	[type]
Vehicle age - The age parameter is defined to influence the fuel consumption of a vehicle. Based on the analyses conducted and the research results presented in publication *"Measuring CO_2 Emissions in E-Commerce Deliveries: From Empirical Studies to a New Calculation Approach", Damian Dubisz, Paulina Golińska-Dawson, Przemysław Zawodny, Sustainability - 2022, vol. 14, iss. 23, s. 16085-1-16085-20* an dedicated index was determined to verify increase in fuel consumption along with the age of the vehicle. The developed index was incorporated into a calculation model and included in a new model for managing transport processes and their carbon footprint within sustainable supply chains.	[years]

Parameter description	Unit
Lift - The calculation model allows to indicate whether the vehicle is equipped with a rear lift. This parameter affects the total purchase cost of the means of transport.	[type]
Cooling unit type, Load-Lok thermal divider, Fan with thermostat - these parameters affect the total cost of the vehicle. The cooling unit selection affects the additional fuel consumption resulting from the operation of the unit (the model is based on diesel-powered cooling units).	[type]

Among the key parameters that have to be entered into the model in order to assess the level of transport emissions and cost parameters are ‘Input data’. The data entered is classified into operational and financial parameters. The **Tab. 4**.4 below explains the meaning and impact of each parameter.

Tab. 4.4 Description of the “Input data” category parameters included within the LDQ model
Source: own elaboration.

Parameter description	Unit
km travelled per vehicle - By defining this parameter, the total monthly number of kilometres travelled by a single vehicle is entered into the model. The value entered affects the environmental parameters and the total carbon footprint of transport processes calculated in the model, as well as the price parameters. The total costs and the final cost rate in PLN/km are referred to the number of kilometres travelled in the further part of the calculation model.	[km/month]
Daily number of operating hours of the cooling unit - Determining the number of daily working hours of the unit is essential for calculating the carbon footprint arising from fuel combustion, as well as for determining the total fuel purchase costs.	[hours]
Month - Specifying the name of the month is important in terms of the amount of fuel consumption by the cooling unit, in reference to average temperatures in Poland in the years 1998–2018. Depending on the adopted GVM of the vehicle and the month, the fuel consumption factor may increase during the summer months, which has been reflected in the calculation model.	[name of month]
Method of financing - Parameters related to the form of vehicle financing. The model allows for the consideration of the parameters of traditional leasing, down payment, and redemption value. The user should enter the annual interest rate. The values are entered in the subsequent lines of the ‘leasing’ parameters section. If the option to purchase the vehicle for a one-off cash payment is selected, ‘cash’ should be selected. In this case, only the approximate usage period of the vehicle needs to be defined.	[type]

The next set of parameters to be entered is “market data”. Currently, the model is configured to take into account the characteristic of distribution in Poland. However, after feeding LDQ model with a new data, it allows parameters to be calculated for other countries. Market parameters include consideration of fuel costs, driver salaries depending on the voivodeship, as well as parameters related to insurance and local taxes for vehicles with a GVW above 3.5 tonnes. Market data details are presented in the following **Tab. 4.5. The Tab. 4.5** below also includes one parameter from the ‘other costs parameters’ section. This section contains only one parameter that needs to be defined by the user and concerns the number of tyre replacements during the declared service life.

Tab. 4.5 Description of the "Market data" and "other costs parameters" category parameters included within the LDQ model

Source: own elaboration.

Parameter description	Unit
Fuel price / kWh - The price parameter for 1 litre of fuel purchased for a vehicle. Due to the possibility of measuring emissions and costs for electric vehicles, it is possible to define the price of electricity. For this purpose, please enter the purchase price of 1 kWh.	[PLN] *(or other currency if needed)*
Location of the carrier's base (voivodeship) - This parameter influences the model's automatic selection of average earnings in a given voivodeship and the cost of insurance. The LDQ model automatically retrieves pre-entered market data to assess the level of costs.	[select]
Provincial city - The choice between the main provincial city ("provincial city") and other areas of a voivodeship affects drivers' earnings. According to statistics published by the Central Statistical Office in Poland, there is a significant difference in wages between urban agglomerations and peripheral areas. In LDQ, an algorithm modifying the level of drivers' earnings has been included in the model. Following differences between Provincial city and rest of the region has been incorporated into the logic of the LDQ model in terms of driver's salary level calculation. Data has been sourced from Central Statistical Office (GUS) providing detailed statistical data for Poland (GUS, 2022).	[select]

Average monthly salary level	Average monthly salary in 2022		
	Provincial city	Rest of the region	%
woj. mazowieckie	8 058.00 zł	7 423.00 zł	8.55%
woj. pomorskie	7 240.00 zł	6 685.00 zł	8.30%
woj. dolnośląskie	7 137.00 zł	7 019.00 zł	1.68%
woj. opolskie	6 680.00 zł	6 027.00 zł	10.83%
woj. zachodniopomorskie	6 532.00 zł	6 167.00 zł	5.92%
woj. łódzkie	6 458.00 zł	6 250.00 zł	3.33%
woj. lubelskie	5 800.00 zł	5 770.00 zł	0.52%
woj. warmińsko-mazurskie	5 700.00 zł	5 505.00 zł	3.54%
woj. kujawsko-pomorskie	5 850.00 zł	5 726.00 zł	2.17%
woj. lubuskie	5 401.00 zł	5 783.00 zł	-6.61%
woj. świętokrzyskie	5 263.00 zł	5 306.00 zł	-0.81%
woj. podlaskie	5 013.00 zł	5 310.00 zł	-5.59%
woj. wielkopolskie	7 075.00 zł	5 790.00 zł	22.19%
woj. podkarpackie	6 830.00 zł	5 395.00 zł	26.60%
woj. śląskie	9 034.00 zł	7 423.00 zł	21.70%
woj. małopolskie	7 908.00 zł	6 650.00 zł	18.92%

Parameter description	Unit
AdBlue unit price - Parameter specifying the average cost of AdBlue. The user manually enters the cost of 1 litre of AdBlue. Consumption of AdBlue depends on the distance travelled and the GVW of the vehicle.	[type in]
Municipality tax - The user may enable the option of adding additional charges resulting from transport taxes applicable in a given voivodeship.	[select]
Number of tyres set replacements per usage period - Defining the number of tyre replacements for a vehicle during the analysed period. Information about the number of wheels in each vehicle type and the average cost of a single tyre is embedded in	[quantity]

Parameter description	Unit
the model and divided into monthly vehicle maintenance costs. The cost of purchasing tyres is divided according to the declared period of usage or lease. Defining the number of tyre replacements for a vehicle during the analysed period. Information about the number of wheels in each vehicle type and the average cost of a single tyre is embedded in the model and divided into monthly vehicle maintenance costs. The cost of purchasing tyres is divided according to the declared period of usage or lease.	

Once the input data has been entered into the LDQ model, a set of output parameters is calculated. These include detailed information on maintenance, labour and overall costs. It is also possible to aggregate the cost levels and determine a single rate in local currency, e.g. [PLN/km]. Furthermore, the LDQ model allows for the assessment of the emission levels of individual vehicles and vehicle groups. A **Fig. 4.20** below shows the method of presentation of information on the emission level of vehicles within heterogeneous fleet.

Simplified Approach - Low Data Quality - Estimating the level of emissions from a heterogeneous fleet		Units	Group of own vehicles 1	Group of own vehicles 2
Vehicle type	*Vehicle*	*[pcs.]*	DMC 3,5 t. Vehicle 1	DMC 7,2 t. Vehicle 1
	DMC	*[kg]*	3500	7200
	Engine capacity	*[cm3]*	2287cm3	3000cm3
	Type of fuel	*[type]*	Diesel	Diesel
	Vehicle age [years]	*[years].*	1	1
	Combustion standard	*[type]*	Euro 6	Euro 6
	Lift	*[type]*	No	No
	Truck body type	*[type]*	Isothermal without cooling unit	Isothermal without cooling unit
Input data	km travelled per vehicle	*[km/month].*	8000	8000
Market data	Fuel price / kWh	[PLN]	5.92	5.92
	Location of the carrier's base - voivodeship		woj. wielkopolskie	woj. wielkopolskie
	Provincial city		Yes	Yes
	Driver total labor costs	[PLN/month]	10 306.11 zł	12 473.03 zł
	Rate of third party liability, AC, accident and pe	[PLN]	2 688.80 zł	3 230.95 zł
	AdBlue unit price	[PLN/litre]	3.00 zł	3.00 zł
	Municipality tax	[constans]	Max. TAX rate	Max. TAX rate
	Tax on means of transport	[PLN/year]	0.00 zł	880.77 zł
Environmental parameters - One vehicle	**Carbon dioxide**	**[kg CO2/month]**	1914.553152	3796.30368
	Methane	**[kg CH4/month]**	0.08	0.80
	Nitrogen oxide	**[kg N2O/month]**	14.8811904	47.8438272
Retail price parameters	*Total cost of carrier / km*	*[zł/km]*	2.80 zł	3.33 zł
	Margin	*[%]*	20%	20%
	Retail price of the transport service	*[zł/km]*	3.36 zł	4.00 zł
	Revenue	*[zł]*	26 850.60 zł	32 012.13 zł
	Income	*[zł]*	4 475.10 zł	5 335.35 zł
Cost structure	Leasing or monthly financing cost	*[%]*	13%	11%
	Operating costs	*[%]*	1%	1%
	Insurance	*[%]*	1%	1%
	Fuel and AdBlue	*[%]*	30%	31%
	Driver salaries	*[%]*	38%	39%
	Margin	*[%]*	17%	17%

Fig. 4.20 Cost and environmental parameters in the main panel of the Low Data Quality CF assessment model.

Source: own elaboration.

Additionally, in order to enable a quick comparison of the cost level and the specific emission of vehicles, a chart has been included in the final part of the LDQ model. It shows all cost components as well as the emission level. Thus, the rate per kilometre and the estimated emission level can be easily verified. However, it is important to define the estimated monthly distance travelled by the vehicle in the input parameters. Unlike the HDQ model, where the actual distance travelled is calculated, in the LDQ model the calculations are based on the assumption of a monthly distance. The presentation method of the CF assessment and costs results is shown in **Fig. 4.21** below.

Simplified Approach - Low Data Quality - Estimating the level of emissions from a heterogeneous fleet		Units	Group of own vehicles 1	Group of own vehicles 2
Vehicle type	*Vehicle*	*[pcs.]*	DMC 3,5 t. Vehicle 1	DMC 7,2 t. Vehicle 1
	DMC	*[kg]*	3500	7200
	Engine capacity	*[cm3]*	2287cm3	3000cm3
	Type of fuel	*[type]*	Diesel	Diesel
	Vehicle age [years]	*[years].*	1	1
	Combustion standard	*[type]*	Euro 6	Euro 6
Environmental parameters - Heterogenious fleet / month	**Carbon dioxide**	**[kg CO2/month]**	1 914.55	3 796.30
	Methane	**[kg CH4/month]**	0.0800	0.80
	Nitrogen oxide	**[kg N2O/month]**	14.88119	47.84
	CO_2-equivalent	**[kgCO2e/month**	1 929.51	3 844.95

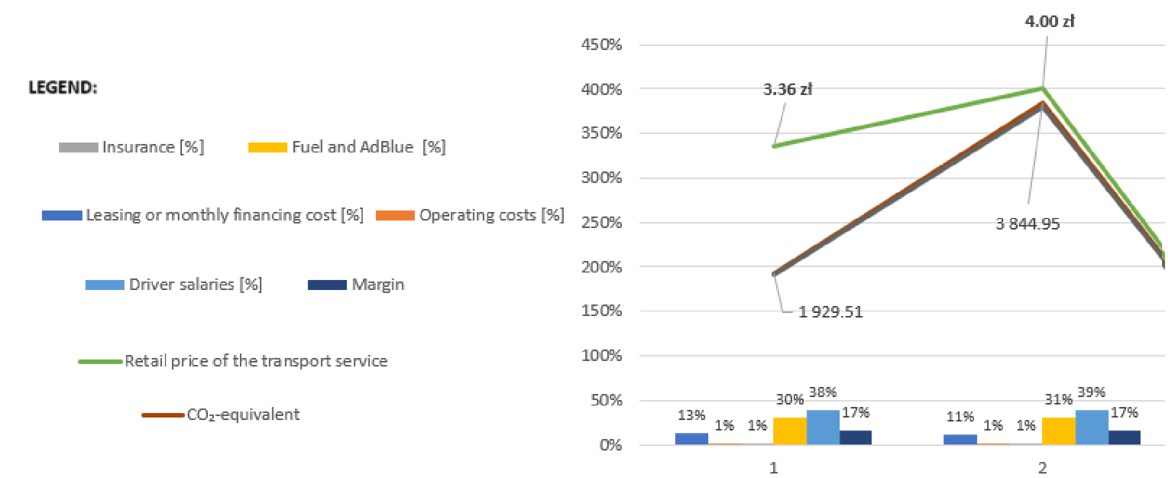

Fig. 4.21 Presentation of the final level of costs and emissions in the chart in the LDQ model
Source: own elaboration.

Due to the high degree of complexity of the relationships between parameters in LDQ, the following **Tab. 4.6** presents a network of mutual interdependencies. The matrix shows the impact of individual control parameters on the calculated cost and emission level of individual vehicles.

Tab. 4.6 Matrix of mutual interdependencies between parameters within the LDQ model

Source: own elaboration.

	Description
L	Selected from a list
A	Parameter calculated by the calculation model based on input criteria
M	Parameter entered manually by the user

			Control parameters				Result parameter										Environmental parameters		
			Fuel consumption [l/100km]	Average fuel	Cost of cooling units	Vehicle financing costs	Cost of purchasing a vehicle	Depreciation costs	Tire replacement cost	Insurance costs	Maintanance costs	Vehicle fuel cost	Fuel cost for cooling units	AdBlue costs	Total driver labor costs	Total taxes	Carbon Dioxide	Metan	Nitrogen oxide
Vehicle type	L	Vehicle					+				+								
	A	Gross Vehicle Mass (GVM)								+					+	+	+	+	+
	A	Engine size								+									
	A	Fuel type										+					+	+	+
	L	Vehicle age [years]	+			+	+				+	+							
	L	Truck body type			+	+	+						+						
	L	Cooling unit type			+	+	+						+						
	L	Load-Lok thermal divider & Fan with thermostat				+	+												
Input data	M	Distance travelled per vehicle (km)										+		+			+	+	+
	L	Daily operating hours of the cooling unit		+									+						
	L	Financing method					+	+											
	L	Month											+						
	L/M	Leasing parameters					+	+											
	L	Number of tire replacements							+										
Market data	M	Fuel price										+	+						
	L	Voivodeship								+	+				+				
	L	Selection of provincial city or rural area													+				
	M	Unit price of AdBlue												+					
	M	Municipality Tax rate														+			
	A	Tire cost							+										
	A	Insurance costs								+									
	A	Driver total labor costs													+				
Multiplier		Amount of vehicles					+	+	+	+	+	+	+	+	+	+	+	+	+

4.3. Multi-Criteria Decision Analysis for supporting Carbon Footprint Assessment in distribution supply chains

The use of Multi-Criteria Decision Analysis (MCDA) is well-established in scientific literature as a method for supporting complex decision-making processes that involve multiple, often conflicting criteria. MCDA is widely applied in environmental management, logistics, and sustainability assessments (Cinelli et al., 2014). It is related to MCDA approach ability to integrate quantitative (DiStefano and Krubiner, 2020) and qualitative factors (Dahmani et al., 2023) into a single, transparent evaluation framework. Its structured approach facilitates the comparison of alternatives, taking into account trade-offs between environmental impact, operational efficiency, social and economic performance (Rivero Gutiérrez et al., 2022). The increase in transport needs within the cities, points to the need for appropriate management of transport processes in the agglomeration area. For this purpose, sustainable urban mobility plans (SUMPs) are being developed across Europe. The selection of appropriate sustainable supply chain settings, outlined in SUMPs can be supported through the use of multi-criteria analysis (MCDA) what has been presented in a research by Kiba-Janiak and Witkowski (2019). This allows the needs of different stakeholder groups to be taken into account and leads to the mitigation of emissions resulting from the transport processes.

To support decision-making in the assessment model of CF level in distribution supply chain, a dedicated MCDA matrix was developed. This solution enables a structured comparison of multiple transport scenarios based on a set of relevant criteria. Each criterion is assigned a specific weight, reflecting its relative importance in the overall assessment. The final score for each scenario is calculated as a weighted sum of its performance across all selected criteria.

The matrix allows for the integration of both environmental and operational indicators, such as carbon emissions, transport distance, fleet age, load weight, and cost per kilometre. This approach provides a consistent and transparent basis for evaluating alternative transport strategies. However, it should be pointed out that the fundamental functionality of MCDA is to support decision-making in relation to environmental, cost and quality parameters of the transport distribution chain.

The MCDA matrix is particularly valuable when dealing with varying levels of data quality. The proposed solution enables support for the decision-making process, regardless of the quality of the basic data. The results of the emission level assessment obtained using the HDQ CF assessment model and the LDQ CF assessment model can be used in the proposed multi-criteria assessment matrix. Emission values generated using the High Data Quality (HDQ) model based on detailed, real-world operational data can be directly used to enhance the accuracy of the analysis. The Low Data Quality (LDQ) CF assessment model provides estimated values, which can also be included for comparative purposes.

