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“Made in Germany”? Labour, wages and carbon footprints of consumption and production of the motor vehicles industry

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ABSTRACT

Production is fragmented in global production networks, and consumption relies on global markets. Their impacts and profits are unevenly distributed in the international division of labour. Such complexity and entanglement call for footprint approaches that capture these regional and sectoral distributions. We calculate through Multi-Regional Input-Output Analysis (MRIOA) the working time, compensation of employees, and GHG emissions and their regional and sectoral distribution in two global value chains related to the Motor vehicles industry in Germany (1995–2020): (1) the Supply system of global Motor Vehicles Industry to Germany, which provides vehicles and replacement parts to Germany and (2) the German Final production system of Motor Vehicles Industry, which manufactures “made in Germany” vehicles sold in global markets. This unravels the uneven distribution of profits and impacts through global trade and enables different perspectives on social and environmental responsibility of consumers and producers. In both systems, but more intensively in the Final production system, Germany kept most of the compensation of employees while generating less than half of GHG emissions and less than a third of employment. The whole supply-chain production of “made in Germany” vehicles generated 73% of salaries in Germany, while it relied on 63% of emissions and 54% of working time in upstream processes abroad in 2018. In terms of sectors, the Motor vehicles industry obtained about half of the salaries with 5% of emissions in both systems. Producing a vehicle in Germany requires approximately 1400 working hours, the equivalent of one year of labour by a German worker.

1. Introduction

The European motor vehicle industries represent a significant share of jobs and value added in European industries, being 12% of direct industrial employment in Germany in 2018 (Pérez-Sánchez et al., 2024). The German Motor Vehicle Industry (MVI) is one of the most important industries for satisfying the demand for cars domestically and worldwide. Germany was the largest supplier of cars in 2018, contributing 19.8% of the world's export value (Observatory of Economic Complexity, n.d.). Yet, at the same time, Germany was also one of the largest importers, with 8.02% of the global import value (Observatory of Economic Complexity, n.d.). This shows how international trade can be produced at a large scale in both directions (imports and exports), even for the same product group due to product differentiation. The main reason for the large passenger car trade German exports is their specialization in premium higher-end vehicles, which is a niche product valued in global markets (Krzywdzinski, 2014). Therefore, the German automotive industry keeps its significance through the broader idea of cars as a symbol of social distinction (Sheller, 2004; Sheller and Urry, 2000; Urry, 2004) and the specific reputation of German industry for high-quality, high-status vehicles (*Germany's Engineering Culture in a Global Economy: How National Business Philosophies Shape International Commerce | Reuters [WWW Document], n.d.*).

However, the imports and exports of final products do not show the complete picture of trade in the automotive industries. The reliance on intermediate parts and materials from other countries raises the question about what the expression ‘made in Germany cars’ really means in a highly telecoupled global economy. The socio-economic and environmental impacts of goods can be allocated to multiple suppliers across different countries. The German automotive industry has fragmented and offshored production of intermediate parts to its neighbouring countries, mainly to Eastern European countries (Brincks et al., 2016; Chiappini, 2012; Gracia and Paz, 2017). Los et al. (2015) calculated that the foreign value added content in final goods from the transport equipment industry in Germany increased from 21.1% in 1995 to 34% in

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Abbreviations

FD	Final Demand
FPS	Final production system
GHGER	Greenhouse Gas Emission Rate
MVI	Motor vehicles industry
OEM	Original Equipment Manufacturers
RoEU	Rest of the EU
RoW	Rest of the World
SS	Supply system

2008. Dudenhöffer (2005) estimated that 67% of the costs of a Porsche Cayenne assembled in Germany were generated abroad. Most of the environmental impacts in motor vehicle production are those induced to upstream suppliers (i.e., spillover effects) (Alcántara and Padilla, 2020; Hardt et al., 2021).

Production processes are highly fragmented. Jobs, income and impacts are unevenly distributed across sectors and countries in the international division of labour. The actors who capture most value added in a global value chain do not directly produce the most environmental impacts (Ortiz et al., 2022; Pérez-Sánchez et al., 2021). Pre-production (e.g., design and management) and final downstream activities (e.g. sales, finance, etc.) generally capture more value than the rest of the value chain (Ali-Yrkkö et al., 2011). This uneven distribution of producer surplus is illustrated by the concept of the smile curve (Baldwin and Ito, 2021; Del Prete and Rungi, 2017; Rungi and Prete, 2018). The sectoral allocation of income is also related to the geographical allocation of activities and the international division of labour. Some countries accumulate higher-value design and management, whereas others devote themselves to more impactful upstream activities such as material extraction and manufacturing parts. However, also the salaries for same activity in core countries will be higher than in the periphery, generating uneven purchasing power in global markets according to the ecologically unequal exchange literature (Alsamawi et al., 2014; Chang, 2002; Hickel et al., 2024; Hornborg et al., 2007; Muradian and Martinez-Alier, 2001; Reinert, 2008).

