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TRANSPORTATION PRODUCT CARBON FOOTPRINT: A FRAMEWORK FOR SEMICONDUCTOR SUPPLY CHAIN

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ABSTRACT

This paper presents a comprehensive framework for modeling the Product Carbon Footprint (PCF) associated with the transportation activities within the semiconductor industry, specifically focusing on the gate-to-gate supply chain. The study reveals that the mode of transportation, distance traveled, and weight of shipments, particularly the weight added by packing, significantly influence the transportation PCF. Despite the inherent complexities and dependencies within the semiconductor supply chain, this research provides a robust foundation that increases transparency and facilitates comparable studies across the industry. The adaptability of the methodology shows potential for broader applications, contributing to sustainability efforts across related sectors such as the electronics industry. The study emphasizes the step-by-step methodology over quantification of carbon emissions, thereby contributing to industry-wide efforts to understand and mitigate environmental burdens.

1 INTRODUCTION

The importance of semiconductors is ever-rising with the global megatrends of renewable energy, electric vehicles, AI, data centers, IoT, and smart cities (Devinder Kumar and Vlachos 2024). These trends drive a surge in demand for smaller, more efficient, and more powerful semiconductors. For instance, renewable energy systems require power electronics devices for energy conversion based on semiconductors (Muttumthala and Yadav 2022). Electric vehicles need semiconductors for battery management and motor control (Wangsupphaphol et al. 2023). AI and data centers rely on semiconductor-based processors for computing power. IoT devices and smart city infrastructures are built upon semiconductor sensors and communication devices. As these trends continue to evolve, the role of semiconductors will become even more pivotal, underpinning the technologies that will shape our future.

With the demand for digitalization and decarbonization, it is necessary to understand the carbon footprint of semiconductors. As the world moves towards a more digital and low-carbon economy, the semiconductor industry faces the dual challenge of meeting the increasing demand for its products, while minimizing its environmental impact (Ghezelbash et al. 2024). The carbon footprint of semiconductors is not just about the energy used in their production but also includes the emissions from their transportation, which is the focus of this paper. By understanding and addressing the carbon footprint of semiconductors, we can make strides toward a more sustainable future where technology and environmental responsibility go hand in hand.

Despite the necessity of understanding the carbon emissions of semiconductors, it is challenging to quantify semiconductors' carbon footprint. This is mainly due to three reasons: Firstly, semiconductor manufacturing is complex. It involves numerous intricate processes, each with energy requirements and potential for carbon emissions (Zhou et al. 2024). This complexity makes it difficult to accurately measure and attribute the carbon footprint. Secondly, the semiconductor industry has a long cycle time, restricting flexibility. The time from the initial design of a semiconductor to its final production can span several months or even years (Chen 2013). This is due to the complexity of the chips, the precision required in manufacturing, and the rigorous testing needed to ensure reliability. This long cycle time makes it challenging to implement rapid changes in response to new findings about carbon emissions. Thirdly, semiconductor fabrication plants are located globally (Gopal et al. 2022). This global distribution adds another layer of complexity to calculating the carbon footprint, as it necessitates the consideration of different energy sources, transportation methods, and regulatory standards in various countries. Given these challenges, it is crucial to develop robust methodologies and tools for accurately quantifying the carbon footprint of semiconductors. This will help the industry to understand its environmental impact, identify opportunities for improvement, and contribute to global decarbonization efforts.

The Product Carbon Footprint (PCF) is a comprehensive method for assessing a product's climate impact throughout its entire life cycle. The calculation encompasses several sectors due to their significant contributions to greenhouse gas emissions. Electricity consumption is a primary factor, accounting for the energy used in manufacturing processes and during the product's use phase (Winter et al. 2023). Transportation is another key sector, encompassing emissions from the movement of raw materials, components, and finished products via various modes of transport. Waste generation during manufacturing and the product's end-of-life also contributes to the PCF. Other sectors often considered include raw material acquisition, involving the extraction and processing of raw materials, and product use, which considers emissions resulting from the product's operation. Each of these sectors contributes to the overall PCF, underscoring the importance of a comprehensive, life-cycle approach to carbon footprint analysis.

In recent studies on the environmental impacts of semiconductors, the research is focused on the electricity consumption of semiconductor manufacturing (Lin et al. 2020). However, transportation plays a crucial role in PCF calculation, particularly in the semiconductor industry (Gopal et al. 2022). This is due to the global nature of the semiconductor supply chain, which often involves transporting raw materials, components, and finished products across multiple countries and continents. Each mode of transport, whether by air, sea, or land, has its own carbon emissions profile, contributing to the overall transportation PCF. Furthermore, the semiconductor industry is characterized by high product sensitivity and rapid product cycles, necessitating specific transportation conditions and expedited shipping, which can lead to higher carbon emissions. Despite the long cycle time for individual chips, the semiconductor industry as a whole moves very quickly. New technologies and applications are constantly emerging, driving the need for new and improved chips. As a result, semiconductor companies often have multiple product cycles running concurrently, with new products being introduced frequently (Mönch et al. 2018). Therefore, understanding and optimizing the semiconductor supply chain's transportation aspect is critical in reducing the industry's overall carbon footprint.