By standardizing the evaluation process and presenting results in a comparable format, the MCDA matrix supports informed decision-making related to emission reduction strategies, logistics planning, and process optimisation. General design of proposed MDCA Matrix is presented in **Tab. 4.7** below. The logic of the MCDA analysis presented in the table below has been expanded and presented further in detail in the following tables and in **Appendix 9 - MCDA Matrix.xlsx**

Tab. 4.7 Proposed general layout of MCDA matrix for evaluation of the result parameters in all alternative scenarios

Source: own elaboration.

		Scenario As Is	Scenario 1	Scenario (n)
Criterion 1	Total road transport emissions [kgCO_2e]			
	Weight of criterion 1			
Criterion 2	Total distance [km]			
	Weight of criterion 2			
Criterion 3	Average fleet age			

	Weight of criterion 3			
Criterion 4	Total weight of transported goods [kg]			
	Weight of criterion 4			
Criterion (n)	Average transport cost currency/km			
	Weight of criterion (n)			
	Overall score of scenario	1	1	1

The set of parameters may vary depending on the parameters in the analysed supply chain. In each case, the parameters should be selected to correspond to the specific characteristics of the analysed supply chain. However, the categories of parameters identified in the literature review should be taken into account. According to the conclusions of the review of the essential parameters assessed, presented in **chapter 3.1** and **Tab. 3.6** include:

- Fleet parameters (including vehicle capacity and its alignment with cargo volume)
- CO_2 efficiency parameters
- Road parameters

Other detailed parameters identified in the literature research, such as fuel and traffic parameters that are, are external parameters difficult to reflect. However, it should be underlined that this area may be the subject of further research on the management of distribution transport emissions within sustainable supply chains.

The table below presents examples of parameters that should be taken into account when performing a multi-criteria assessment in scenarios. Presented list refers directly to the parameters covered by the LDQ and HDQ CF assessment models. Depending on the availability of the data and the selected assessment approach, the parameters of some criteria may vary. Therefore, it is necessary to limit the maximum number of available information and criteria. The table below presents a set of criteria suggested for assessment and indicates which model (HDQ or LDQ) allows for their consideration during the MCDA.

Tab. 4.8 Parameters assessed in the multi-criteria analysis and suggested assessment model
Source: own elaboration.

Criteria	High Data Quality Model	Low data Quality Model
Total road transport emissions [$kgCO_2e$]	Yes	Yes
Total distance [km]	Yes	Yes
Average emissions indicator for all product groups [$kgCO_2e/m^3$]	Yes	No
Average emissions indicator for all product groups [$kgCO_2e/kg$]	Yes	No
Average fleet age [years]	Yes	No
Introduction of more efficient and sustainable packaging	Yes	No
Average cost per km [Currency/km]	No	Yes
Fleet downtime rate [days/month]	Additional quality parameter for transport processes. Not included in the environmental performance assessment model. The user assigns the weights of the parameters independently.	
Fleet availability		
Carrier flexibility		
Risk of damage to goods due to the quality of the carrier's means of transport		

The multi-criteria assessment allows for the quality parameters of transport processes to be considered. However, these are not reflected in the HDQ and LDQ CF assessment models. Nevertheless, the user can assign their own parameter values and weights in MCDA.

The development of Multi-Criteria Decision Making has required the definition of a method for determining the weights of the specific criteria. Based on comparative theoretical and empirical research conducted by Triantaphyllou (2000), the possibility of using the Likert scale in the process of determining parameter weights has been indicated. On this basis, the following assessment scale was defined, hence it is recommended that the significance of each parameter be determined on a five-point Likert scale during the preparation to decision-making analysis. The following scale can be applied to the parameter importance assessment:
1 = Very Low Importance
2 = Low Importance
3 = Medium Importance
4 = High Importance
5 = Very High Importance

The Likert scale parameter values should be converted into detailed weights, the sum of which must equals 1. This approach makes the weighting process more user-friendly and allows for easier determination of them. The criteria weights can be calculated using the presented below **Formula 14.**

w_i	Normalized weight
S_i	Likert score for criterion *i*
$\sum_{j=1}^{n}$	It has to be ensured, that total value j of all weights equals 1.
n	Total number of criteria

Formula 14 Weight calculation formula for parameters reflected in multi-criteria analysis
Source: own elaboration based on Triantaphyllou (2000).

$$w_i = \frac{S_i}{\sum_{j=1}^{n} S_i}$$

The proposed MCDA solution is based not only on a literature review. The practical application of the approach was also verified in the course of the research described in **chapter 2.1**. The proposed approach to the analysis of the significance of parameters and their scope correspond to the model for assessing the CF level of distribution transport processes in a supply chain. The layout of the Multi Criteria Decision Matrix allows for assessment and further conclusions based on the results of simulations using the LDQ and HDQ CF assessment models. The use of MCDA is the final fifth step in the proposed model supporting the management of distribution transport processes from an environmental perspective. It allows for effective modelling of processes and making decisions dependent on the current values of the organisation in terms of environmental, social, and governance aspects. The logical integration of the proposed new distribution transport CF management model is consistent with the assumptions of essential standards and regulations related to ESG reporting and the principles of sustainable development in the area of transport processes outlined in **chapter 2**.

Tab. 4.9 below presents the first step of the MCDA assessment. It consists in determining the level of significance for each criterion in accordance with the Likert scale provided. The proposed solution allows different weights to be assigned depending on the scenario being assessed. However, it is recommended to use the same weights for all scenarios in order to precisely indicate differences in the level of effectiveness between scenarios. The assignment of different significance to the criteria can be employed in the decision-making process of scenario selection and negotiations conducted by a panel of experts(Tanujaya et al., 2022; Vinogradova et al., 2018).

Tab. 4.9 Multi Criteria Decision Matrix layout enabling assessment of parameter significance using the Likert scale in each scenario
Source: own elaboration.

		Scenarios						
Criteria	Likert Scale	1.0	2.0	2.1	2.2	3.0	3.1	3.2
Total road transport emissions	1-5							
Total distance	1-5							
Emissions indicator [$kgCO_2e/m^3$]	1-5							
Emissions indicator [$kgCO_2e/kg$]	1-5							
Average fleet age	1-5							
Sustainable packaging	1-5							
Average cost per kilometer	1-5							
Fleet downtime rate	1-5							
Risk of damage to goods	1-5							
Fleet availability	1-5							
Carrier flexibility	1-5							
Total value per scenario		0	0	0	0	0	0	0

Subsequently, the values of the Likert scale criteria have to be converted into weights according to **Formula 14**. This conversion can be carried out using **Tab. 4.10**, which has been provided tab "Scale to weight" in **Appendix 9 - MCDA Matrix.xlsx.** Once scales are typed in first column, weight is calculated automatically.

Tab. 4.10 Multi Criteria Decision Matrix layout enabling assessment of parameter significance using the Likert scale in each scenario
Source: own elaboration.

Criteria	Likert Score	Calculated Weight
Total road transport emissions [$kgCO_2e$]		
Total distance [km]		
Average emissions indicator for all product groups [$kgCO_2e/m^3$]		
Average emissions indicator for all product groups [$kgCO_2e/kg$]		
Average fleet age [years]		
Introduction of more efficient and sustainable packaging		
Average cost per km [Currency/km]		
Fleet downtime rate [days/month]		
Risk of damage to goods due to quality of carrier's means of transport		
Fleet availability		
Carrier flexibility		

Once all criteria parameters are typed in the next following **Tab. 4.11**, all result parameters can be calculated automatically. In below **Tab. 4.11** presents the layout of a tab containing result parameters in each scenario. Based on those values, final grades are calculated. In following example, matrix design, ranks spread from 1 to 7. Rate 1 states for the best scenario and logistics set up, while 7 states the worst possible scenario according to provided importance rates. The table below shows some example values in order to illustrate the presentation of MCDA results.

Tab. 4.11 Multi Criteria Decision Matrix result parameters for each scenario, including rates comparison between scenarios

Source: own elaboration.

		Scenarios						
Criteria	Weight	1.0	2.0	2.1	2.2	3.0	3.1	3.2
Total road transport emissions	*0.143*							
Total distance	*0.143*							
Emissions indicator [$kgCO_2e/m^3$]	*0.114*							
Emissions indicator [$kgCO_2e/kg$]	*0.114*							
Average fleet age	*0.086*							
Sustainable packaging	*0.086*							
Average cost per kilometer	*0.142*							
Fleet downtime rate	*0.057*							
Risk of damage to goods	*0.057*							
Fleet availability	*0.029*							
Carrier flexibility	*0.029*							
Total Score	*1.00*							
Ranking		0	0	0	0	0	0	0

	Scenarios						
Parameter	1	2	2.1	2.2	3	3.1	3.2
Scenario description							
Rank	*6*	*2*	*7*	*4*	*5*	*1*	*3*

The proposed MCDA allows for complete analysis of the best logistics setup of distribution supply chains. The collected information can be incorporated into company's strategic planning of a company and support key ideas and investment plans. Consideration of not only organisational parameters but also financial and environmental aspects allow the introduction of the ESG approach into a supply chain. A new model for CF assessment within distribution supply chains covers all requirements of the methodological aspects pointed out in GHG Protocol, ISO 14 064:2018 standard and the UK Defra emission factors and also those identified during the literature review on sustainable distribution supply chains.

5. Model validation

This chapter presents the validation process for the assessment of carbon footprint (CF) with the HDQ and LDQ models applied to the analysis of the real-life transport processes in distribution supply chains. The goal of the validation is to confirm the accuracy, reliability, and applicability of both the High Data Quality (HDQ) model and the Low Data Quality (LDQ) model under different data conditions and transport scenarios. Validation was carried out using anonymised primary data of a distribution company executing transport processes. Model validation is a crucial step in ensuring that the calculations reflect real-world conditions, enabling the results to be applied to support decision-making process.

The validation process involves comparing results generated by both models in multiple predefined scenarios, ranging from As-is scenario conditions to scenarios involving changes in fleet parameters, warehouse location, and packaging type. This validation approach reflects conducted research results related to various transport processes parameters presented in previous chapters. Differences in results between the detailed and simplified approaches are examined to highlight the impact of data quality on carbon footprint estimations. In addition, the transparency and usability of each model will be assessed, particularly in the context of compliance with environmental reporting standards such as ISO 14064.

Through this validation, the strengths and limitations of each model are identified, providing a basis for selecting the appropriate approach depending on the availability of data and the goals of the analysis. The validation of the new CF assessment model for transport processes begins with the identification of the requirements for its verification. The process commences with an analysis of transport processes in order to understand the mutual interdependencies between their elements. Subsequently, the quality of the data required for CF assessment is examined, followed by the definition of relevant scenarios to conduct the CF assessment in relation to process flows and data quality. A set of qualitative indicators is then established, while quantitative indicators are parameterised. This leads to an initial assessment of the calculated parameters applied in both the HDQ and LDQ models. The models are subsequently employed to perform CF emissions assessment, using either detailed (HDQ) or simplified (LDQ) approaches. The results are subjected to a multi-criteria analysis, applying defined parameter weights to identify the most efficient scenario in terms of emissions and transport process execution costs. Finally, the evaluation of the validation process is carried out. Conclusions are formulated regarding the practical use of the HDQ and LDQ models, the conduct of process analysis, and the appropriate methods for assessing data quality with accuracy.
The chosen validation approach which integrates process analysis, data-quality assessment, scenario exploration, and multi-criteria decision analysis (MCDA)—is grounded in contemporary environmental and transport modelling best practices. MCDA is widely acknowledged as a robust framework for navigating multifaceted decision problems, particularly within logistics and green supply chain contexts, by enabling structured evaluation of competing criteria (Macharis and Bernardini, 2015).

According to research conducted by Yates et al. (2023), the selection of appropriate models in ecological research requires the application of cross-validation. In line with this principle, the proposed validation process assessed CF levels using both the HDQ and LDQ models. Comparing the outcomes of the two models not only revealed differences in CF estimations but also served as a means of testing the consistency and robustness of the approach. Furthermore, the adopted validation logic enabled verification of the practical utility of the results generated through the MCDA analysis.

The detailed logic of the performed validation of the CF assessment model of transportation processes is presented in the following **Fig. 5.1.**

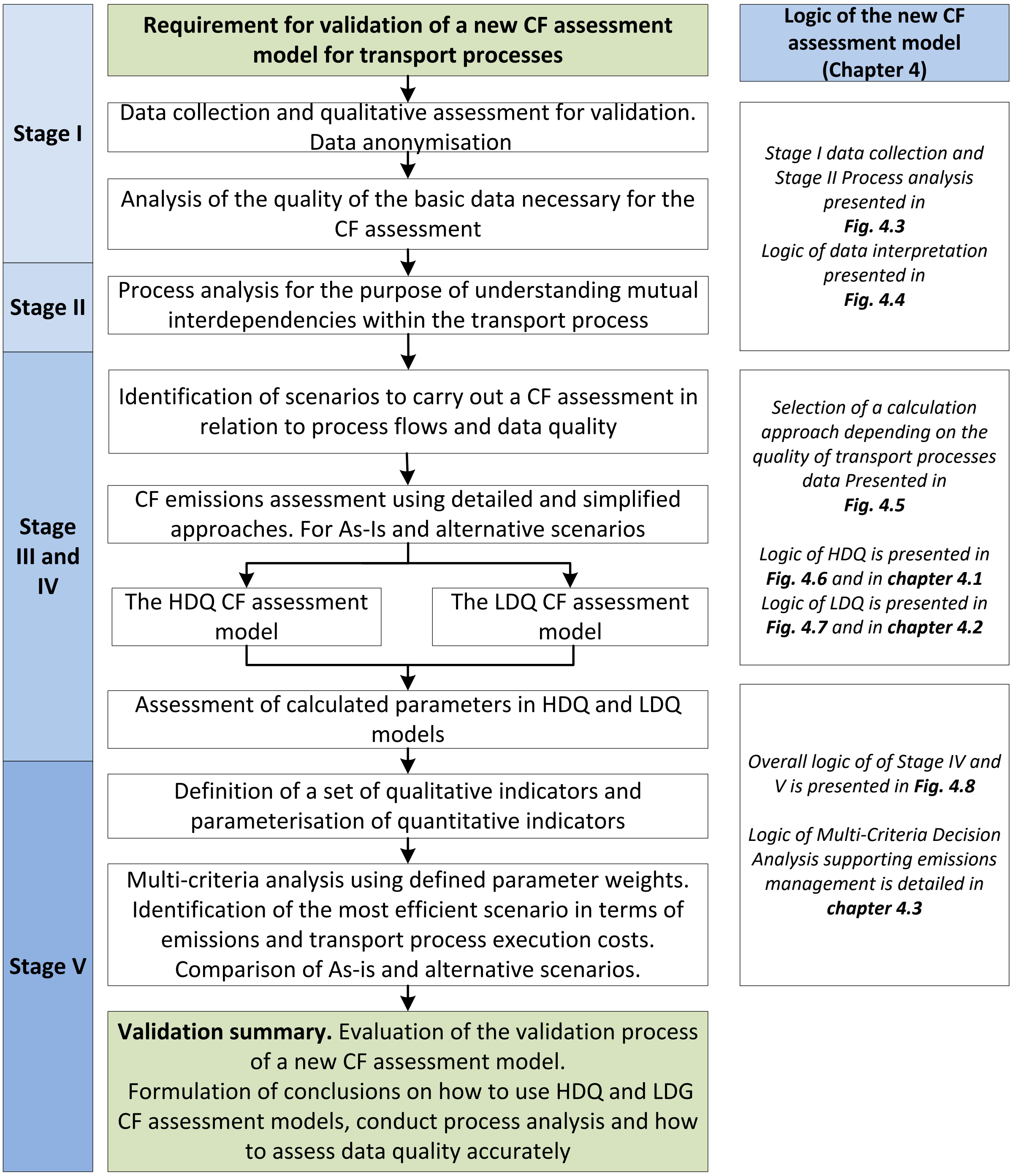

Fig. 5.1 The validation framework of a new CF assessment model

Source: own elaboration.

The subsequent steps of model validation drew upon the logic of the new CF assessment model as outlined in **chapter 4** and illustrated in the general diagram in **Fig. 4.1**. Chosen validation framework provided a structured basis for conducting the validation process, ensuring that the applied methods remained consistent with the conceptual design of the model. This approach reinforced the connection between the model's theoretical foundations and their practical validation

5.1. Process analysis

The current process of handling of transport orders involves multiple departments and external partners working in a coordinated sequence, starting from customer order placement to final delivery. Customers, including retail, wholesale, and e-commerce partners, can place orders through several channels, such as email, phone, online forms, EDI, or e-commerce platforms. Once received, the Customer Service Department records the order in the ERP-class system, ensuring that all key details such as product codes, quantities, and specific requirements are captured. The Warehouse and Stock Replenishment Department then checks product availability. If the requested items are not in stock, the system triggers a replenishment request and estimates the availability date, which is communicated back to the customer. Upon customer confirmation, the order is approved and prepared for dispatch.

Order fulfilment may involve internal production or receipt from an external supplier. Once completed, the Logistics Department initiates shipment preparation. The shipment details are verified, such as dimensions, temperature control needs, load stability, and volume. Orders are then assessed for potential consolidation with others, based on route efficiency and delivery deadlines.

Logistics planning is managed through a Transport Management System (TMS), where decisions are made regarding the type of transport (parcel, less-than-truckload, or full-truckload) and whether to use the company’s own fleet or an outsourced third-party logistics provider (3PL). Vehicle selection depends on the nature and volume of the shipment, with weight and regulatory parameters taken into account.

Once a transport order is finalized, the shipment is scheduled, the vehicle is dispatched, and the goods are loaded. The customer is kept informed at every stage via system-generated updates or email notifications. Delivery is completed either by own fleet or 3PL, with signed transport documentation (e.g. CMR, packing list, invoice) collected and logged. Final status updates are shared with the customer to confirm successful receipt.

The process is supported by ERP and TMS systems, enabling transparency, control, and efficiency throughout the logistics chain. It ensures that all stakeholders, from warehouse teams to transport planners, work on shared data to coordinate timely and accurate deliveries. The path of transport order handling and the scope of activities of individual participants in the process are presented in **Fig. 5.2** below.

Due to the high degree of complexity of the process map, the **Fig. 5.2** below should be treated as symbolic. A precise process map can be found in the **Appendix 10 - General map of process As Is.pdf**.

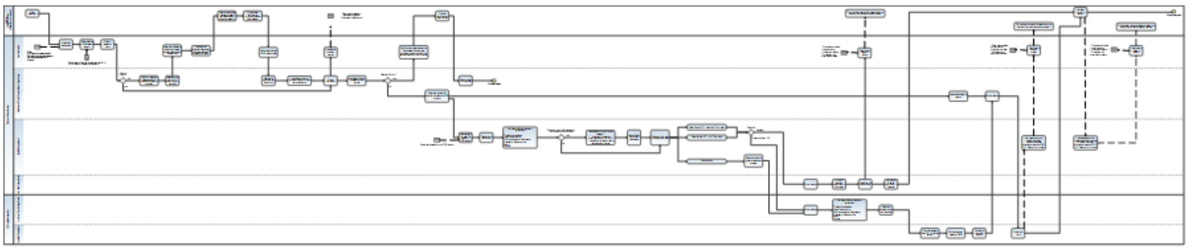

Fig. 5.2 Transport order flow - current process analysis

Source: own elaboration

In the next step, the process was reviewed to identify the presence of management elements from an environmental perspective. **Tab. 5.1** outlines the key participants involved, critical decision-making points, and the main criteria guiding the process.

Tab. 5.1 Operational scope of current distribution transport process design and verification of the presence of environmental management elements

Source: own elaboration.

Decision Step	Decision Point	Responsible process participant or relevant IT tool	Key process efficiency criteria	Carbon footprint management elements
Product availability	Is product available Product in stock?	- Warehouse Department - Stock Replenishment Department - ERP-class System	- Inventory data	None
Replenishment	Information about stock shortages, stock out	- Warehouse Department - Stock Replenishment Department	- Lead time, - External supplier delivery details	None
Transport method	Usage of own fleet or outsourced transport services	- Logistics Department - Own Fleet Management - External transport service provider (3PL) -	- Distance - Cost - Fleet availability	None
Shipment type	Parcel, LTL, FTL	- Logistics Department	- Volume - Weight	None
Consolidation	Is it possible to merge with other order to improve shipment efficiency?	- Transport Management System (TMS) - Logistics Department	- Route design. - Requested by customer order delivery date	None
Loading schedule	Goods are ready for loading	- Transport Management System (TMS) - External transport service provider (3PL) - Own Fleet Management	- Delivery slot at loading bays - Availability of goods - Availability of means of transport	None

Possible solution of integrating emissions management into the existing distribution supply chain

The revised process introduces the Carbon Footprint Management function, and embeds environmental considerations throughout the transport workflow. While the core sequence remains aligned with the AS-IS model, starting from order placement to final delivery, the To-Be scenario enhances the process with CF tracking, reporting, and decision support based on emission level data.

When a customer places an order (via EDI, web platform, phone, etc.), the data is recorded in the ERP-class system not only for operational processing but also for future inclusion in the GHG inventory. At multiple stages, such as shipment planning, fleet selection, and consolidation, the carbon footprint is calculated or estimated using parameters like vehicle type, weight, load efficiency, route length, and topography. Key decisions of choosing between FTL, LTL, or parcel services, or own fleet vs. outsourced 3PL services incorporate carbon emissions as one of the evaluation criteria, alongside cost and capacity. Therefore, in the last fifth step of a new CF assessment and management model the multi-criteria decision-making (MCDM) matrix may be applied to help identify the optimal logistics solution based on environmental and operational performance.

The following emissions assessment steps are focused on specific KPI calculations. This solution allows for CF assessment per delivery route and per loading unit (considering mass and volume). According to the proposed To-Be scenario, these CF assessment results should be uploaded into ERP and GHG reporting systems. Detailed information about CF level related to distribution transport processes can be communicated to customers as part of the delivery confirmation process. Depending on specifics of the fleet engaged, emissions can be considered as Scope 1 for own fleet usage or Scope 3 downstream emissions according to GHG guidelines for external fleet engagement.

Integration of ERP and GHG reporting systems ensures that environmental performance can be considered in real-time during operational decisions, making the logistics process not only efficient but also more sustainable and compliant with climate reporting standards. The proposal to include elements of environmental management, taking into consideration the analysis of the carbon footprint generated by transport processes, is presented in **Fig. 5.3** below.

Due to the high degree of complexity of the process flow, the **Fig. 5.3** below should be treated as symbolic. A precise process map can be found in the **Appendix 11 - General map of process To Be.pdf**.

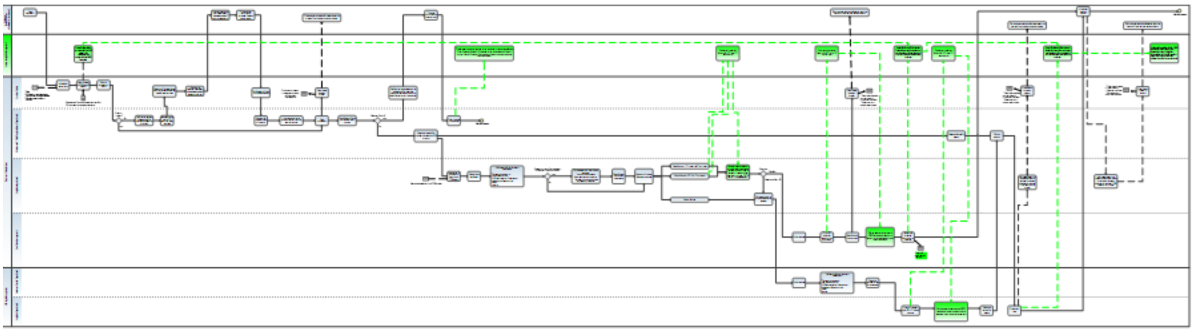

Fig. 5.3 The transport order handling process enhanced with environmental management
Source: own elaboration

Tab. 5.2 below presents an overview of the main process participants of the process and the decision-making points. Regarding each of them, the proposed scope of carbon footprint management has been indicated. Decision-making based on the obtained emission level allows for reconfiguring the supply chain in order to mitigate emissions. Proper planning of appropriate steps and the use of information obtained during the assessment of the carbon footprint of distribution transport processes allows for improving its overall efficiency.

Tab. 5.2 Recommendation for the application of environmental management elements in the existing process of handling and executing transport orders
Source: own elaboration.

Decision Step	Decision Point	Responsible process participant or relevant IT tool	Key process efficiency criteria	Carbon footprint management elements
Product availability	Is product available Product in stock?	- Warehouse Department - Stock Replenishment Department - ERP-class System	- Inventory data	- Order data recorded for GHG inventory
Replenishment	Information about stock shortages, stock out	- Warehouse Department - Stock Replenishment Department	- Lead time, - External supplier delivery details	- None
Transport method	Usage of own fleet or outsourced transport services	- Logistics Department - Own Fleet Management - External transport service provider (3PL) -	- Distance - Cost - Fleet availability	- Decision supported by emissions data (MCDM matrix)
Shipment type	Parcel, LTL, FTL	- Logistics Department	- Volume - Weight	- CF estimation for LTL and FTL service levels
Consolidation	Is it possible to merge with other order to improve shipment efficiency?	- Transport Management System (TMS) - Logistics Department	- Route design. - Requested by customer order delivery date	- Consolidation logic considers emissions
Loading schedule	Goods are ready for loading	- Transport Management System (TMS) - External transport service provider (3PL) - Own Fleet Management	- Delivery slot at loading bays - Availability of goods - Availability of means of transport	- Selection based on vehicle age and route topography

In accordance with the proposed logic for the CF assessment, a specific calculation approach should be selected at this stage. A detailed approach to the assessment of GHG is possible if the high-quality data are available. A simplified approach is possible if lower-quality data is available. In the next step, an assessment of the emission level within the supply chain was conducted in the As-is scenario. Subsequent scenarios for alternative transport organisation were presented in separate scenarios. The validation process is consistent with the proposed logic of the model for assessing the carbon footprint of transport processes.

5.2. The assessment of Carbon Footprint from transport processes within supply chain – with LDQ and HDQ approach with comparative analysis

To assess the carbon footprint of transport processes within a distribution chain, reference was made to the specific characteristics of transport orders identified during the process analysis. This analysis enabled the identification of key loading points, customer locations, and types of road transport used.

The first step involved verifying the quality of the available data. It was determined that the data was suitable for evaluating carbon footprint (CF) levels using the HDQ model. By adopting a detailed approach, a range of precise emission indicators was identified, categorized by transport mode and location. The data quality also allowed for the use of a simplified method (the LDQ model) enabling validation through both calculation models. Comparing the results from both models is essential to understanding the margin of error introduced by the simplified LDQ approach.

A scenario-based methodology was proposed to evaluate CF level using a new model designed for measuring and managing transport emissions. Below **Tab. 5.3** provides a general overview of each scenario, listing the control parameters included or excluded. Value of 0 indicates the parameter is not present, and 1 indicates occurrence of a control parameter within scenario.

Tab. 5.3 New CF assessment model validation scenarios supported by HDQ and LDQ calculation models
Source: own elaboration.

Parameter	Scenarios						
	1.0	2.0	2.1	2.2	3.0	3.1	3.2
Scenario description	As-Is	- Change of age of the vehicle -5 years	- Change of central warehouse (MC001) location from post code 86-160 (Warlubie) to Central-PL, post code 95-040 (Stryków).	- Change of age of the vehicle -5 years - Change of central warehouse (MC001) location from post code 86-160 (Warlubie) to Central-PL, post code 95-040 (Stryków).	- Use of sustainable packaging reducing the weight and volume of transported goods by 11%	- Use of sustainable packaging reducing the weight and volume of transported goods by 11% - Change of age of the vehicle -5 years	- Use of sustainable packaging reducing the weight and volume of transported goods by 11% - Change of age of the vehicle -5 years - Change of central warehouse (MC001) location from post code 86-160 (Warlubie) to Central-PL, post code 95-040 (Stryków).
Change of age of the vehicle	*0*	*1*	*0*	*1*	*0*	*1*	*1*
Change of central warehouse location	*0*	*0*	*1*	*1*	*0*	*0*	*1*
Incorporation of sustainable packaging	*0*	*0*	*0*	*0*	*1*	*1*	*1*
Scenario reflected in detailed appraoch - High Data Quality CF Assessment model	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Scenario reflected in simplified approach - Low Data Quality CF Assessment model	Yes	Yes	Yes	Yes	No	No	No

Scenario 1.0 serves as the baseline or "as-is" scenario, reflecting the current carbon footprint of transport activities within the supply chain. Scenarios 2.0 through 3.2 incorporate changes such as organisational adjustments, fleet parameter updates, and modifications to packaging all of which influence vehicle load space utilisation and payload weight. Detailed information regarding each scenario has been presented as follows:

Scenario 1.0: Baseline (As-Is)
Scenario 1.0 represents the baseline condition, reflecting the current level of carbon footprint generated by existing transport operations. Both the High Data Quality (HDQ) and Low Data Quality (LDQ) models are employed to calculate emission levels. The difference in the results obtained from the two models serves as a reference point for evaluating the relative accuracy and reliability of the simplified approach in subsequent scenarios.

Scenario 2.0: Change in Fleet Age
Scenario 2.0 introduces a change in the average age of vehicles used in transport operations. The resulting variation in fuel consumption is quantified and incorporated into both the HDQ and LDQ models. This integration enables dynamic modification of the fleet age parameter and facilitates the assessment of its impact on all transport-related emissions throughout the organisation.

Scenario 2.1: Relocation of Central Warehouse
In Scenario 2.1, the central warehouse (MC001) is relocated from its current site in Poland with postal code 86-160 to a new site with postal code 95-040. This change reflects the company's strategic investment objectives and provides a basis for evaluating the environmental implications of relocating the primary distribution centre. The HDQ model supports this scenario through dynamic recalculation of delivery distances using an embedded distance matrix and detailed transport order data. This allows for automated computation of travel distances from the new warehouse location to all identified customer destinations. In contrast, the LDQ model does not support distance recalculations; however, it permits the manual input of total kilometres travelled by each vehicle as determined from the HDQ output. This enables cross-verification between the two models and supports an evaluation of discrepancies in carbon footprint estimation.

Scenario 2.2: Combined Change in Fleet Age and Warehouse Location
Scenario 2.2 integrates the changes introduced in Scenarios 2.0 and 2.1, combining the updated vehicle age and new warehouse location. The scenario captures the cumulative effects of improved fuel efficiency and altered transport distances on carbon emissions. Both HDQ and LDQ models are used to recalculate this scenario, allowing for a comparative analysis of results derived from high and low data quality approaches.

Scenario 3.0: Packaging Optimisation Based on Volume Reduction
Scenario 3.0 examines the impact of adopting alternative packaging solutions, resulting in an eleven percent reduction in transported volume. This change influences vehicle load capacity utilisation and overall transport efficiency. Due to the level of detail required, this scenario can only be assessed using the HDQ model. The LDQ model lacks the necessary data granularity to capture changes in volumetric characteristics.

Scenario 3.1: Combined Change in Packaging and Fleet Age
Scenario 3.1 builds on Scenario 3.0 by combining the volumetric reduction from alternative packaging with a reduction in vehicle age by five years. This dual modification affects both the mass and fuel efficiency of transport operations. As with the previous scenario, only the HDQ model provides sufficient detail to recalculate and assess the carbon footprint under these new conditions.

Scenario 3.2: Integrated Optimisation of Packaging, Fleet Age, and Warehouse Location

Scenario 3.2 represents a comprehensive intervention, combining all three factors examined in earlier scenarios. This includes the introduction of a lighter packaging type that reduces cargo weight, a reduction in vehicle age by five years, and the relocation of the central warehouse from the current site (postal code 86-160) to a new site (postal code 95-040). Due to the complexity and data requirements of this scenario, the assessment is conducted exclusively using the HDQ model. Scenarios 1.0, 2.0, 2.1 and 2.2 enable cross-verification of the accuracy level of both detailed and simplified approaches during the new CF assessment model validation.

Detailed approach – High Data Quality CF assessment model

To verify the detailed approach with the High Data Quality (HDQ) model, it was necessary to obtain precise and comprehensive data, including information on transport orders, vehicle categories, goods flows, product attributes, and customer locations. In order to secure credible outcomes, the model also incorporated the most recent emission factors, drawing on the latest indices published by UK DEFRA. The HDQ model's capabilities made it possible to simulate all the planned scenarios. However, due to the fact that the model takes into account a large amount of highly detailed data, it is considered to provide a highly accurate calculation of the CF level within supply chain. The **Tab. 5.6** below presents the parameters obtained by the HDQ CF assessment model. For each scenario, dedicated environmental performance indicators were calculated, including:

- Total road transport emissions [$kgCO_2e$]
- Average emissions per mean of transport [$kgCO_2e$]
- Average emissions per mean of transport [$kgCO_2e$]
- Total weight of transported goods [kg]
- Total distance [km]
- Average emissions indicator for all product groups [$kgCO_2e/m^3$]
- Average emissions indicator for all product groups [$kgCO_2e/kg$]
- Emission according to distance [$kgCO_2e/km$]
- Change of total road transport emissions [$kgCO_2e$]
- Change of an average change per route road transport emissions [$kgCO_2e$]
- Change of average emissions per mean of transport [$kgCO_2e$]
- Change of an average emissions indicator for all product groups [$kgCO_2e/m^3$]
- Change of an average emissions indicator for all product groups [$kgCO_2e/kg$]
- Total distance increase/decrease [km]
- Total cargo weight increase/decrease [kg]
- Overall change of road transport emissions in compare with As Is scenario [%]

For each scenario, the percentage increase or decrease in emissions was determined, taking into account changes in scenario parameters. The trend in CF levels was referenced to the baseline scenario 1.0 (As-Is) in order to identify the potential for reducing the carbon footprint of transport processes in each scenario.