This paper's research scope is limited to the gate-to-gate transportation PCF of a typical semiconductor company, a global leader in power systems and IoT. This means we will be examining the carbon emissions associated with the transportation of semiconductors from the moment they arrive at the company's gates until they reach their final destination. By focusing on this specific aspect, researchers could identify potential areas for reducing carbon emissions and contribute to the broader goal of sustainability in the semiconductor industry.

This research aims to explain how to model the transportation PCF arising from the semiconductor industry. To achieve this, we modeled the gate-to-gate supply chain of a semiconductor company. This model considers various factors such as the distance traveled, the CO_2e factor depending on the transport mode, and the weights of transported semiconductor products. The emphasis of this research is not on the calculations, nor the numbers themselves, but rather on the approach that applies to the complex semiconductor supply chain. By focusing on the methodology, we aim to provide a framework that can be adapted and applied to other companies in the semiconductor industry, thereby contributing to industry-wide efforts to understand and reduce carbon emissions from transportation.

This research offers several benefits that align with societal demands and industry needs: Firstly, it addresses the growing customer and societal demand for sustainability, clearly understanding the carbon footprint associated with semiconductor transportation. Secondly, identifying hotspots in the carbon footprint enables targeted efforts to reduce the PCF in the most impactful areas. Thirdly, this research increases the transparency of the semiconductor supply chain, smoothing operations and facilitating more informed decision-making. Lastly, the findings of this research could serve as a baseline for future strategies aimed at reducing the PCF, paving the way for more sustainable practices in the semiconductor industry.

This paper is structured into four main sections following the introduction. The Fundamentals and Methodology sections will detail the approach and techniques used to model the transportation PCF. This includes the semiconductor basics, the data collection process, the assumptions made, and the modeling techniques employed. The Results section will present our research findings, providing a detailed analysis of the transportation PCF of semiconductors. In the Discussion section, we will interpret these results, identify the study's limitations, and suggest future research. Finally, the Conclusion section will summarize the key findings of our research and discuss the implications for the semiconductor industry. Each section is designed to provide a comprehensive understanding of the transportation PCF and contribute to the broader goal of sustainability.

2 FUNDAMENTALS

For calculating the transportation PCF, it is essential to distinguish between different parts of intermediate and finished products within a semiconductor supply chain. The following section will define those fundamentals. Figure 1 depicts materials, intermediate products such as processed wafers, and finished products. At various parts of the supply chain, the weight of the products changes due to the intricate manufacturing process.

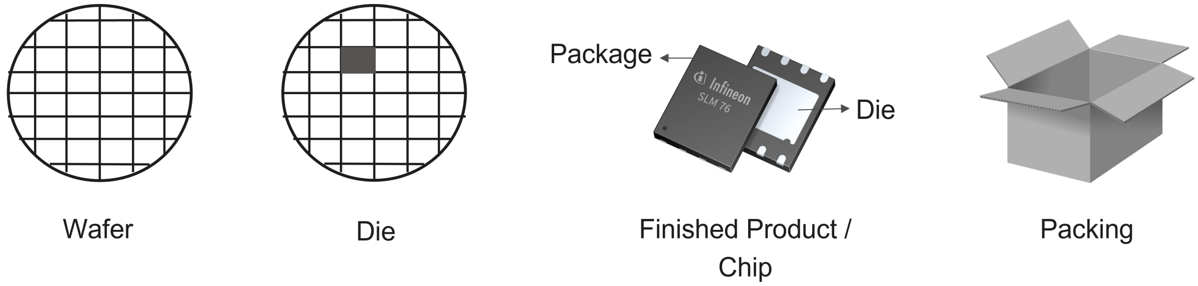

Figure 1: Semiconductor materials, intermediate and final product definition.

A semiconductor Frontend (FE) factory sources raw unprocessed *wafers* as an input for the manufacturing process. The semiconductor is manufactured on a wafer substrate material, such as silicon or silicon carbide. Since the density of the substrate material can vary, the weight of a wafer depends on the substrate. Wafer manufacturing handles different wafer diameters, such as 6, 8, or 12 inches, which leads to more surface area, a higher number of chips per wafer, and heavier unprocessed wafers. FE manufacturing creates the necessary structures on the wafer through hundreds or even thousands of manufacturing process steps.