The detailed approach also allows for the determination of emissions related to the execution of transport processes from a specific location and by a specific vehicle executing loadings and unloadings, as indicated in individual transport orders. The control parameters adopted in each scenario in terms of vehicle age (**Tab. 5.4**) and the specific postcode of each location according to their identification ID (**Tab. 5.5**) are also presented below.

Tab. 5.4 Age of the vehicles applied in scenarios for detailed CF assessment supported by HDQ model
Source: own elaboration.

Registration plate	Scenario ID - age of the vehicle applied in the CF assessment						
	1.0	2.0	2.1	2.2	3.0	3.1	3.2
CSWYW95	9	4	9	4	9	4	4
CSWYR97	16	11	16	11	16	11	11
CSWYR96	9	4	9	4	9	4	4

Registration plate	Scenario ID - age of the vehicle applied in the CF assessment						
	1.0	2.0	2.1	2.2	3.0	3.1	3.2
CSWYR34	15	10	15	10	15	10	10
CSWYN51	7	2	7	2	7	2	2
CSWYN23	12	7	12	7	12	7	7
CSWYM26	13	8	13	8	13	8	8
CSWYE86	16	11	16	11	16	11	11
CSWVY10	10	5	10	5	10	5	5
CSWUW87	13	8	13	8	13	8	8
CSWUW86	15	10	15	10	15	10	10
CSWRX47	9	4	9	4	9	4	4
CB94907	11	6	11	6	11	6	6
CSW8U18	14	9	14	9	14	9	9
CSWSP82	16	11	16	11	16	11	11
CSWSP83	15	10	15	10	15	10	10
CSW3F02	9	4	9	4	9	4	4
CSW70RT	14	9	14	9	14	9	9
CSW9S97	16	11	16	11	16	11	11
CB94908	6	1	6	1	6	1	1

Tab. 5.5 Location post codes reflected in CF assessment supported by HDQ model
Source: own elaboration.

Location ID	Scenario ID - Each location post code applied in the CF assessment						
	1.0	2.0	2.1	2.2	3.0	3.1	3.2
MC001	86-160	86-160	95-040	95-040	86-160	86-160	95-040
DO012	80-718	80-718	80-718	80-718	80-718	80-718	80-718
DO014	86-060	86-060	86-060	86-060	86-060	86-060	86-060
DO011	86-060	86-060	86-060	86-060	86-060	86-060	86-060
DO015	59-230	59-230	59-230	59-230	59-230	59-230	59-230
DO016	74-506	74-506	74-506	74-506	74-506	74-506	74-506
DO017	05-180	05-180	05-180	05-180	05-180	05-180	05-180
DO019	11-010	11-010	11-010	11-010	11-010	11-010	11-010
DO028	75-120	75-120	75-120	75-120	75-120	75-120	75-120
DO013	60-104	60-104	60-104	60-104	60-104	60-104	60-104
DO030	87-500	87-500	87-500	87-500	87-500	87-500	87-500
DO031	81-198	81-198	81-198	81-198	81-198	81-198	81-198
DO032	62-093	62-093	62-093	62-093	62-093	62-093	62-093
DO033	80-555	80-555	80-555	80-555	80-555	80-555	80-555
DO034	70-605	70-605	70-605	70-605	70-605	70-605	70-605
DO042	62-093	62-093	62-093	62-093	62-093	62-093	62-093
DO036	64-915	64-915	64-915	64-915	64-915	64-915	64-915
DO045	05-205	05-205	05-205	05-205	05-205	05-205	05-205
DO046	51-501	51-501	51-501	51-501	51-501	51-501	51-501
DO047	68-206	68-206	68-206	68-206	68-206	68-206	68-206

Detailed result parameters for each scenario are presented in the **Tab. 5.6** below.

Tab. 5.6 Result parameters of CF assessment supported by HDQ model

Source: own elaboration.

↓ Parameters Scenarios ->	1.0	2.0	2.1	2.2	3.0	3.1	3.2
Total road transport emissions [kgCO_2e]	339 738	324 324	379 845	362 631	337 601	322 283	360 350
Average emissions per mean of transport [kgCO_2e]	370.993	354.110	410.317	391.673	368.557	351.783	389.164
Average emissions per mean of transport [kgCO_2e]	16 987	16 216	18 992	18 132	16 880	16 114	18 018
Total weight of transported goods [kg]	43 929 060	43 929 060	43 929 060	43 929 060	39 096 863	39 096 863	39 096 863
Total distance [km]	364 274	364 274	407 215	407 215	364 274	364 274	407 215
Average emissions indicator for all product groups [kgCO_2e/m^3]	5.681	5.423	6.352	6.064	6.340	6.055	6.771
Average emissions indicator for all product groups [kgCO_2e/kg]	0.0077	0.0074	0.0086	0.0083	0.0086	0.0082	0.0092
Emission according per km [kgCO_2e/km]	0.9326	0.8903	0.9328	0.8905	0.9268	0.8847	0.8849
Change of total road transport emissions [kgCO_2e]	-	- 15 414	40 107	22 893	- 2 137	- 17 455	20 612
Change of an average change per route road transport emissions [kgCO_2e]	-	- 16.883	39.324	20.680	- 2.440	- 19.210	18.171
Change of average emissions per mean of transport [kgCO_2e]	-	- 770.679	2 005.332	1 144.665	- 107.000	- 872.735	1 030.614
Change of an average emissions indicator for all product groups [kgCO_2e/m^3]	-	- 0.2577	0.6707	0.3828	0.6620	0.3742	1.0894
Change of an average emissions indicator for all product groups [kgCO_2e/kg]	-	- 0.0004	0.0009	0.0005	0.0009	0.0005	0.0015
Total distance increase/decrease [km]		-	42 941	42 941			42 941.0000
Total cargo weight increase/decrease [kg]	-	-	-	-	- 4 832 197	- 4 832 197	- 4 832 197
Overall change of road transport emissions in compare with As Is scenario [%]	-	-4.54%	11.81%	6.74%	-0.63%	-5.14%	6.07%
Emission of location MC001 [kgCO_2e]	38 110	36 432	66 239	63 308	37 757	36 094	62 668
Emission of location DO012 [kgCO_2e]	84 923	81 121	91 705	87 594	84 359	80 582	87 071
Emission of location DO014 [kgCO_2e]	25 933	24 746	27 771	26 499	25 687	24 511	26 270
Emission of location DO011 [kgCO_2e]	21 829	20 822	22 471	21 434	21 713	20 711	21 329
Emission of location DO015 [kgCO_2e]	39 124	37 355	39 027	37 263	38 820	37 065	36 975
Emission of location DO016 [kgCO_2e]	47 093	44 928	47 202	45 032	47 024	44 863	44 979
Emission of location DO017 [kgCO_2e]	892	847	1 067	1 013	880	835	1 001
Emission of location DO019 [kgCO_2e]	708	675	708	675	704	671	671
Emission of location DO028 [kgCO_2e]	3 487	3 324	3 827	3 649	3 476	3 314	3 646

↓ Parameters Scenarios ->	1.0	2.0	2.1	2.2	3.0	3.1	3.2
Emission of location DO013 [kgCO_2e]	24 205	23 029	24 244	23 067	24 031	22 864	22 904
Emission of location DO030 [kgCO_2e]	4 447	4 243	4 419	4 216	4 422	4 218	4 195
Emission of location DO031 [kgCO_2e]	9 514	9 089	9 916	9 473	9 288	8 873	9 261
Emission of location DO032 [kgCO_2e]	1 197	1 138	1 197	1 138	1 192	1 133	1 133
Emission of location DO033 [kgCO_2e]	35 224	33 668	36 999	35 363	35 213	33 658	35 353
Emission of location DO034 [kgCO_2e]	661	628	661	628	654	622	622
Emission of location DO042 [kgCO_2e]	390	371	390	371	390	371	371
Emission of location DO036 [kgCO_2e]	285	273	285	273	285	273	273
Emission of location DO045 [kgCO_2e]	553	525	553	525	548	521	523
Emission of location DO046 [kgCO_2e]	390	373	390	373	390	373	373
Emission of location DO047 [kgCO_2e]	773	737	773	737	769	733	734
Emission of vehicle CSWYW95 [kgCO_2e]	18 101	17 211	19 169	18 227	18 018	17 132	18 218
Emission of vehicle CSWYR97 [kgCO_2e]	13 992	13 389	14 036	13 431	13 940	13 338	13 380
Emission of vehicle CSWYR96 [kgCO_2e]	17 390	16 535	18 879	17 952	17 313	16 462	17 879
Emission of vehicle CSWYR34 [kgCO_2e]	1 490	1 430	1 490	1 430	1 490	1 430	1 430
Emission of vehicle CSWYN51 [kgCO_2e]	17 316	16 492	17 644	16 805	17 117	16 303	16 616
Emission of vehicle CSWYN23 [kgCO_2e]	20 307	19 364	20 938	19 966	20 221	19 282	19 884
Emission of vehicle CSWYM26 [kgCO_2e]	21 851	20 857	21 799	20 807	21 754	20 765	20 714
Emission of vehicle CSWYE86 [kgCO_2e]	6 547	6 265	6 547	6 265	6 542	6 260	6 260
Emission of vehicle CSWVY10 [kgCO_2e]	12 410	11 813	12 453	11 854	12 323	11 730	11 772
Emission of vehicle CSWUW87 [kgCO_2e]	12 844	12 260	12 827	12 243	12 826	12 242	12 226
Emission of vehicle CSWUW86 [kgCO_2e]	20 580	19 741	22 708	21 782	20 306	19 479	21 464
Emission of vehicle CSWRX47 [kgCO_2e]	18 994	18 061	19 080	18 142	18 903	17 974	18 056
Emission of vehicle CB94907 [kgCO_2e]	17 211	16 454	17 089	16 338	17 083	16 332	16 216
Emission of vehicle CSW8U18 [kgCO_2e]	21 786	20 815	26 443	25 264	21 710	20 742	25 140
Emission of vehicle CSWSP82 [kgCO_2e]	19 319	18 486	24 310	23 262	19 196	18 369	23 144
Emission of vehicle CSWSP83 [kgCO_2e]	17 140	16 442	19 667	18 865	16 905	16 216	18 640
Emission of vehicle CSW3F02 [kgCO_2e]	4 373	4 158	6 904	6 565	4 358	4 144	6 550
Emission of vehicle CSW70RT [kgCO_2e]	26 944	25 743	35 922	34 320	26 672	25 483	34 043
Emission of vehicle CSW9S97 [kgCO_2e]	36 999	35 404	44 832	42 899	36 905	35 313	42 701
Emission of vehicle CB94908 [kgCO_2e]	14 141	13 404	17 106	16 214	14 017	13 287	16 018

To highlight the variations in results across the different scenarios and to visualise them clearly, a specific index was employed to represent emissions per unit of distance [kgCO_2e/km]. This measure was presented together with the total distance travelled in each scenario. Such an approach is important, as lowering emissions per kilometre is a primary goal, yet the overall distance covered in each case also plays a crucial role in modelling the total carbon footprint within supply chain. The outcomes of the carbon footprint assessment based on the High Data Quality (HDQ) model are illustrated in **Fig. 5.4** below.

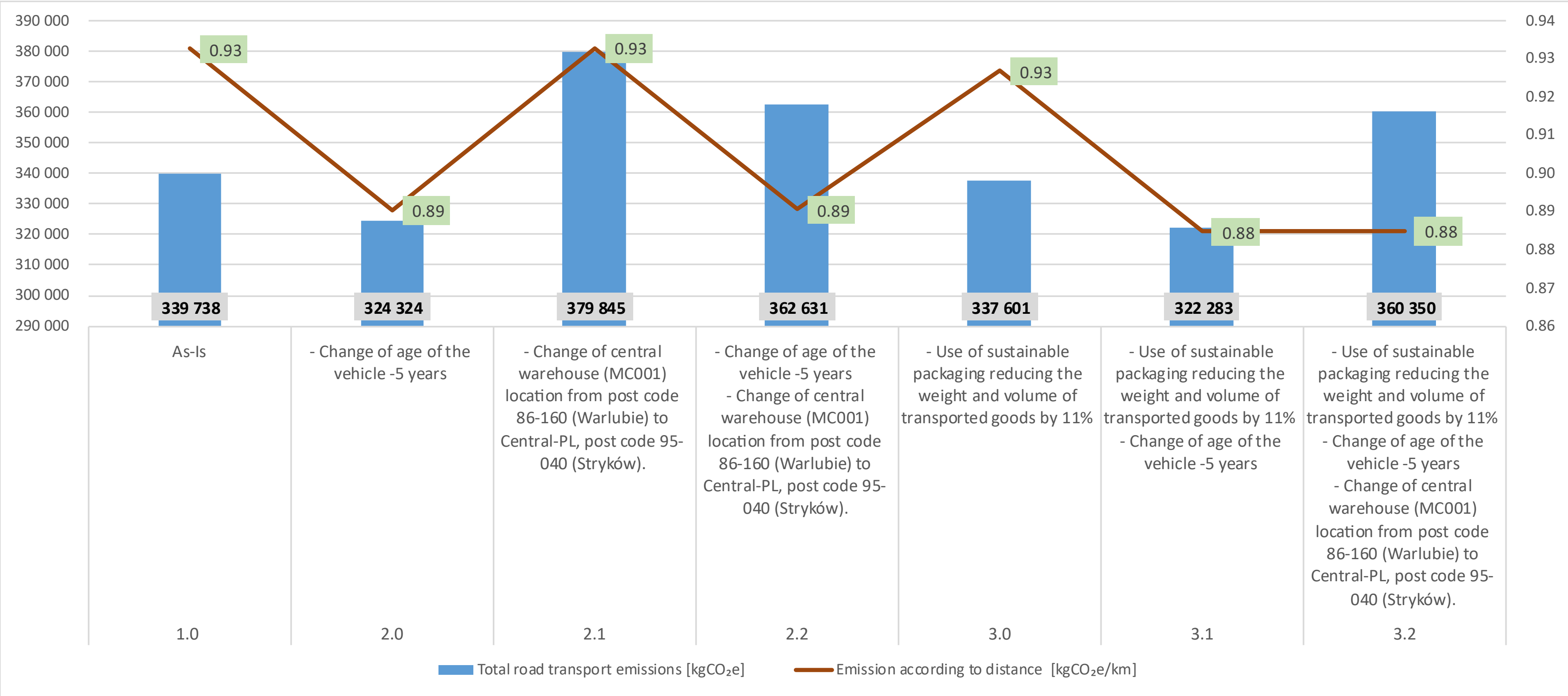

Fig. 5.4 Detailed approach - HDQ model - Total road emission level [kgCO_2e] vs. Emission per km ratio [kgCO_2e/km]

Source: own elaboration.

In the following validation steps, a simplified approach (supported by LDQ model) was used to assess the carbon footprint level, based on the same primary information such as distance travelled, vehicle types, gross vehicle mass (GVM), and vehicle age. LDQ CF assessment allows for costs calculation, hence obtained results have been treated as supplementary to HDQ CF assessment and used in further MCDA to support decision making process.

Simplified approach – Low Data Quality CF assessment model

The simplified approach to assessing the carbon footprint (CF), supported by the Low Data Quality (LDQ) model, is based on several vehicle parameters included in the greenhouse gas (GHG) calculation method. One of the key factors that affects emissions is the gross vehicle mass (GVM), which influences the vehicle's load capacity and volume. However, the simplified model does not make it possible to assess how vehicle volume impacts transport capacity. To evaluate this properly, a detailed model (HDQ) is needed, along with access to high-quality, detailed data.

Simultaneously, an important element is the vehicle age parameter, a change of which results in changes in the fuel consumption per vehicle. The determined fuel consumption change coefficient is an important element of the model created for measuring and managing CO_2 emissions within sustainable supply chains.

Using the simplified model, the CF levels were recalculated for the As-Is, 2.0, 2.1, and 2.2 scenarios. For scenarios 2.1 and 2.2, which involve changing the location of the central warehouse, it was necessary to first calculate the distance travelled by each vehicle. This was done using the High Data Quality (HDQ) model, which can automatically calculate distances. If detailed data is not available, the LDQ model allows users to enter the total distance manually.

It is important to note that relying on assumptions in the CF assessment process can increase the risk of error. Any such assumptions should be clearly documented in the emissions report to maintain transparency and ensure alignment with ISO 14064 requirements.

The obtained parameters gathered in each of the scenarios that allowed for the LDQ CF assessment are presented in **Tab. 5.7**, **Tab. 5.8**, **Tab. 5.9** and **Tab. 5.10** below.

Detailed result information can be also found in tab 'LDQ CF Assessment' in **Appendix 12 - Model validation.xlsx.**

Tab. 5.7 As-Is 1.0 Scenario result parameters evaluated in the simplified CF assessment approach supported by Low Data Quality model
Source: own elaboration.