Each manufactured wafer in the FE is diced into individual rectangular *dies* via sawing. The quantity and size of dies vary between semiconductor products which can lead to variations in the weight of a die.

The die is sensitive to environmental conditions, which could lead to mechanical or electrical failures. Therefore, each die is housed inside a *package*. The die is protected from moisture, physical stress, or other contamination within the package. A package can be manufactured from different materials like metal, plastics, and ceramics, each with different densities, dimensions, and weights.

At the end of the manufacturing process, the final product can be shipped to customers inside *packing* containers, which protects the product during transit. Packing containers of different sizes and weights are also used to ship processed wafers from FE to BE or finished products from BE to the Distribution Center (DC).

For the overall calculation of the transportation PCF, we need to consider the weight of the finished and intermediate products at different points inside the semiconductor supply chain.

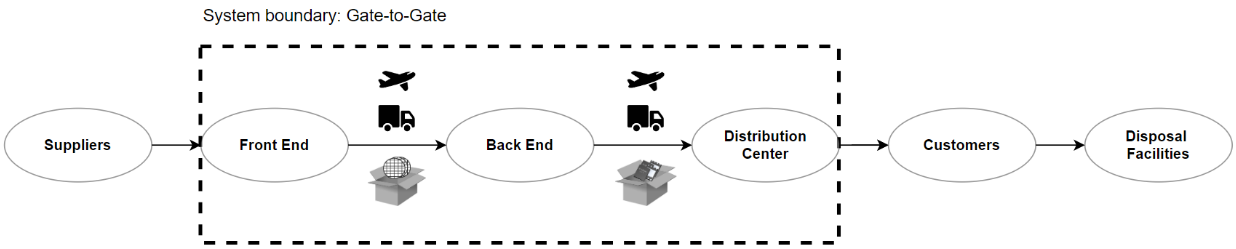

Figure 2: Transportation flow of a semiconductor product: Single route.

Figure 2 represents a simple single-route transportation flow of a semiconductor manufacturing supply chain. Each path between two subsequent locations is generally handled by an airplane or truck due to the complex global semiconductor supply chain and the lightweight nature of products. The dotted outline represents the system boundary for our gate-to-gate study. Wafer Suppliers supply raw, unprocessed wafers of different substrate materials to semiconductor manufacturers. After FE manufacturing is finished, the processed wafers, including packing, are shipped to the BE sites. Finally, finished products are sent from the BE manufacturing site to a DC and subsequently shipped to the customer. In a globalized semiconductor supply chain, the distance to the customer is essential to operate in the regional market and quickly deliver to customers. Therefore, multiple DCs are utilized, which are located, for example, in Asia, Europe, or the US. Figure 3 depicts the setting of a multi-route transportation flow, which can be routed through one of various regional DCs after the BE manufacturing has concluded.

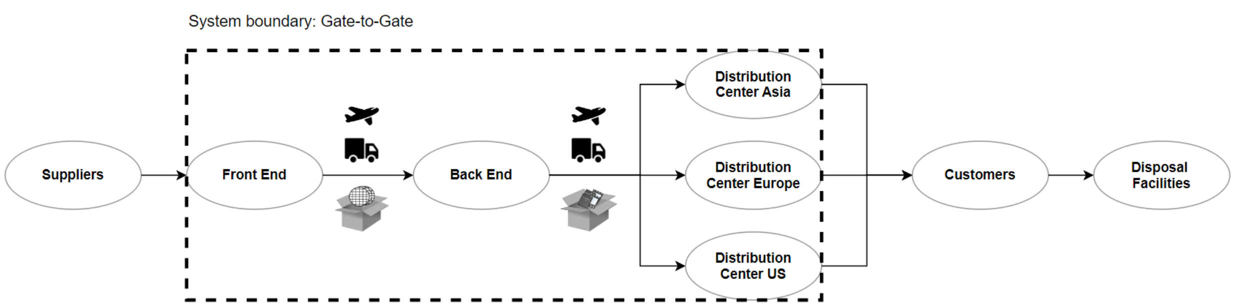

Figure 3: Transportation flow of a semiconductor product: Multi-route.

Our methodology can be applied to single and multi-route semiconductor supply chains. The simplified transportation model will serve as the baseline for the subsequent transportation PCF calculation outlined in the methodology.