		Scenario 1.0 As Is																			
Parameter	Unit	Vehicle 1	Vehicle 2	Vehicle 3	Vehicle 4	Vehicle 5	Vehicle 6	Vehicle 7	Vehicle 8	Vehicle 9	Vehicle 10	Vehicle 11	Vehicle 12	Vehicle 13	Vehicle 14	Vehicle 15	Vehicle 16	Vehicle 17	Vehicle 18	Vehicle 19	Vehicle 20
GVM	[kg]	40000	40000	40000	40000	40000	40000	26000	26000	26000	40000	40000	40000	40000	40000	40000	40000	26000	26000	26000	40000
Vehicle age [years]	[years]	9	16	9	15	7	12	13	16	10	13	15	9	11	14	16	15	9	14	16	6
Distance	[km/month]	20728	15344	20111	1641	20489	21227	25354	7024	13669	14705	21805	21844	20041	22936	19508	18062	4309	25883	33979	15615
Carbon dioxide	[kg CO_2/month]	21 362	16 684	20 726	1 784	20 728	22 478	27 088	7 637	14 216	15 711	23 709	22 512	21 033	24 722	21 211	19 639	4 441	27 898	36 946	15 502
Methane	[kg CH_4/month]	4.52	3.53	4.38	0.38	4.38	4.76	5.73	1.62	3.01	3.32	5.02	4.76	4.45	5.23	4.49	4.15	0.94	5.90	7.82	3.28
Nitrogen oxide	[kg N_2O/month]	269	210	261	22	261	283	341	96	179	198	299	284	265	311	267	247	56	351	465	195
Total emission	[kgCO_2e)	21 635	16 897	20 991	1 807	20 994	22 766	27 435	7 735	14 398	15 912	24 012	22 800	21 302	25 038	21 483	19 891	4 498	28 255	37 419	15 701

As - Is 1.0 scenario Result parameters	**Value**	**Unit**
Emission according to distance	1.0732884	[kgCO_2e/km]
Total distance	364274	[km]
Total Carbon dioxide Emission	386 026	[kg CO_2]
Total Methane Emission	81.66	[kg CH_4]
Total Nitrogen oxide Emission	4 863	[kg N_2O]
Total CO_2-equivalent	390 971	(kgCO_2e)
Average cost per kilometer	4.69	[zł/km]

Tab. 5.8 2.0 Scenario result parameters evaluated in the simplified CF assessment approach supported by Low Data Quality model
Source: own elaboration.

		Scenario 2.0 - Change of age of the vehicle -5 years																			
Parameter	Unit	Vehicle 1	Vehicle 2	Vehicle 3	Vehicle 4	Vehicle 5	Vehicle 6	Vehicle 7	Vehicle 8	Vehicle 9	Vehicle 10	Vehicle 11	Vehicle 12	Vehicle 13	Vehicle 14	Vehicle 15	Vehicle 16	Vehicle 17	Vehicle 18	Vehicle 19	Vehicle 20
GVM	[kg]	40000	40000	40000	40000	40000	40000	26000	26000	26000	40000	40000	40000	40000	40000	40000	40000	26000	26000	26000	40000
Vehicle age [years]	[years].	4	11	4	10	2	7	8	11	5	8	10	4	6	9	11	10	4	9	11	1
Distance	[km/month].	20728	15344	20111	1641	20489	21227	25354	7024	13669	14705	21805	21844	20041	22936	19508	18062	4309	25883	33979	15615
Carbon dioxide	[kg CO_2/month]	19 990	16 103	19 395	1 707	19 372	21 475	25 890	7 372	13 312	15 016	22 678	21 066	19 896	23 637	20 473	18 785	4 156	26 674	35 661	14 764
Methane	[kg CH_4/month]	4.23	3.41	4.10	0.36	4.10	4.54	5.48	1.56	2.82	3.18	4.80	4.46	4.21	5.00	4.33	3.97	0.88	5.64	7.54	3.12
Nitrogen oxide	[kg N_2O/month]	252	203	244	22	244	271	326	93	168	189	286	265	251	298	258	237	52	336	449	186
Total emission	[kgCO_2e)	20 246	16 310	19 643	1 729	19 620	21 750	26 221	7 466	13 482	15 208	22 968	21 336	20 151	23 940	20 736	19 026	4 209	27 016	36 117	14 953

Scenario 2.0 Result parameters	Value	Unit
Emission according to distance [kgCO_2e/km]	1.0215578	[kgCO_2e/km]
Total distance	364274	[km]
Total Carbon dioxide Emission	367 421	[kg CO_2]
Total Methane Emission	77.73	[kg CH_4]
Total Nitrogen oxide Emission	4 629	[kg N_2O]
Total CO_2-equivalent	372 127	[kgCO_2e)
Average cost per kilometer	4.63	[zł/km]

Tab. 5.9 2.1 Scenario result parameters evaluated in the simplified CF assessment approach supported by Low Data Quality model
Source: own elaboration.

		Scenario 2.1 - Distance rise according to change of central warehouse (MC001) location from post code 86-160 (Warlubie) to Central-PL, post code 95-040 (Stryków).																			
Parameter	Unit	Vehicle 1	Vehicle 2	Vehicle 3	Vehicle 4	Vehicle 5	Vehicle 6	Vehicle 7	Vehicle 8	Vehicle 9	Vehicle 10	Vehicle 11	Vehicle 12	Vehicle 13	Vehicle 14	Vehicle 15	Vehicle 16	Vehicle 17	Vehicle 18	Vehicle 19	Vehicle 20
GVM	[kg]	40000	40000	40000	40000	40000	40000	26000	26000	26000	40000	40000	40000	40000	40000	40000	40000	26000	26000	26000	40000
Vehicle age [years]	[years]	9	16	9	15	7	12	13	16	10	13	15	9	11	14	16	15	9	14	16	6
Distance	[km/month]	21731	15404	21788	1641	20978	21899	25280	7024	13716	14690	23945	21969	19867	28158	25200	20967	7179	34776	41357	19646
Carbon dioxide	[kg CO_2/month]	22 396	16 749	22 454	1 784	21 223	23 190	27 009	7 637	14 265	15 695	26 036	22 641	20 850	30 350	27 400	22 798	7 399	37 483	44 968	19 504
Methane	[kg CH_4/month]	4.74	3.54	4.75	0.38	4.49	4.91	5.71	1.62	3.02	3.32	5.51	4.79	4.41	6.42	5.80	4.82	1.57	7.93	9.51	4.13
Nitrogen oxide	[kg N_2O/month]	282	211	283	22	267	292	340	96	180	198	328	285	263	382	345	287	93	472	566	246
Total emission	[kgCO2e)	22 682	16 963	22 742	1 807	21 495	23 487	27 355	7 735	14 448	15 896	26 369	22 931	21 117	30 739	27 751	23 090	7 493	37 964	45 544	19 754

Scenario 2.1 Result parameters	Value	Unit
Emission according to distance [kgCO_2e/km]	1.0740306	[kgCO_2e/km]
Total distance	407215	[km]
Total Carbon dioxide Emission	431 830	[kg CO_2]
Total Methane Emission	91.35	[kg CH_4]
Total Nitrogen oxide Emission	5 440	[kg N_2O]
Total CO_2-equivalent	437 361	[kgCO_2e)
Average cost per kilometer	4.95	[zł/km]

Tab. 5.10 2.2 Scenario result parameters evaluated in the simplified CF assessment approach supported by Low Data Quality model

Source: own elaboration.

		Scenario 2.2 - Distance rise according to change of central warehouse (MC001) location from post code 86-160 (Warlubie) to Central-PL, post code 95-040 (Stryków) and change of age of the vehicle -5 years																			
Parameter	Unit	Vehicle 1	Vehicle 2	Vehicle 3	Vehicle 4	Vehicle 5	Vehicle 6	Vehicle 7	Vehicle 8	Vehicle 9	Vehicle 10	Vehicle 11	Vehicle 12	Vehicle 13	Vehicle 14	Vehicle 15	Vehicle 16	Vehicle 17	Vehicle 18	Vehicle 19	Vehicle 20
GVM	[kg]	40000	40000	40000	40000	40000	40000	26000	26000	26000	40000	40000	40000	40000	40000	40000	40000	26000	26000	26000	40000
Vehicle age [years]	[years]	4	11	4	10	2	7	8	11	5	8	10	4	6	9	11	10	4	9	11	1
Distance	[km/month].	21731	15404	21788	1641	20978	21899	25280	7024	13716	14690	23945	21969	19867	28158	25200	20967	7179	34776	41357	19646
Carbon dioxide	[kg CO_2/month]	20 957	16 166	21 012	1 707	19 834	22 155	25 814	7 372	13 357	15 000	24 904	21 187	19 723	29 019	26 447	21 806	6 923	35 839	43 404	18 575
Methane	[kg CH_4/month]	4.43	3.42	4.45	0.36	4.20	4.69	5.46	1.56	2.83	3.17	5.27	4.48	4.17	6.14	5.59	4.61	1.46	7.58	9.18	3.93
Nitrogen oxide	[kg N_2O/month]	264	204	265	22	250	279	325	93	168	189	314	267	248	366	333	275	87	451	547	234
Total emission	[kgCO2e)	21 226	16 373	21 281	1 729	20 088	22 438	26 145	7 466	13 528	15 192	25 223	21 458	19 976	29 391	26 786	22 086	7 012	36 299	43 960	18 813

Scenario 2.2 Result parameters	**Value**	**Unit**
Emission according to distance [kgCO_2e/km]	1.0227268	[kgCO_2e/km]
Total distance	407215	[km]
Total Carbon dioxide Emission	411 202	[kg CO_2]
Total Methane Emission	86.99	[kg CH_4]
Total Nitrogen oxide Emission	5 180	[kg N_2O]
Total CO_2-equivalent	416 470	[kgCO_2e)
Average cost per kilometer	4.86	[zł/km]

In order to better understand the results obtained from the CF level assessment using the LDQ model, the following **Fig. 5.5** was developed. Similarly to the HDQ model, kgCO_2e/km coefficient is an important criterion to verify the in relation to the total distance travelled.

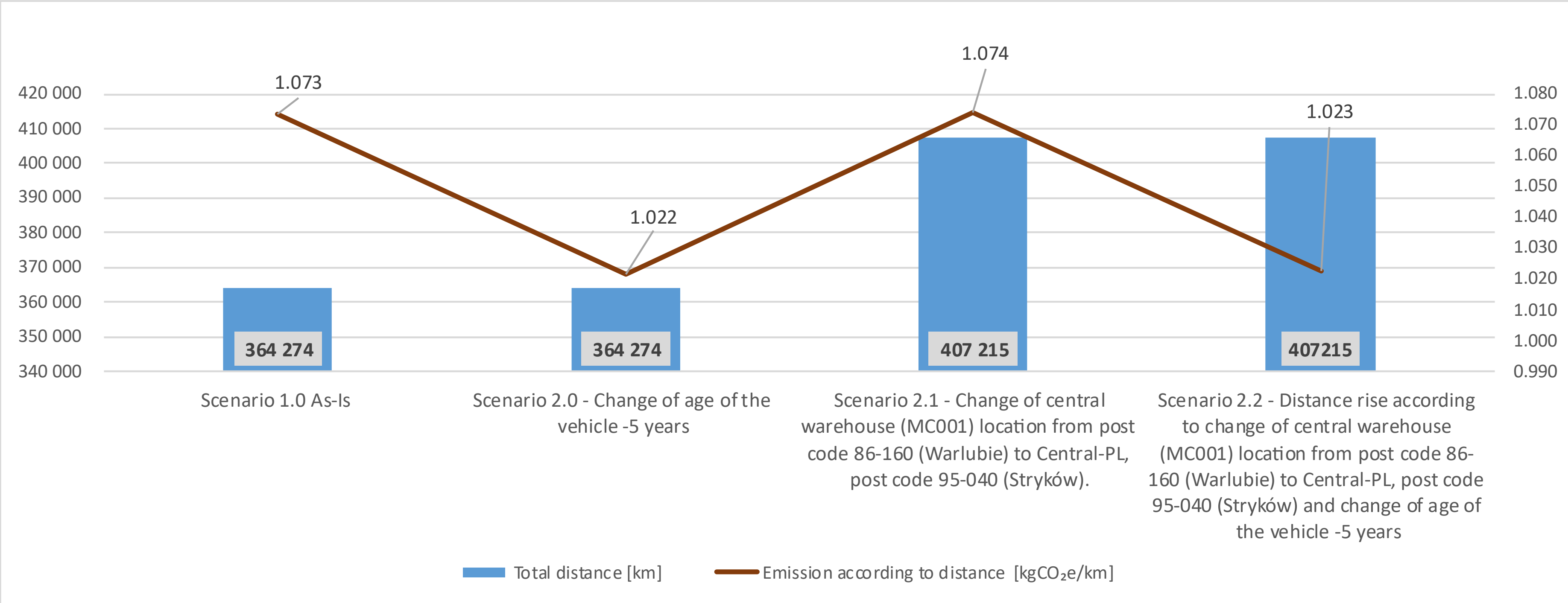

Fig. 5.5 Simplified approach - LDQ model - Total road emission level [kgCO_2e] vs. emission per km ratio [kgCO_2e/km]
Source: own elaboration.

Subsequently, the obtained results with LDQ CF assessment model were compared to the results obtained with HDQ CF assessment model in order to determine the level of discrepancy between the two models.

Detailed approach supported by the HDQ model and simplified approach supported by the LDQ model comparison

The comparison of the results aims to indicate the possible level of tolerance of each approach. Knowledge of the level of inaccuracy arising from generalisations or the adoption of specific assumptions in the LDQ model can support the determination of the level of uncertainty for the substantive contribution to company emissions reports prepared in accordance with ISO 14064 and GHG Protocol guidelines. For more details, see uncertainty level determination under ISO 14064 presented in **chapter 2.1**.

It was decided to compare the results obtained from the CF assessment performed by both models. A comparison was possible for scenarios 1.0, 2.0, 2.1 and 2.2. Due to the structure of the LDQ, CF assessment mode only ten vehicles of different types could be assessed at one time, hence presented below comparison structure reflect this limitation. The scope of the HDQ and LDQ results comparison is presented in **Tab. 5.11**, **Tab. 5.12**, **Tab. 5.13**, **Tab. 5.14** below.

Tab. 5.11 As Is 1.0 Scenario - Comparison of carbon footprint assessment results by the HDQ model and the LDQ model
Source: own elaboration.

	"As Is" Scenario 1.0 for both HDQ and LDQ models			
	High Data Quality model - Detailed CF Assessment approach results		Low Data Quality model - Simplified CF Assessment approach results	
	Trucks 1 - 10 emissions [$kgCO_2e$]	Trucks 11-20 emissions [$kgCO_2e$]	Trucks 1 - 10 emissions [$kgCO_2e$]	Trucks 11-20 emissions [$kgCO_2e$]
	18 101	20 580	21 635	24 012
	13 992	18 994	16 897	22 800
	17 390	17 211	20 991	21 302
	1 490	21 786	1 807	25 038
	17 316	19 319	20 994	21 483
	20 307	17 140	22 766	19 891
	21 851	4 373	27 435	4 498
	6 547	26 944	7 735	28 255
	12 410	36 999	14 398	37 419
	12 844	14 141	15 912	15 701
Partial sum of CF per vehicle group [$kgCO_2e$]	142 249	197 489	170 572	220 399
Total road transport emissions per CF assessment approach [$kgCO_2e$]		339 738		390 971

Difference between CF assessment models	*15.08%*

The result obtained for the as-is 1.0 baseline scenario indicates a difference of 15.08% between the LDQ and HDQ models. This level of uncertainty should be reported in accordance with ISO 14064. Details of the reporting of discrepancies under the norm are presented in **Tab. 2.6** in **chapter 2.1.**

Tab. 5.12 Scenario 2.0 - Comparison of carbon footprint assessment results by the HDQ model and the LDQ model
Source: own elaboration.

	HDQ Scenario 2.0 vs. LDQ Scenario 2.0 Comparison - "Change of age of the vehicles -5 years"			
	High Data Quality model - Detailed CF Assessment approach results		Low Data Quality model - Simplified CF Assessment approach results	
	Trucks 1 - 10 emissions [$kgCO_2e$]	Trucks 11-20 emissions [$kgCO_2e$]	Trucks 1 - 10 emissions [$kgCO_2e$]	Trucks 11-20 emissions [$kgCO_2e$]
	17 211	19 741	20 246	22 968
	13 389	18 061	16 310	21 336
	16 535	16 454	19 643	20 151
	1 430	20 815	1 729	23 940
	16 492	18 486	19 620	20 736
	19 364	16 442	21 750	19 026
	20 857	4 158	26 221	4 209
	6 265	25 743	7 466	27 016
	11 813	35 404	13 482	36 117
	12 260	13 404	15 208	14 953
Partial sum of CF per vehicle group [$kgCO_2e$]	135 616	188 709	161 675	210 452
Total road transport emissions per CF assessment approach [$kgCO_2e$]		324 324		372 127

Difference between CF assessment models	*14.74%*

The level of difference between the HDQ and LDQ models, at 14.74%, is very close to the as-is baseline 1.0 scenario. This value allows us to assume that the change od vehicle's age introduced in the scenarios do not increase significantly the difference between the models. Hence, it indicates that the model works correctly when the vehicle age parameter is changed.

Tab. 5.13 Scenario 2.1 - Comparison of carbon footprint assessment results by the HDQ model and the LDQ model
Source: own elaboration.