3 METHODOLOGY

For calculating the overall transportation PCF, the distance of all transportation paths, as shown in the transportation model in Figure 3, need to be aggregated. Our framework can then be applied to calculate the transportation PCF of semiconductor products, determined by the following formula:

$$\text{Transportation PCF} = \text{Distance} \times \text{Weight} \times CO_2e \text{ Factor per Transportation Mode.} \tag{1}$$

In Formula (1), transportation PCF quantifies the product carbon footprint in $kgCO_2e$, considering the Distance traveled in km, the Weight in tons, and the CO_2e factor per Transportation Mode in $kgCO_2e$/ton/km. The transportation PCF methodology outlines three stages, which are shown in Figure 4: (1) Goal and Scope Definition, (2) Data Extraction, and (3) Data Engineering.

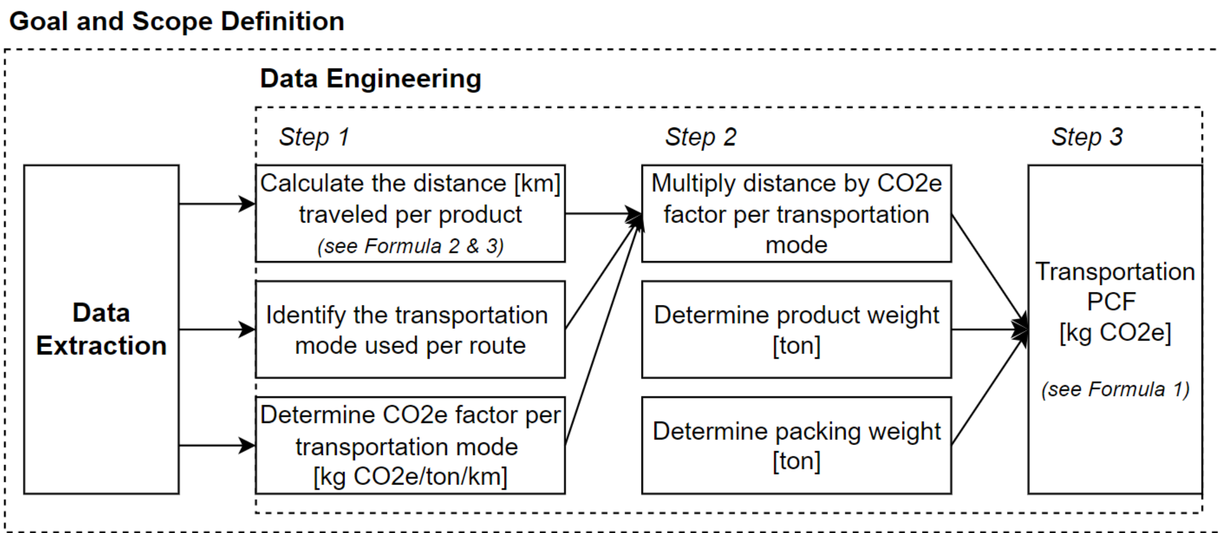

Figure 4: Product carbon footprint transportation framework.

3.1 Goal and Scope Definition

The methodology aims to provide a comprehensive framework for calculating the gate-to-gate transportation PCF, which can be adapted and refined according to the specific needs of different semiconductor products. It seeks to promote transparency in the semiconductor industry by quantifying the environmental impact of product transportation, thereby enabling stakeholders to make more informed decisions. The approach is designed to be flexible and scalable, allowing for adjustments and enhancements as more precise data becomes available or as transportation practices evolve. While the current scope is focused on gate-to-gate transportation of semiconductors, the methodology could be extended to other industries, contributing to a broader understanding of transportation-related carbon footprints. The ultimate goal is to drive sustainability efforts in the semiconductor industry and beyond by providing a robust tool for measuring and reducing emissions from transportation.

3.2 Data Extraction

In the initial phase of our research methodology (steps 1-3 in Algorithm 1, as outlined below), we leveraged three essential datasets: details about a product, the location map including longitude and latitude for each site, and a catalog of FE, BE, and DC locations. These datasets provide vital information, such as the unique identifier for each product (finished or unfinished), the quantity of dies, wafer size, and other relevant specifics. We designed a function to read these datasets, perform necessary cleaning operations, merge the datasets, and eliminate rows with missing or duplicate data. This preprocessing step is essential for accurately calculating the transportation PCF in our study. Subsequently, we developed a web scraping tool using Python to gather the latest routing information for the respective product.

3.3 Data Engineering

In the subsequent part of our methodology (steps 4-15 in Algorithm 1), we focused on data engineering and merging. This phase entailed extracting necessary columns from the aforementioned datasets, classifying the values into 'FE' or 'BE', and implementing a routing extraction algorithm to enumerate routes for each product.

Reflecting the globalized nature of semiconductor manufacturing and the chips' inherent lightweight, transportation predominantly involves airplanes and trucks. We adopted a simplified assumption due to a lack of data on the transportation mode: For distances beyond 500 km, airplanes are employed, and for distances under 500 km, trucks are chosen. The CO_2e factors are derived from the greenhouse gas reporting conversion factors for 2023, as published by DEFRA (Department for Environment, Food and Rural Affairs, British Government), setting 1.23 kgCO_2e/ton/km for international freight flights including Well-to-Tank (WTT) emissions and 0.12 kgCO_2e/ton/km for an average loaded Heavy Goods Vehicle (HGV) truck including WTT emissions (DEFRA. 2023).

Our approach to estimating the transportation PCF starts with route extraction and site location mapping. Next, we calculate the distance using the Haversine Formulae (2) and (3). These formulae compute the great-circle distance between two points on Earth, using longitude and latitude coordinates (Azdy and Darnis 2020). For the most precise transportation PCF calculation, it would be recommended to use real-time routing distances. However, because of limitations in data accessibility, Haversine Formulae were chosen as the approximation. The formulae assume a perfectly spherical Earth, simplifying calculations but introducing potential inaccuracies, especially at the street level, due to the assumption of direct routing. To refine our distance estimations, we would propose to incorporate an adjustment factor.

$$d = 2R \cdot \text{atan2}\left(\sqrt{a}, \sqrt{1-a}\right) \tag{2}$$

$$a = \sin^2\left(\frac{\Delta\phi}{2}\right) + \cos(\phi_1) \cdot \cos(\phi_2) \cdot \sin^2\left(\frac{\Delta\lambda}{2}\right) \tag{3}$$

The weight determination in our study is influenced by three primary factors: the unfinished wafer weight, the finished product weight (device or chip), and the weight of the packing materials. These elements collectively contribute to the overall weight assessment in our investigation. This comprehensive approach ensures a more accurate and holistic understanding of the weight dynamics in our study. For simplicity, we have chosen silicon as the substrate material for our semiconductor wafer.

Algorithm 1 presents a comprehensive method designed to calculate the PCF associated with transportation in the semiconductor industry. It considers various factors such as the mode of transportation, the distance traveled, and the weight of the shipments. The initial steps 1-3 involve data preprocessing, including downloading the relevant dataset and applying necessary cleaning, filtering, and merging operations. The weight is then determined based on the product's movement, either from FE to BE (steps 4-6) or from BE to DC (steps 7-9). The gross packing weight includes the packing and the total weight of the goods transported. The subsequent steps involve distinguishing between a single route (steps 10-11) and multiple routes (steps 12-15), calculating the distance based on the routing data, and determining the CO_2e factor for the mode of transportation (step 16). The final computation of the Transportation PCF is a product of the distance, weight, and CO_2e factor (step 17) according to the transportation PCF Formula (1).

This methodology provides a comprehensive approach to understanding the carbon footprint of semiconductors, taking into account the key factors and stages in the supply chain.

Algorithm 1 Transportation PCF calculation

Require: Dataframes *df* and mapping tables *mt* ▷ Input data
Ensure: All datasets are preprocessed in a manner that allows for possible merging
Download the relevant dataset *ds* ▷ Get the data
Apply necessary cleaning, filtering and merging of *mt* and *df* ▷ Preprocess the data
Extract routing data *rd* from product using a webscraper or other sources ▷ Get routing data
if Product moves from FE to BE **then** ▷ Check the product movement
  $w \leftarrow$ gross packing weight / number of wafers per packing / number of dies per wafer
  ▷ Weight for FE to BE
else if Product moves from BE to DC **then**
  $w \leftarrow$ gross packing weight / number of finished products per packing ▷ Weight for BE to DC
end if
if *rd* contains a single route **then** ▷ Check the number of routes
  $d \leftarrow$ distance via haversine Formulae (2) and (3) ▷ Distance for single route
else if *rd* contains more than one route **then**
  $d \leftarrow$ weighted average distance of all routes via haversine Formulae (2) and (3)
  ▷ Distance for multiple routes
end if
$f \leftarrow CO_2$e factor for transportation mode ▷ Get CO_2e factor
Compute Transportation PCF $t = d \times w \times f$ ▷ Calculate PCF
return t ▷ Return the result

4 RESULTS

This section presents an overview of the results from our analysis of the transportation PCF. We aimed to gain a conceptual understanding of the transportation PCF and identify where relevant information is needed. The Table 1 provides a summary of the key factors influencing transportation PCF, including mode of transportation, distance, weight of shipments, regional distribution, packing weight, and material density and weight, along with their respective impacts on transportation PCF.

Table 1: Summary of key factors influencing transportation PCF.