	HDQ Scenario 2.1 vs. LDQ Scenario 2.1 Comparison - "Central Warehouse location change"			
	High Data Quality model - Detailed CF Assessment approach results		Low Data Quality model - Simplified CF Assessment approach results	
	Trucks 1 - 10 emissions [$kgCO_2e$]	Trucks 11-20 emissions [$kgCO_2e$]	Trucks 1 - 10 emissions [$kgCO_2e$]	Trucks 11-20 emissions [$kgCO_2e$]
	19 169	22 708	22 682	25 223
	14 036	19 080	16 963	21 458
	18 879	17 089	22 742	19 976
	1 490	26 443	1 807	29 391
	17 644	24 310	21 495	26 786
	20 938	19 667	23 487	22 086
	21 799	6 904	27 355	7 012
	6 547	35 922	7 735	36 299
	12 453	44 832	14 448	43 960
	12 827	17 106	15 896	18 813
Partial sum of CF per vehicle group [$kgCO_2e$]	145 783	234 062	174 610	251 002
Total road transport emissions per CF assessment approach [$kgCO_2e$]		379 845		425 612

Difference between CF assessment models	*12.05%*

The 12.05% difference obtained in scenario 2.1 between the HDQ and LDQ models indicates a comparable level of difference with respect to the baseline scenario 1.0. The change in location using the detailed and simplified models does not show any anomalies that could undermine the reliability of the CF evaluation results obtained.

Tab. 5.14 Scenario 2.2 - Comparison of carbon footprint assessment results by the HDQ model and the LDQ model

Source: own elaboration.

	HDQ Scenario 2.2 vs. LDQ Scenario 2.2 Comparison - "Central Warehouse location change" & "Change of age of the vehicles -5 years"			
	High Data Quality model - Detailed CF Assessment approach results		Low Data Quality model - Simplified CF Assessment approach results	
	Trucks 1 - 10 emissions [$kgCO_2e$]	Trucks 11-20 emissions [$kgCO_2e$]	Trucks 1 - 10 emissions [$kgCO_2e$]	Trucks 11-20 emissions [$kgCO_2e$]
	18 227	21 782	21 226	25 223
	13 431	18 142	16 373	21 458
	17 952	16 338	21 281	19 976
	1 430	25 264	1 729	29 391
	16 805	23 262	20 088	26 786
	19 966	18 865	22 438	22 086
	20 807	6 565	26 145	7 012
	6 265	34 320	7 466	36 299
	11 854	42 899	13 528	43 960
	12 243	16 214	15 192	18 813
Partial sum of CF per vehicle group [$kgCO_2e$]	138 978	223 653	165 467	251 002
Total road transport emissions per CF assessment approach [$kgCO_2e$]	362 631		416 470	

Difference between CF assessment models	*14.85%*

The combination of the change in the location of the central warehouse and the age of vehicles in scenario 2.2 results in a difference of 14.85%, which is very close to the baseline scenario 1.0. This result indicates a high reliability of the CF assessment using both models in a situation of change in location and age. **When using the LDQ model to report a company's distribution transport carbon footprint level, the average uncertainty level of 14.18% should be considered** in calculation in accordance with the ISO 14064 guidelines (see **Tab. 2.6**). The value of 14.18% is derived by averaging the difference levels calculated in scenarios 2.2. 2.1. 2.0 and 1.0. The results obtained indicate that the calculation models function correctly and are capable of considering various changes in the control parameters without abnormal impact of the evaluation quality. It has been proved that both LDQ and HDQ calculation models can be used to assess the CF level within the distribution supply chains.

5.3. Multi-Criteria Decision Making analysis

In accordance with the defined foundations of the Multi-Criteria Decision Analysis (MCDA) method, indicated in **chapter 4.3** the following steps were conducted during the validation. Each of the criteria was assigned an appropriate level of significance, depending on the selected scenario. For this purpose, a Likert scale was used according to Triantaphyllou (2000) research. A **Tab. 5.15** below shows all the criteria ratings for each scenario. The complete multi-criteria evaluation matrix sheet is available in **Appendix 9 - MCDA Matrix.xlsx**

Tab. 5.15 Criteria importance assessment according to Likert Scale
Source: own elaboration.

		Scenarios						
Criteria	Likert Scale	1.0	2.0	2.1	2.2	3.0	3.1	3.2
Total road transport emissions	1-5	5	5	5	5	5	5	5
Total distance	1-5	5	5	5	5	5	5	5
Emissions indicator [$kgCO_2e/m^3$]	1-5	4	4	4	4	4	4	4
Emissions indicator [$kgCO_2e/kg$]	1-5	4	4	4	4	4	4	4
Average fleet age	1-5	3	3	3	3	3	3	3
Sustainable packaging	1-5	3	3	3	3	3	3	3
Average cost per kilometer	1-5	5	5	5	5	5	5	5
Fleet downtime rate	1-5	2	2	2	2	2	2	2
Risk of damage to goods	1-5	2	2	2	2	2	2	2
Fleet availability	1-5	1	1	1	1	1	1	1
Carrier flexibility	1-5	1	1	1	1	1	1	1
Total value per scenario		35	35	35	35	35	35	35

The values incorporated into the matrix were determined on the basis of the expert study presented in **chapter 3.2**. The choice of criteria weights is based on individual user preferences. however, the validation of the CF evaluation model outlined their significance based on the evaluation of the responses obtained in the Expert Research and the importance of each criterion as described in the literature reviewed. However, the parameters should be regarded as indicative, as they were introduced solely for the purpose of validation, to verify whether the CF assessment model functions correctly. Following the determination of the significance of the parameters, their individual weights were calculated. In order to ensure the correct calculation of the weights, **Formula 14** was used. It was important to ensure that the sum of all weights was equal to 1. **Tab. 5.16** below presents the detailed weights of all individual criteria.

Tab. 5.16 Criteria weight calculation based on provided importance level
Source: own elaboration.

Criteria	Likert Score	Calculated weight
Total road transport emissions [$kgCO_2e$]	5	0.143
Total distance [km]	5	0.143
Average emissions indicator for all product groups [$kgCO_2e/m^3$]	4	0.114
Average emissions indicator for all product groups [$kgCO_2e/kg$]	4	0.114
Average fleet age [years]	3	0.086
Introduction of more efficient and sustainable packaging	3	0.086
Average cost per km [Currency/km]	5	0.142
Fleet downtime rate [days/month]	2	0.057

Criteria	Likert Score	Calculated weight
Risk of damage to goods due to quality of carrier's means of transport	2	0.057
Fleet availability	1	0.029
Carrier flexibility	1	0.029
Total value	35	1

Subsequently, the parameters derived from the HDQ and LDQ models were incorporated into the multi-criteria assessment matrix. The choice of parameter sources followed the guidelines provided in **Tab. 4.8**, presented in **chapter 4**. According to the higher reliability of the HDQ model, it was prioritized as the primary source of criteria values. The LDQ CF assessment model was used as a source of information on costs. The result of the calculations performed with the support of the LDQ model was used as the source of the 'Average cost per kilometre' parameter value.

In addition to the criteria calculated by the models, the multi-criteria assessment allows for the consideration of qualitative parameters. A five-point scale was used to introduce the values of qualitative parameters not calculated by the LDQ and HDQ models:

1 - Very unlikely
2 - Unlikely
3 - Neutral / Possible
4 - Likely
5 - Very likely / Almost certain

The quality parameters considered in the validation include:

- Sustainable Packaging - the consideration of a new type of packaging in the analysed scenarios was marked as '1' in the multi-criteria analysis, while '0' indicates that this type of packaging was not used.
- Fleet downtime rate - a quality parameter that can be defined by the user based on his experience of cooperation with a transport operator or on the assumptions made. The higher the value of the criterion, the lower the final score.

- Risk of damage to goods due to quality of carrier's means of transport - The quality of means of transport often affects the cost of freight. However, as the quality of means of transport decreases, the risk of damage to the transported products increases. In this way, the user of the multi-criteria evaluation matrix has the opportunity to take this parameter into account in the decision-making process. The higher the value of the criterion, the lower the final score.

- Fleet availability - fleet availability is an important parameter in cooperation with transport operators and when using own fleet. The response time of the transport operator to transport needs is an important quality element, subject to negotiation and recorded in service level agreements (SLA). The higher the value of the criterion, the higher the final score.

- Carrier flexibility - The operator's flexibility parameter is an unmeasurable criterion that affects the quality of cooperation. A change of loading location, or unloading time, can often occur in distribution processes. The flexibility of the transport operator contributes to the sustainable development of distribution supply chains. Therefore, it was decided to include this quality parameter in the model validation. The higher the parameter value, the higher the final score.

Tab. 5.17 Input of criteria's actual values calculated with HDQ and LDQ models
Source: own elaboration.

		Scenarios						
Criteria	Weight	1.0	2.0	2.1	2.2	3.0	3.1	3.2
Total road transport emissions	0.143	339 738	324 324	379 845	362 631	337 601	322 283	360 350
Total distance	0.143	364 274	364 274	407 215	407 215	364 274	364 274	407 215
Emissions indicator [$kgCO_2e/m^3$]	0.114	5.6812	5.4234	6.3518	6.0640	6.3400	6.0554	6.7706
Emissions indicator [$kgCO_2e/kg$]	0.114	0.0077	0.0074	0.0086	0.0083	0.0086	0.0082	0.0092
Average fleet age	0.086	12.25	7.25	12.25	7.25	12.25	7.25	7.25
Sustainable packaging*	0.086	0	0	0	0	1	1	1
Average cost per kilometer **	0.142	4.69 zł	4.63 zł	4.95 zł	4.86 zł	4.69 zł	4.63 zł	4.86 zł
Fleet downtime rate ***	0.057	3	1	3	1	3	1	1
Risk of damage to goods ***	0.057	2	1	2	1	2	1	1
Fleet availability ***	0.029	5	5	4	4	5	5	4
Carrier flexibility ***	0.029	5	5	4	4	5	5	4
Total Score (∑ weighted values)	1.00							

** For quality criteria such as* ***introduction of more sustainable packaging, that is*** *more suitable for the goods, please consider '1' for parameter exist in scenario, and '0' for parameter doesn't exist in scenario.*

*** Due to limitations of LDQ model scenarios 3.0, 3.1 and 3.2 could not consider introduction of sustainable packaging. Hence average costs per kilometre are taken from parallel scenarios: 3.0 - 1.0, 3.1 - 2.0, 3.2 - 2.2*

**** For other* ***quality criteria*** *that requires user to assign the score please use grades presented below:*
1 - Very unlikely
2 - Unlikely
3 - Neutral / Possible
4 - Likely
5 - Very likely / Almost certain

The next **Tab. 5.18** shows the calculated parameter values, with the consideration of the previously defined weights. The logic of the calculation formulas embedded in the spreadsheet presented in **Appendix 9 - MCDA Matrix.xlsx** considers the beneficial impact of higher values of quality parameters related to the use of sustainable packaging and greater operator flexibility. Simultaneously, it takes into account the negative impact of an increase in the values of parameters indicating fleet failure and the risk of damage to goods.

Tab. 5.18 Calculation of result parameters according to defined weights and actual criteria values
Source: own elaboration.

		Scenarios						
Criteria	Weight	1.0	2.0	2.1	2.2	3.0	3.1	3.2
Total road transport emissions	0.143	-1.51%	-2.09%	0.00%	-0.65%	-1.59%	-2.17%	-0.73%
Total distance	0.143	-1.51%	-1.51%	0.00%	0.00%	-1.51%	-1.51%	0.00%
Emissions indicator [$kgCO_2e/m^3$]	0.114	-1.83%	-2.27%	-0.71%	-1.19%	-0.73%	-1.20%	0.00%
Emissions indicator [$kgCO_2e/kg$]	0.114	-1.83%	-2.27%	-0.71%	-1.19%	-0.73%	-1.20%	0.00%
Average fleet age	0.086	0.00%	-3.51%	0.00%	-3.51%	0.00%	-3.51%	-3.51%
Sustainable packaging	0.086	8.60%	8.60%	8.60%	8.60%	0.00%	0.00%	0.00%
Average cost per kilometer	0.142	-0.75%	-0.93%	0.00%	-0.27%	-0.75%	-0.93%	-0.27%
Fleet downtime rate	0.057	11.40%	0.00%	11.40%	0.00%	11.40%	0.00%	0.00%
Risk of damage to goods	0.057	5.70%	0.00%	5.70%	0.00%	5.70%	0.00%	0.00%
Fleet availability	0.029	0.00%	0.00%	0.58%	0.58%	0.00%	0.00%	0.58%
Carrier flexibility	0.029	0.00%	0.00%	0.58%	0.58%	0.00%	0.00%	0.58%
Total Score	1.00							
Rank		0.182675901	-0.039773205	0.254497643	0.029496892	0.118049588	-0.10526045	-0.033566331

The following **Tab. 5.19** presents a summary of the most important parameters of the scenarios used in the validation and a synthetic summary of the scenarios. The assessments result directly from the final values of each scenario, calculated and presented in **Tab. 5.18**. A value of 1 represents the best scenario, while a value of 7 represents the worst scenario. The assessment was conducted using the multi-criteria assessment matrix provided in **Appendix 9 - MCDA Matrix.xlsx.**

Tab. 5.19 Scenarios final assessment ranks

Source: own elaboration.

	Scenarios						
Parameter	1	2	2.1	2.2	3	3.1	3.2
Scenario description	As-Is	- Change of age of the vehicle -5 years	- Change of central warehouse (MC001) location from post code 86-160 (Warlubie) to Central-PL, post code 95-040 (Stryków).	- Change of age of the vehicle -5 years	- Use of sustainable packaging reducing the weight and volume of transported goods by 11%	- Use of sustainable packaging reducing the weight and volume of transported goods by 11%	- Use of sustainable packaging reducing the weight and volume of transported goods by 11%
				- Change of central warehouse (MC001) location from post code 86-160 (Warlubie) to Central-PL, post code 95-040 (Stryków).		- Change of age of the vehicle -5 years	- Change of age of the vehicle -5 years
							- Change of central warehouse (MC001) location from post code 86-160 (Warlubie) to Central-PL, post code 95-040 (Stryków).
Rank	6	2	7	4	5	1	3

The use of the proposed multi-criteria analysis proved the usefulness of the proposed CF assessment model. Both LDQ and HDQ models enable the conducted assessment of emission levels within the distribution supply chain. Simultaneously, cost parameters and additional user-defined quality parameters can be taken into account. Based on the defined criteria significance and the weights calculated, the most advantageous direction of change from a management perspective was determined. Scenario 3.1, assuming a change in packaging types, resulting in better utilisation of vehicle load space and a 5-year reduction in the age of the fleet, resulted in the greatest benefit for the distribution supply chain. Not only cost parameters were given consideration, but also emissions and quality parameters.

The conducted calculations using the HDQ CF assessment model identified that changing the location of the central warehouse (MC001), taking into account the current locations of customers and warehouses, would increase the overall distance travelled. This would have a direct impact on emissions and costs increase.

A conducted comparison of the results obtained in the LDQ and HDQ models showed discrepancies in the calculated CF level between 12.05% and 15.08%. The predictable level of discrepancy allows for its proper reporting in accordance with the guidelines of ISO 14 064:2018. The detailed model (HDQ) allows for precise estimation of emission levels due to the structure of emission factors published by UK DEFRA. Depending on the vehicle's load, a different Defra's emission factor is used. The simplified model (LDQ) does not consider the volume or weight of goods transported, therefore the results obtained will not be as detailed as in the case of the HDQ CF assessment model.

Conducted research has resulted in the development of a CO_2 assessment model and a complete approach for carbon footprint (CF) measurement and management. It is supported by dedicated computational models (HDQ and LDQ), designed to determine the carbon footprint of transport processes within existing enterprises. Process efficiency analyses of supply chains from an emission perspective are possible with the support of the proposed solution. The findings specify the reporting requirements for companies, define the scope of necessary data, and propose an environmental performance indicator for distribution processes that can be incorporated into existing KPI sets. The model not only calculates GHG emissions in CO_2 equivalents but also provides insights into energy efficiency and the utilisation of transport resources, offering an objective measure of the technological advancement of the supply chain and process effectiveness. The CF assessment results can be applied in multi-criteria decision analysis (MCDA) to support the management of transport processes within sustainable supply chains. This creates opportunities for improving transport processes and for designing strategies for CO_2 emission management across the entire supply chain.

The validation of a new CF assessment model in terms of process analysis identified that it can be applied in distribution supply chains. The presented example of a distribution process and the indicated possibilities of adapting the new model within the distribution supply chain management process indicate the high utility value of the developed CF assessment model. Depending on the characteristics of a specific supply chain, the model is also flexible sufficiently to be adapted to the actual requirements of the actual organisation.

Limitations of the proposed approach

The current HDQ model for assessing the CF of transport processes enables the performance of simulations within the territory of Poland. This is due to the embedded distance grid, which, owing to its high level of detail, considerably influences the spreadsheet’s computing capacity. Consequently, it is necessary to supply the model with data on postal codes and distances only for those countries where transport orders have been identified during process analysis. Adding information on countries in which no transport has been carried out would negatively affect the stability of the HDQ assessment model and reduce the efficiency of its evaluation.

The complexity of the HDQ CF assessment models requires the use of data of very high quality. Supply chains in which detailed data are not available must carry out the evaluation using the LDQ CF assessment model. The use of the LDQ CF assessment model necessitates the adoption of assumptions regarding monthly mileage, which increases the level of uncertainty defined in ISO 14064:2018 (**chapter 2.1** , **Tab. 2.6**). The application of the LDQ model does not allow for the determination of emissions for individual products, product groups, or specific locations within the supply chain.