Factor	Description	Impact on transportation PCF
Mode of Transportation	Airplane (>500km) or truck (<=500km)	Using airplanes increases transportation PCF by approximately ten times more than using trucks when the weight and distance stay the same
Distance	Frequent shipments between Asia, the US, and Europe	Higher transportation PCF due to long-distance air travel
Regional Distribution	Centralization of BE sites in Asia	Higher consolidation of shipments may alter transportation PCF
Weight of Shipments	Includes both the chips and the packing material	Increased weight leads to higher accumulated transportation PCF
Packing Weight	Packing materials can weigh three to four times more than the chips	A substantial increase in total shipment weight
Material Density and Weight	Variability in the density and weight of different substrate materials	Can alter the transportation PCF; needs further research

After the process of data extraction and engineering, the results of transportation PCF could be attained like the Figure 5. This graphically represents the dynamics of transportation PCFs expressed in gCO_2e. For analytical clarity, we categorized transportation PCF into different ranges. Initially, we sorted our

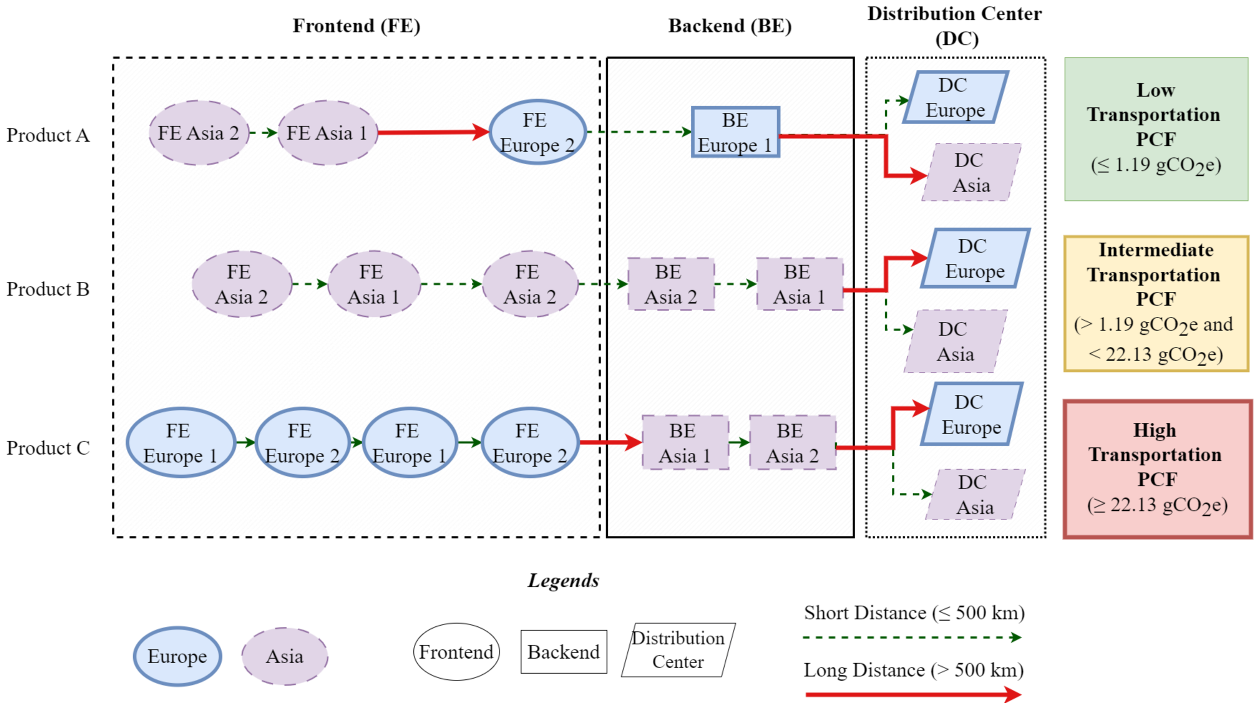

Figure 5: An illustration of transportation PCF results.

data on emissions from smallest to largest to see the pattern they followed. Three distinct emissions classifications were established: low, intermediate, and high. The "low" range was defined by the first quartile of our data points, encapsulating emissions less than or equal to 1.19 gCO_2e. Conversely, the "high" range was determined by the third quartile, representing emissions greater than or equal to 22.13 gCO_2e. The "intermediate" range refers to the median, covering all the values between 1.19 gCO_2e and 22.13 gCO_2e. We also removed any unusually high or low outliers that could distort our analysis. This way, we ensured our categories were clear and representative of the typical carbon emissions found in our research, which allowed us to draw more accurate conclusions about the transportation PCF within the semiconductor industry.