In conclusion, the main limitations of the proposed approach to CF assessment stem from the quality and availability of data on transport processes. A further important limitation concerns the computational efficiency of the HDQ CF assessment model when postal codes from multiple countries are incorporated.

6. Conclusions and further research

The conducted research allowed the complete the achievement of the stated **scientific, cognitive and utility aims.** Furthermore, it was possible to formulate answers to all the research questions posed. As a result of the in-depth literature and empirical research conducted, the limitations of the current research were also pointed out and further directions were indicated.

The defined **scientific aim** to establish a *holistic CO_2 emissions management model within supply chains, taking into account the emissions generated by transport processes involving heterogeneous fleets* has been fully achieved. The literature review on sustainability in supply chains conducted in **chapter 1.1** allowed for the identification of the boundary conditions necessary for the operation of CF management model. Based on the essential parameters for controlling CO_2 emissions presented in **chapter 1.1**, the key factors were grouped into the following categories: Road, Traffic, Cargo, Fleet, and Fuel. The review of these parameters is presented in tabular form **in Tab. 3.1, Tab. 3.2, Tab. 3.3, Tab. 3.4, Tab. 3.5**. The research presented in **chapter 3.3** demonstrates the influence of vehicle age on emission levels. The proposed calculation **Formula 13** for estimating emissions from a heterogeneous fleet incorporates vehicles with different gross vehicle masses and ages. The findings from the literature review, together with the identified boundary conditions and the parameters regulating transport processes, have led to the development of a new model for assessing the carbon footprint of transport processes, presented in **chapter 4.**

The **cognitive aim** focused on *identification of a key sustainable supply chain parameters influencing changes in CO2 emissions resulting from transport processes both in literature and real market conditions* has been realised in two ways. During the literature review, key parameters were identified whose occurrence and values may influence both the design of sustainable supply chains and their efficiency. The identification of parameters was carried out through an in-depth analysis of the literature on the key parameters that had to be included in the new model for assessing the CF of transport processes presented in **chapter 4**.

The analysis of the Triple Bottom Line concept conducted in **chapter 1** indicated the "Environmental Responsibility" dimension within sustainable supply chains, where there is a need to reduce emissions and to use resources efficiently. These elements were included in the logic of the new CF assessment model for transport processes. The SWOT analysis of sustainable supply chains presented in **Tab. 1.1** highlighted their strengths, including a high capacity for adaptation and flexibility depending on variable external parameters. However, any change in the distribution transport process requires a detailed assessment, which can be carried out from the perspective of evaluating the change in emission levels. A significant opportunity for the development of sustainable supply chains is the integration of risk management as well as a legal environment supporting such solutions. Currently, many enterprises are eager to implement Green Supply Chain Practices, whose main task is the mitigation of emissions resulting from transport processes and the overall environmental impact of operations.

The analysis of threats pointed mainly to the lack of sufficient research focused on methods supporting sustainable development of distribution supply chains. According to literature research, it is common for developing countries that the implementation of sustainability may have a limited or chaotic character, potentially leading to results opposite to those intended. There is also a risk of greenwashing. The structure of the proposed new CF assessment model seeks to minimise risks defined in the weaknesses and threats arising from the specifics of sustainable distribution supply chains.

In addition to the literature studies, a series of empirical studies was also conducted. The expert study, presented in **chapter 3.2**, helped to determine the significance of the identified parameters. Precise significance values of individual parameters are presented in **Tab. 3.11** and **Tab. 3.12**. Vehicle parameters were also empirically verified. Based on data from a real distribution company, the impact of Gross Vehicle Mass (GVM) and vehicle age on changes in fuel consumption levels was verified. On this basis, the use of appropriate calculation formulas was proposed for heterogeneous fleets (**Formula 13**) and homogeneous fleets (**Formula 12**). Subsequently, the impact of packaging on the efficiency of the distribution transport process was verified. In **chapter 3.4**, real data were used to examine the impact of loading units on the demand for transport resources. **Tab. 3.25** shows how the application of different types of packaging, tailored to the specifics of the transported goods, may influence the achieved level of emissions. Consequently, the model logic presented in Chapter 4 enabled the inclusion of packaging parameters in the HDQ CF assessment model. In the validation presented in **chapter 5,** the impact of the use of tailored packaging reducing cargo volume on the overall level of emissions was determined. The scope of scenarios considering the application of alternative packaging is presented in **Tab. 5.3.**

The **utility aim,** *'Development of a CF assessment approach supported by the holistic computational model within sustainable supply chains'*, was fully accomplished. The research also enabled the creation of a holistic computational model designed to support CF assessment in transport processes. Owing to variations in the quality of process data, it was necessary to develop separate computational models. The model intended for CF assessment within low quality data supply chains was termed the Low Data Quality CF Assessment model (LDQ). Its detailed logic is presented in **Tab. 4.6.** The detailed LDQ model parameters identified through both literature (in **chapter 1** and **chapter 2**) and empirical research (**chapter 3**) were applied in the CF assessment process. These are provided in **Tab. 4.3** and **Tab. 4.4**.

Chapter 4 outlines the recommendations for employing both of the models. The logic for applying the LDQ model is presented in **Fig. 4.7**, while the use of the HDQ model is outlined in **Fig. 4.6.** The scope of CF assessment of distribution transport processes supported by each model is shown in **Tab. 4.1**. Although both models enable the evaluation of CF level, their operation is complementary. The HDQ model facilitates the calculation of precise emission values per product, commodity group, carrier. The LDQ model allows for linking CF levels to individual vehicles, but it does not provide the emission data for products or product groups. A key advantage of the LDQ model lies in its ability to establish cost levels and integrate the cost parameter into subsequent MCDA analysis, thereby supporting the decision-making process.

The research identified several key factors influencing changes in transport emissions within distribution supply chains. The study showed that the Triple Bottom Line (TBL) concept can serve as a foundation for a new approach to carbon footprint (CF) assessment. This has been outlined in **chapter 1**. Potential of introducing CF management of distribution transport processes has been presented in **Fig 1.1**. Therefore, any new CF assessment model should integrate both environmental responsibility and the economic interests of stakeholders in distribution supply chains. It has been revealed based on literature review, that sustainable supply chains are characterized by diversity, transparency, and a strong willingness to improve, which creates an opportunity to introduce such a model (**chapter 1.1**). The literature review also highlighted key features of a Sustainable Supply Chain Management for emission-focused transport management that may affect the efficiency of transport processes (**Fig 1.3**).

Scientific input

The literature review and empirical research carried out have resulted in a valuable research contribution. Important research step was to identify the main drivers behind measuring and managing emissions in distribution supply chains. Legal frameworks and quality standards largely determine how final greenhouse gas (GHG) reports are presented. At the same time, stakeholders, business owners, and managers continuously seek to improve process efficiency, and more effective CF management can support this goal. Local communities and stakeholders also show interest in Corporate Social Responsibility (CSR) initiatives, which can be addressed through emission reduction and a smaller environmental impact. In addition, developing supply chains often pursue efficiency gains through technological innovation. Investments in digitalizing transport processes can provide access to more detailed data, enabling high-quality CF assessment. To address this, the research proposed a High Data Quality (HDQ) CF assessment model. These motivations were further validated through expert research, which confirmed the findings of the literature review.

The study also included a review of existing methods for carbon footprint management. It was found that widely recognized frameworks such as the GHG Protocol define the essential elements of CF evaluation. The ISO 14064 standard was also identified as a useful reference for dealing with uncertainty and reporting transport-related emissions across different scopes. Furthermore, reliable sources of emission factors were identified, with the UK DEFRA database selected for the new CF model. This database is updated annually by a UK government agency and is freely available what created a proper source of emission factors for a new CF assessment model. Additionally, the European emission regulations and calculation methods were reviewed to ensure that the algorithms embedded in the new HDQ and LDQ (Low Data Quality) models comply with international standards.

The literature review further highlighted that risk management is a critical aspect of transport process management within distribution supply chains. Sustainable supply chains demonstrate relatively high resilience to external changes under risk-control conditions. Accordingly, the new CF model incorporates the impact of risk on potential changes in emission levels. In the model's multi-criteria analysis, users can assess quality parameters, including risk-related factors, using a five-point scale and weighted evaluation.

The study also classified essential parameters influencing emission levels into five categories: road, traffic, cargo, fleet, and fuel. These include gross vehicle weight, fuel type, distance travelled, route topography, and vehicle age. Vehicle wear was shown to directly affect fuel consumption. The research identified an annual growth rate of fuel consumption, which was integrated into both the LDQ and HDQ models. Formulas were also proposed to estimate emissions for homogeneous fleets (vehicles of the same weight and fuel type) and heterogeneous fleets (vehicles of varying weights and different age).

The further research focused on the use of loading units tailored to the type of goods transported. A case study of a biomass processing company showed that improved loading units could reduce transport emissions by increasing vehicle space utilisation. This aspect was incorporated into the CF model, allowing packaging changes to improve vehicle filling rates and lower emissions. The level of transport capacity utilisation and the selection of the appropriate UK Defra emission factor have also been considered in the new CF assessment model. Due to this detailed approach, it has been possible to minimise emission measurement error.

The study verified possibility of introduction of multi-criteria analysis as a decision-support tool for both emission reduction and transport service level selection. The analysis confirmed that it is possible to balance cost, environmental, and quality factors when choosing between Full Truck Load (FTL) and Less than Truckload (LTL) services. A key quality factor identified was fleet availability, which was also included in the multi-criteria framework. It was also possible to include other quality parameters in the multi-criteria analysis based on the flexibility of the subcontractor's fleet. The positive results of the research allowed the inclusion of multi-criteria analysis in the new CF assessment model as the final element supporting the management of transport emissions within the distribution supply chain.

The research carried out provided an answer to **RQ1:** 'How to manage emissions from vehicles in heterogeneous fleets in supply chains?' Managing emissions from vehicles in heterogeneous fleets in supply chains requires a combination of accurate measurement, technological innovation, and strategic optimisation. The research on vehicle parameters within a heterogeneous fleet that influence the dynamics of emission levels is presented in **chapter 3.3**. On the basis of this research, calculation formulas were developed for determining emissions in heterogeneous fleets (**Formula 13**) and homogeneous fleets (**Formula** 12). The study also enabled the determination of a fuel consumption growth coefficient, dependent on vehicle GVM, as shown in **Tab. 3.22**. This can be obtained with proposed CF assessment model. A CF assessment result parameters can be incorporated into decision making process using proposed multi criteria decision matrix and analysis logic presented in **chapter 4.3**. The application of calculation **Formula 14** is essential for determining the weights of the parameters by relating their values to the levels of significance defined by the user. The method of applying the parameters after the determination of their weights, considering alternative scenarios, is presented in **Tab. 4.11**. However, the essential element of management activity is the accurate and continuous collection of data on transport processes. Increasing the technological advancement of processes within the distribution supply chain may positively influence the level of detail for CF assessment and improve the management of emissions from heterogeneous fleet.

In addressing **RQ2**: 'Which sustainable supply chain process parameters are crucial for managing emissions?' it can be concluded that effective management requires balancing social responsibility, environmental awareness, and cost efficiency. This arises from the literature review on the characteristics of sustainable supply chains. The analysis of the Triple Bottom Line approach in **chapter 1** highlighted the significance of these parameters. The key factors relevant from the perspective of emission management are illustrated in **Fig. 1.1**. The dimension of Environmental Responsibility emphasises the importance of waste management, energy efficiency, and emission reduction. However sustainable transport processes can be achieved by optimizing routing and scheduling, which minimize unnecessary distances and improve delivery process, leading to lower fuel use (related research has been presented in **chapter 1.1** in **Tab. 3.5)**. The load factor, indicating how efficiently vehicle capacity is employed, plays a decisive role in determining the emissions produced per trip (as per literature review presented in **chapter 1.1** in **Tab. 3.3)**. Furthermore, traffic conditions play a vital role in CF mitigation, however this parameter is rather out of control in management process (related literature has been aggregated in **Tab. 3.2**). However, there are other parameters that reveal importance in CF management process. The adoption of alternative fuels and low-emission vehicle technologies offers a strategic approach to reducing the long-term environmental footprint of transport activities. Hence, the new CF assessment model enables the evaluation of emissions from alternative fuel powered vehicles. Both the HDQ and LDQ models allow for the verification of emissions from hybrid and electric vehicles. The logic of both models is presented in **Fig. 4.6** and **Fig. 4.7**.

With reference to **RQ 3**: 'How to gather the basic data necessary to assess the carbon footprint of transport processes and coordinate their flow between participants within the supply chain?' the significance of data quality necessary to carry out a CF assessment was identified. In **chapter 2.1** dedicated to the review of emission assessment methods, the importance of data quality levels was demonstrated across various approaches such as CDP, IPCC 2006, ISO 14064:2018, with particular emphasis on the GHG Protocol. The analysis led to the development of **Fig. 2.4**, which illustrates the decision points in the emission assessment process within Scope 1, 2, and 3 of transport activities. **Chapter 4** defines the scope of data necessary to assess emission levels. The data structure and presented validation indicate the scope of data that needs to be collected to enable the execution of carbon footprint management of transport processes. The indicated scope of data should form the foundation for information exchange between participants within sustainable supply chains. Furthermore, this ensures the transparency of processes and increases their resilience in accordance with the conclusions of the conducted literature research (**chapter 1**).

According to **RQ 4**: 'How to ensure the quality of the exchange of basic process data necessary to assess the CO_2 emissions of all sustainable supply chain participants?' the data can be exchanged between supply chain participants in *.xls format as per new CF assessment basic data requirements outlined in **chapter 4.1** in **Fig. 4.10, Fig. 4.11, Fig. 4.12, Fig. 4.13, Fig. 4.14**. However, it is recommended to implement automatic forms of information transfer between the systems of process participants according to review methods (outlined in **chapter 2.1**). This allows for higher process efficiency and enables each participant in the distribution process to react and take action in the event of a sudden increase in emissions. Dynamic data exchange between process participants' IT systems may be supported by Electronic Data Interchange (EDI) protocols enables the updating of detailed process information in real time. The introduction of advanced technology allows for the maintenance of high quality data exchange necessary for assessing the CO_2 level of transport processes.

In reference to **RQ 5**: "What elements should be reflected in a holistic emissions management method supporting the measurement of transport processes?", the conducted research defined the full scope of a holistic approach to CF management. An important element is the process of data collection, quality verification, and improvement. A further important element of the holistic model for managing and measuring the carbon footprint of transport processes within the distribution supply chain is process analysis, which enables the identification of the specific characteristics of the processes involved. Next, depending on the quality of the data, a CF evaluation is carried out. For this purpose, it is possible to use the HDQ CF assessment model for a detailed approach, or the LDQ CF assessment model for a simplified approach. Afterwards, in accordance with the proposed model, the most advantageous configuration of transport processes within the distribution supply chain is analysed. The results obtained in each scenario should be subjected to a multi-criteria assessment. In order to perform this assessment, it is important to designate all important process parameters. Qualitative parameters that are not measured by the calculation models require an indication of their level of significance. Based on an assessment of all scenarios parameters, the most efficient transport process configuration can be identified. It is important to include all five stages presented in **Fig. 4.1** in **chapter 4**.

According to the conducted research, it is recommended that the carbon footprint of transport processes can be reduced through effective management of information flow among supply chain participants. It is further recommended that increasing the technological advancement of transport operations enhances the quality of data required for carbon footprint evaluation and supports more efficient management. According to the most important control parameters, it is recommended to maximize the utilisation of vehicle loading space in order to lower emissions. Matching loading units to the characteristics of the transported goods is also recommended as a practical measure for mitigating the carbon footprint of transport activities. It is also recommended not to change the location of the central warehouse without a comprehensive analysis of recipient locations, transshipment warehouses, and the customer network. The model validation presented in **chapter 5** revealed an increase in emissions resulting from a change of location. In **scenario 2.1**, higher emissions were observed in compare with the as-is situation. Relocating a warehouse without conducting an appropriate analysis of customer locations within distribution supply chains may adversely affect the environmental performance of the supply chain. The comparative results between scenarios are provided in **Tab. 5.19.** Such a change, if not carefully examined, may lead to a substantial rise in CO_2 emissions from transport processes.

Filling the research gap

The defined research gap highlighted the absence of appropriate methods for measuring emissions in sustainable supply chains that also support the decision making process in transport-oriented supply chains. A fundamental requirement for such an approach is the ability to take into account the dynamically changing parameters of heterogeneous fleets. This gap was identified from the literature, which emphasises the continuous pursuit of greater efficiency in transport processes within supply chains. The analysis revealed a lack of methodologies that enable the management of transport operations through a scenario-based approach, which would allow for the identification of the most effective supply chain configuration. Consequently, there is a recognised need to develop a solution that makes it possible to assess CO_2 emissions from transport processes within existing supply chains. Therefore, the proposed CF assessment model must consider the specific characteristics of each supply chain while remaining adaptable to current organisational conditions. At the same time, the increasing complexity of modern supply chains requires the inclusion of multiple control parameters to ensure a detailed assessment of transport-related carbon footprints. This necessity is further underlined by the evolving legal framework, which is gradually introducing regulatory measures to support the decarbonisation of transport processes.

The research gap was filled through a thorough literature review to identify the specifics of sustainable supply chains (**chapter 1**), the logic behind the CO_2 emission measurement principles indicated in international norms and standards (**chapter 2**), and the parameters influencing emission changes (**chapter 3.1**).

Concurrently, the empirical research conducted allowed for the research gap to be entirely covered. The expert research (**chapter 3.2**) determined the importance of control parameters, highlighting the significance of vehicle age, area topography, load weight and volume, and vehicle distance and type. Conducted research influenced the proposed logic of the CF assessment model and decision making process considering environmental parameters presented in **chapter 4**. The proposed Multi Criteria

Decision Making approach allows both quantitative and qualitative parameters to be included in the decision making process. This enables non-measurable parameters to be also considered. The analysis of methods, standards and norms presented in **chapter 2** identified the relevance of the GHG Protocol in defining the logic of CF assessment logic of transport processes. The emission factors proposed by UK DEFRA were identified as a reliable source of the parameters necessary for a CF assessment at a computational model level detailed in **chapter 4.1** for HDQ and in **chapter 4.2** for LDQ. International norm ISO 14064:2018 defines how assessment results should be reported for all scopes (Scope 1, 2 and 3). The new CF assessment model for transport processes enables emissions assessments to be conducted with consideration of both low (LDQ CF assessment model) and high (HDQ CF assessment model) company's basic data quality. Adopting this approach allows transport processes to evolve rather than be revolutionised, and it also responds to the needs of companies, as defined in expert research (**chapter 3.2**). The analysis of European (**Tab. 1.3**) and global (**Tab. 1.4**) legislation presented in **chapter 1.2** has enabled the legal conditions and significance of the new model for CF assessment of transport processes in a regulatory context. The analysis of the results revealed that the defined research gap had been successfully filled.

Filling the application gap

The defined application gap relates to the lack of the sufficient methods that both manage and assess the carbon footprint (CF) of transport processes in sustainable supply chains. The developed new CF assessment model addresses this gap. It meets the legal requirements of the major European acts of law, directives and the reporting standards such as ISO 14064:2018. Defining clear guidelines within the legal framework in **chapter 1.1** and standards was essential to ensure that the proposed solution could be applied in line with current regulations. The analysis of the GHG evaluation step of GHG Protocol presented in **Fig. 2.5** highlighted further steps needed for measuring emissions in supply chains. Simultaneously it supported the identification of recommended sources of reliable emission factors. However, no clear procedures currently exist for assessing emissions in transport processes, as existing standards remain too general and do not explain how emission data should be included in decision-making process. Based on these findings **Fig. 2.5** shows a functional outline of the model for CF management and assessment. Further research allowed the model logic to be developed in detail and presented in **chapter 4** and later validated (**Chapter 5**). Conducted research confirmed its potential for use in real distribution supply chains. The identified application gap has been fully covered, and the practical value of the new CF assessment model has been demonstrated.

Current application of the new CF assessment model for distribution transport processes

The current application of the new model for CF assessment of transport processes is implemented in the professional work of a PhD student, at the Łukasiewicz Research Network - Poznan Institute of Technology. The new CF assessment model, due to its highly applicable character, allows its use in a range of companies where transport process emission assessment is required.

The high variability of actual supply chains and the complexity of transport processes require a flexible approach to assessing the CF level of transport processes. The structure of the new CF assessment model, developed on the basis of process analysis, enables a comprehensive examination of internal dependencies within supply chains. It allows CF levels to be assessed using the HDQ and LDQ computational models. Those allow to perform emission assessments based on low data quality and assumptions. The new CF assessment model also provides the ability to simulate impact on overall CF caused by changes of specific SC control parameters. The verification of effects of such changes on the supply chain in available in scenario-based mode. Overall, the structure of the CF assessment model supports conduction of process efficiency audits within supply chains, enriched with the inclusion of distribution transport related efficiency emission factors.

The **Tab. 6.1** below presents scope of practical usage of the new CF assessment model in the doctoral student ongoing commercial projects at Łukasiewicz Research Network - Poznański Instytut Technologiczny.

Tab. 6.1 Practical application of the new CF assessment model
Source: own elaboration.

Scope of practical usage	A new CF assessment model	
	HDQ CF assessment model	LDQ CF assessment model
Assessment of the CF level of transport processes.	Yes	Yes
Ability to assess CF levels in the lack of detailed process data. Assessment of CF level based on general data and assumptions.	No	Yes
Indicating the optimum location of warehouses, cross docs in relation to the actual and estimated CF level of transport processes	Yes	No
Assessment of the level of CF in reference to the physical form of the products. [kg/litre/m3] of product.	Yes	No
Verification of the efficiency of the use of transport fleet in terms of capacity and weight.	Yes	No
Verification of the impact on the CF level of transport processes as a result of the replacement of combustion vehicles by electric vehicles.	Yes	Yes
Verification of the change in age of heterogeneous fleet vehicles on CF level and operating costs	No	Yes

The new CF assessment model has proven its practical value. Elements of the model are used in commercial projects focused on analysing the efficiency of transport processes in companies. The new CF assessment has been used in following analysis conducted within Łukasiewicz-PIT:

- For assessing the efficiency of current liquid fuel supply chains. Due to the possibility of using the HDQ model, it is possible to take into account the specific characteristics of products in terms of their volume and weight. The high dynamics of changes in fuel loading and unloading locations on a daily basis are reflected in the proposed CF assessment model.
- For assessing the efficiency of companies' own fleets utilisation. Verification of emissions indicator by product group, weight or volume points to the most advantageous configuration of distribution supply chains.
- For food industry CF emission level evaluation. The new CF assessment model is used to determine the emission level of transport processes oof food products. Based on the results obtained, it is possible to identify the most advantageous option for the organisation of the distribution supply chain. Detailed parameters calculated by the HDQ model enable the calculation of emissions per 1 kilogram of food product.
- For verification of the efficiency of the location of main warehouses in the logistics model. The new CF assessment model enables quick verification of the validity of changes in the location of selected warehouses within the distribution supply chain. Thanks to the ability to dynamically re-calculate the distance between defined locations and customers, it is possible to quickly verify the increase or possible decrease in costs related to the execution of transport processes. In the case of supply chains with limited access to historical data, the model allows for the assessment of the CF level, taking into account the relevant supply chain parameters defined in the research and indicated by experts.
- For preparation of emission parameters for the ESG report. Calculations can be made on the foundation of the assumed average monthly distance in the LDQ CF assessment model. The collected information, similar to that calculated using the HDQ CF assessment model, can be used as a substantive contribution to the ESG report. Thanks to the conducted model validation, which identified an average calculation error, a difference level of 14.18% (underestimation of the CF assessment result for transport processes) can be assumed for the results obtained from the LDQ model.

Commercialisation and application potential of the proposed new CF assessment model

The defined practical functionality of the new CF assessment model, partly shown in **Tab. 6.1**, indicates the potential for application of the model in specific companies of different types. The new

CF assessment model can be applied to a wide range of companies that carry out transport processes. It is particularly relevant for logistics service providers, freight forwarders and distribution companies that are responsible for controlling and managing current, complex supply chains with heterogeneous fleets. However, the model can also benefit manufacturing and retail enterprises, as it enables the monitoring and optimisation of emissions within their distribution networks. Furthermore, the presence of both calculation models, HDQ and LDQ, enables the assessment of emission levels within supply chains based on one's own fleet, an outsourced fleet, or a combination of both. The new CF assessment model can be used by e-commerce companies, where high transport intensity and frequent deliveries increase the need for effective emission management. For e-commerce-oriented distribution supply chains, HDQ CF assessment can be applied due to its detailed approach focused on specific transport orders. The new CF assessment model may also be adopted by energy, food and consumer goods companies with extensive distribution operations, as well as third-party logistics (3PL) and fourth-party logistics (4PL) providers, who manage transport on behalf of clients. Furthermore, the model can support any organisation that intends to align its transport operations with sustainability goals and comply with global regulations concerning carbon reporting and its mitigation. The following **Fig. 6.1** shows example sectors in which the new CF assessment model can be applied.

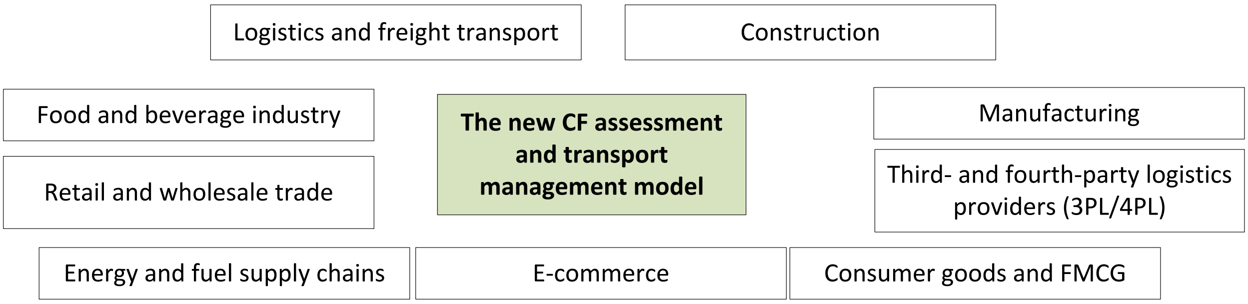

Fig. 6.1 Potential application of the new CF assessment model in specific sectors
Source: own elaboration.

The application of the new CF assessment model can be used to assess the level of CF and manage transport processes using other modes of transport. However, this requires further research according to the logic defined in **Fig. 6.2**.

Research boundaries

The conducted literature review focused on the consideration of sustainable development elements, sources of motivation, and methods for measuring and managing emissions within the supply chain. Simultaneously, the most important international standards and legal acts regulating the measurement and reporting of carbon footprints within distribution supply chains were also reviewed. Further literature research could be conducted towards the main barriers to carbon footprint mitigation in areas of the economy not covered by the expert research.

In the further research the expert research could be extended. The 71 experts who participated in the research allowed only three sectors of the economy to be fully verified:
A - Agriculture, Forestry, and Fishing
C – Manufacturing
H – Transportation and Storage
The perspective of the significance of supply chain parameters for experts from the following industries could be particularly interesting:
B - Mining and quarrying
E - Water supply; sewerage, waste management and remediation activities
G - Wholesale and retail trade; repair of motor vehicles and motorcycles
In subsequent research, experts' responses could be expanded to include the most attractive ways of mitigating GHG emissions arising from the characteristics of the supply chains represented by the

experts. Waste management is an important element of the circular economy concept and is in line with the principles of sustainable development. Therefore, assessing the effectiveness of processes in this area of the economy can be an important factor to analyse from the perspective of emission level.

Currently, the HDQ calculation model is limited to postcodes in Poland. The distance grid defined in **chapter 4.1** covers only the Polish territory. Hence, distances used for dynamic distance calculation in the HDQ CF assessment model are defined only for locations in Poland. However, the distance matrix can be freely expanded to include more countries. The ArcGIS Pro tool with the Network Analyst add-on, which was used to create the matrix, allows for consideration of more countries. However, it should be noted that expanding the matrix available in the HDQ model will result in an increase of the file size.

Further Research

Future research may focused on the **development of the proposed CF assessment model** for distribution transport processes. The application of digital technologies such as IoT telematics, artificial intelligence, and blockchain, which could strengthen the model's capacity to collect real-time data and improve transparency in emission reporting across supply chains. The extension of the model to multimodal and international transport networks should be also considered, where diverse transport modes and regulatory frameworks increase the complexity of CF assessment. The current model is limited to road transport, hence the inclusion of air, sea, and rail modes of transport should be considered as a next research step. Transferring the model to other programming environments would allow the processing and analysis of much larger datasets. Further **Empirical research** may focus on examining how control parameters influence emissions in rail, maritime, and air transport. This includes analysing historical data to identify links between process parameters and CO_2 emission levels. The further **literature research** should review studies on control parameters in non-road transport and intermodal supply chains that may affect CO_2 emissions. Proposed research directions create a path for further improvement of proposed CF assessment model and to extend state of the art within the CO_2 emissions management research field.

Fig. 6.2 below outlines further potential research steps that could both enhance the scientific state of the art and contribute to the development of a new model for assessing CF of transport processes.

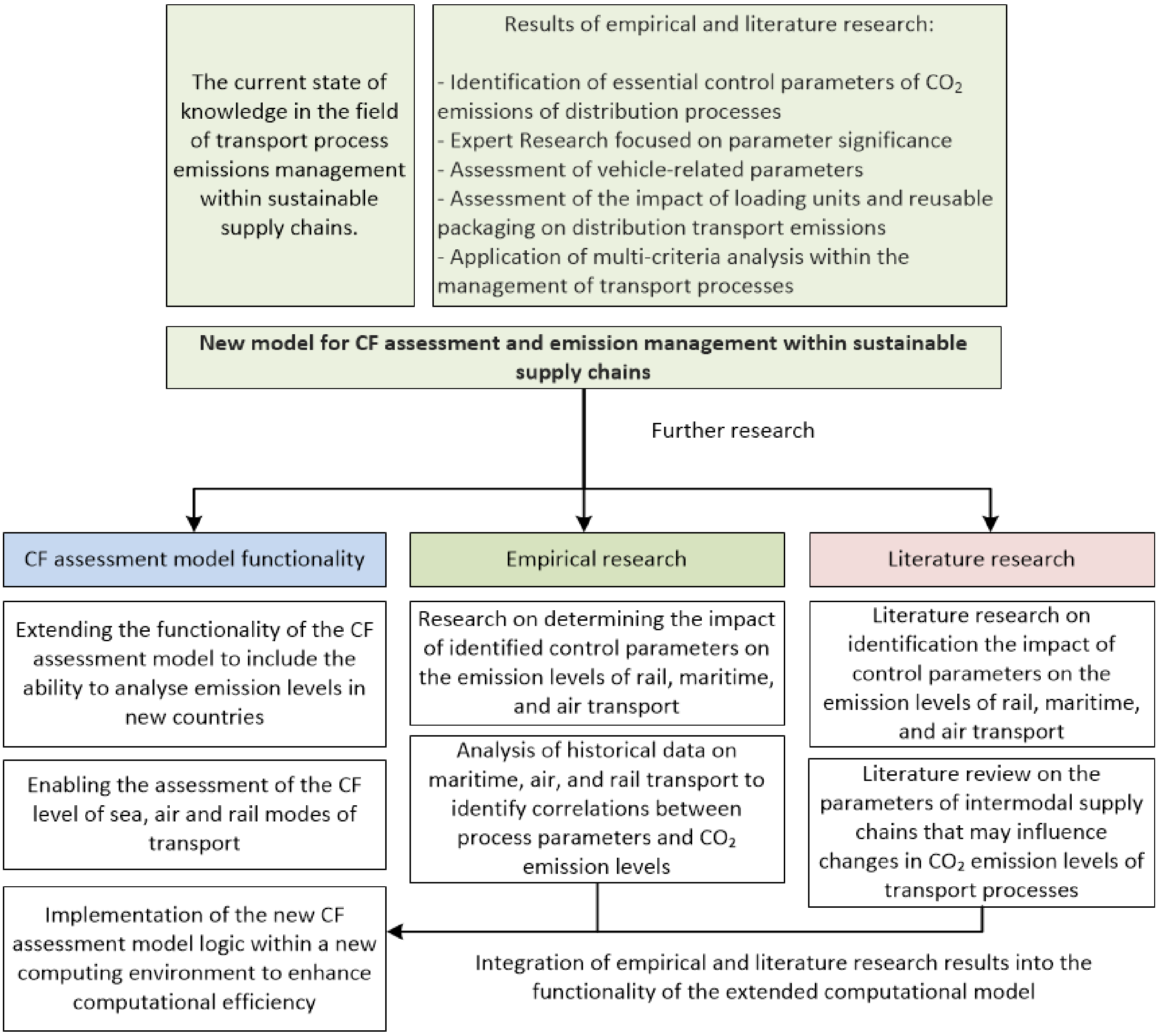

Fig. 6.2 Possible directions of further research
Source: own elaboration.

The defined research gap was entirely covered by the literature and empirical studies conducted. The identified application gap was also filled by developing a CF assessment model for distribution supply chains based on the research findings. Validation of the model confirmed its utility and compliance with international norms and standards. The research provided answers to the five research questions. The main scientific aim of defining a holistic method for assessing CO_2 emissions from transport processes in supply chains, taking into account the parameters of heterogeneous fleets, was thus achieved. The cognitive aim was achieved through the identification of the key parameters influencing changes in CO_2 emissions from transport processes within sustainable supply chains. The practical aim was also achieved through the development of a computational model that supports the assessment of CF levels in transport processes within sustainable supply chains.

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Appendix 5 - Input data form.xlsx

Appendix 6 - Distance matrix PL.xlsx

Appendix 7 - High data quality CF assessment.xlsx

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Appendix 9 - MCDA Matrix.xlsx

Appendix 10 - General map of process As Is.pdf

Appendix 11 - General map of process To Be.pdf

Appendix 12 - Model validation.xlsx

Appendix 13 - Model validation calculations.zip