4.1 Analysis of Primary Factors Affecting Transportation PCF

The subsequent discussion delves into the primary factors influencing the transportation PCF. One of the pivotal factors in determining the transportation PCF is the mode of transportation. This is primarily due to the fact that the CO_2e factor for air transport is approximately ten times higher than that for truck transport. Despite the higher transportation PCF associated with air transport, it remains the dominant mode due to its speed and logistical efficiency—a standard requirement in the fast-paced semiconductor industry. Most semiconductor shipments are made by airplane, significantly escalating the overall transportation PCF. The implications of these findings and potential strategies for transportation PCF reduction will be further discussed in the following sections.

4.2 Global Operations and Their Impact on Transportation PCF

The global operations of the semiconductor industry necessitate frequent shipments between different continents. Semiconductor products often travel between Asia, the US, and Europe, increasing the transportation PCF due to the high emissions of long-distance air travel.

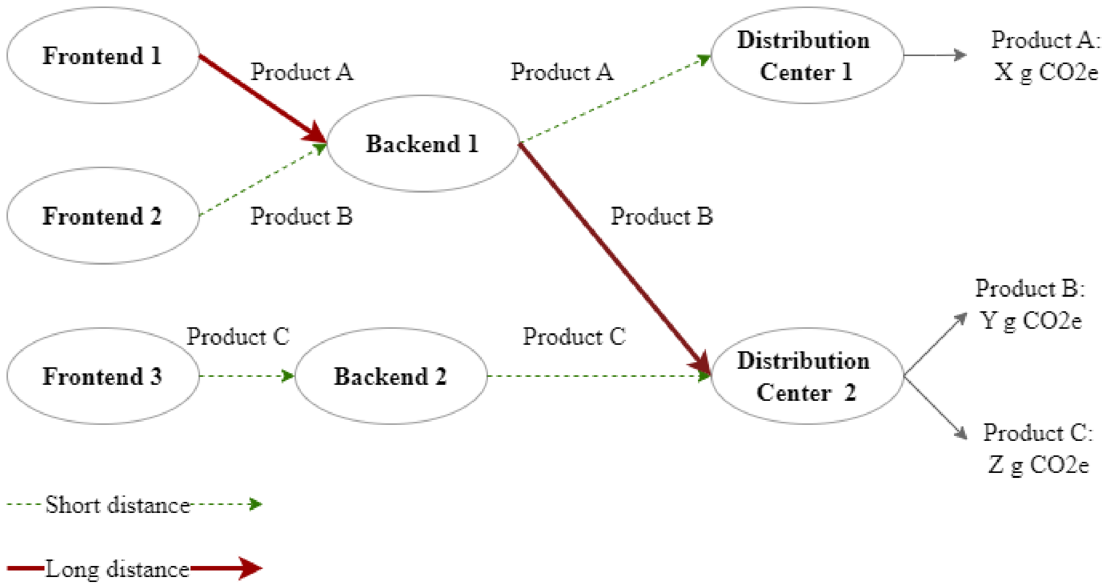

Figure 6: Complexity of global semiconductor supply chain.

Figure 6 presents a simplified representation of the transportation routes from various FE to BE sites and, ultimately, to the final DCs. This depiction abstracts a more intricate supply chain structure. It illustrates how the CO_2e factor can vary significantly based on the location of the sites and the associated distances, which can range from short to long. In reality, a single route could be associated with multiple FE or BE sites, which could substantially influence the CO_2e factor. Accordingly, multi-route scenarios offer a more complex perspective on the transportation PCF. This underscores the complexity of accurately determining the CO_2e factor in the semiconductor supply chain.

In calculating the distance factor of the transportation PCF, we employ the Haversine Formulae (2) and (3), followed by an adjustment using a correction factor. As mentioned, the practical aspects of transportation logistics can lead to deviations from these estimates. The high concentration of BE sites in Asia implies a more significant consolidation of shipments. This consolidation, coupled with regional distributions and the scale of export operations, may introduce variations in the transportation PCF. This highlights the need for a more nuanced approach to calculating the transportation PCF that considers the realities of the semiconductor supply chain.

4.3 Impact of Aggregate Weight and Packing Materials on Transportation PCF

The individual weight of a chip might be minimal, but the aggregate weight of the chips in a batch in association with packing material can significantly affect the transportation PCF. As the complexity and quantity of chips increase in a shipment, so does the total weight, leading to higher accumulated emissions. Conversely, when examining emissions on a per-chip basis, the transportation PCF can appear deceptively low, which underscores the importance of considering the aggregate impact in environmental assessments.

The packing process adds substantial weight to the shipment, with materials used for packing sometimes weighing three to four times more than the chips themselves. This disparity is particularly pronounced for 200mm and 300mm wafers. Since the packing weight is much higher (three to four times) than the unfinished product, it may be a further research topic to investigate. The assumption that a single material represents all chips may not be accurate. Varying densities and weights of different substrate materials could alter the transportation PCF. Assumptions about batch sizes and packing materials could differ from actual practices, influencing the transportation PCF calculation.

5 DISCUSSION

The analysis of the results centers around demonstrating the various parameters that influence transportation PCF, namely the distance traveled between manufacturing or DCs, the transportation mode employed, and the weight of goods transported. The study demonstrates the drawbacks posed by cross-continental transportation between FE and BE manufacturing locations, where products travel back and forth, resulting in multiple trips between processes and, thus, higher emissions. Another observation would be that the lightweight nature of chips contributes to remarkably low emissions per chip.

Despite the valuable insights gained from the study, it is essential to acknowledge the limitations due to the nature of the semiconductor industry and assumptions made to address the complexity of the semiconductor supply chain. To begin with, the FE and BE locations or DCs do not represent the exact site addresses due to the consideration of confidentiality of site and partner information, which may impact the granularity of the study. Additionally, the simplification made for choosing airplanes and trucks based on distance may underrepresent real-life scenarios, like ignoring exceptional travel. Moreover, the distance calculations are based on great circle distances, ignoring the real-life routes and air traffic conditions. In addition, this study exclusively examines silicon substrate products and ignores the impact of different materials and material densities and, thus, weight. To continue, the generalizability of this study is constrained by the examined semiconductor company's specific context as a European semiconductor manufacturer, which in turn restricts the relevance of the findings to other industry players with differing supply chain structures.

While acknowledging the limitations, it is crucial to recognize opportunities for future research. While this study covers the majority of a semiconductor company's products, it would be beneficial to consider the entire product portfolio, e.g. multi-chip products, and modules, for a more comprehensive understanding of emissions associated with transportation. Also, transporting materials or goods between processes represents only a tiny portion of the supply chain activities. Thus, another research opportunity would be to address the whole life cycle in the transportation PCF assessment, such as emissions released by upstream and downstream processes, including materials and equipment manufacturing, chemicals production, use phase, and end-of-life cycle treatments, for a more holistic understanding of environmental effects. Additionally, exploring the impact of alternative substrate materials like silicon carbide or gallium nitride on material density and weight presents an opportunity for future research. Finally, it must be noted that environmental impact assessment should also include other impact categories beyond transportation PCF such as water use, land use, toxicity, ocean acidification, and more (Finnveden et al. 2009).

This study helps practitioners and researchers as a methodological framework to make better-informed decisions in the context of improving the environmental performance of transportation activities in the supply chain. However, it is essential to acknowledge the inherent complexities and dependencies within the semiconductor supply chain. Decisions regarding fab locations are influenced by factors beyond transportation emissions, such as investment considerations, operational dependencies, tax incentives (Tung 2001), etc., highlighting the challenges of implementing significant changes in the semiconductor manufacturing landscape. Finally, the impact of transportation emissions on routing decisions within the semiconductor supply chain is a matter of debate. This is due to the companies' need to maintain flexibility in response to the industry's rapid pace, extensive lead times, and global manufacturing network. This flexibility is imperative for sustaining competitiveness in the market.

6 CONCLUSION

In conclusion, this paper presents a robust methodology for modeling transportation-related carbon emissions within the semiconductor industry. The approach, centered on the gate-to-gate supply chain of a semiconductor company, segments the system by life cycle stages to offer an improved understanding of emissions at each step with relevant weight and distance considerations.

To summarize the findings, the transportation mode selected to transport the goods between life cycle stages affects the transportation PCF due to differing emission factors. This is relevant in the semiconductor industry because of its global manufacturing network and the need for faster delivery. Moreover, the distance traveled directly correlates with emissions, and given the dispersed nature of the global manufacturing network, achieving localization presents a considerable challenge. Notably, emissions related to semiconductor transportation are primarily attributed to the weight and material of the packing rather than the product. Therefore, addressing packing size and material presents an opportunity to make a difference in the transportation PCF of semiconductors.

Finally, the significance of the study lies in the emphasis on methodology rather than merely quantifying emissions. By focusing on carbon emissions released in transportation, which is often overlooked or ignored in carbon accounting, this study contributes to industry-wide efforts to understand and mitigate environmental burdens. The applied framework, rooted in real-world data and practical application, increases transparency and facilitates comparable studies. Moreover, the adaptability of the methodology shows the potential to calculate transportation PCF not only within the semiconductor industry but also in the broader electronics industry. This capability proves the framework's relevance and applicability in efforts to enable sustainability across industries.

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