The fragmentation of production causes challenges in allocating responsibility and action for the abatement of GHG emissions and solving other environmental and socioeconomic issues. This is especially important considering the public debate in EU countries around the government support to automotive industries due to the economic activity generated locally and the jobs-vs-the environment dilemma since it reproduces the private mobility system and vehicle fleets mostly based on internal combustion technologies.

The quantification of impacts in global value chains for sectors or companies using Input-Output Analysis (IOA) has already been addressed in the literature. Huang et al. (2009a) coined the concept of “sub-total supply chain emissions” as “the portion of the total supply chain embedded upstream of a specific supplier, including the supplier itself”. Furthermore, Huang et al. (2009b) estimated the carbon footprint of the supply chain of 9 sectors related to electronics manufacturing and computer services, characterising the largest contributors. Wiedmann et al. (2009) calculated the direct and upstream triple-bottom-line impacts of a specific UK company in the subsector Motion picture and video distribution. Skelton et al. (2011, p. 10517) assessed the influence of the EU industry over foreign supply chain emissions by sector and region using a Total Consumption Attribution, which is “the emissions embodied in a sector's total output of products (i.e., all intermediate and final products)”.

For the automotive industry, Timmer et al. (2015) estimated the foreign and local shares of value added in the final output of the automotive global value chain of 24 countries in 2008. Grodzicki and Skrzypek (2020) calculated the foreign real value added in final goods of the automotive industry in a set of countries. Fana and Villani (2022) estimated the foreign and local labour in the final exports of automotive supply chains of Germany, France, Great Britain and Italy in 2000, 2007 and 2014. Gracia Santos et al. (2024) calculated vertically integrated unit labour costs for the German automotive sector from 1995 to 2007 and flagged the effects of outsourcing and offshoring and the role of wage restraint among suppliers. Godé et al. (2026a) calculated the embodied labour inputs relative to production in Germany from 1995 to 2020 and flagged that Manufacturing of transport equipment is one of the most dependent sectors on foreign upstream sectors.

Footprints of countries have also flagged the unequal distribution of final consumption or household consumption across countries and the increasing role of international resource transfers (Akizu-Gardoki et al., 2021; Donato et al., 2015; Dorninger et al., 2021; Hickel et al., 2024, 2022; Ivanova et al., 2016; Peters et al., 2011; Tukker et al., 2016). Moreover, some papers, apart from analysing the inequalities in footprints, have shown the localisation where impacts are generated and how these relate to the zero-sum game of some resources such as working time (Bruckner et al., 2023; Godé et al., 2026b; Hertwich and Peters, 2009; Hickel et al., 2024; Owen et al., 2018; Pérez-Sánchez et al., 2021; Sánchez-Chóliz and Duarte, 2004; Yang et al., 2020). Papers like Simas et al. (2015), Arto et al. (2014) and Sakai et al. (2017), and Pérez-Sánchez et al. (2021) have analyzed the interplay between GHG emissions, energy and employment footprints and shown how the embodied time in trade can be even larger than other impacts. Moreover, some footprint papers include some level of sectoral differentiation. Country-level consumption-based assessments exist in the literature by final demand sectors (Goodwin et al., 2024; Hertwich and Wood, 2018; Steininger et al., 2018; Vita et al., 2019; Wang et al., 2024). However, the identification of the sectors where impacts happen is less common (Rasul et al., 2024; Steininger et al., 2018; Wang et al., 2024). The analysis of country consumption footprints even when dividing by final demand sector helps flagging inequalities but it is limited when trying to understand the dynamics of distribution of goods and bads in global value chains and, subsequently, its usefulness for policy-making. In this sense, Structural Path Analyses have explored the tiers of impacts due to final consumption of countries (Lenzen and Murray, 2010; Owen et al., 2018; Peters and Hertwich, 2006; Steininger et al., 2018). Here, we aim to analyse the regional and sectoral distribution of the global value chain due to the final demand of the automotive industry no matter the tier.

To the best of our knowledge, impacts embodied in the output and exports of the automotive industry have only been analyzed for value added and employment and their regional distribution. Since there are both imports and exports for the same type of product, the exploration of value chains for local consumption and final production in a triple bottom line perspective gives insights into the qualitative differences between these products and more complex trade dynamics of unequal exchange, such as the different weight of local and foreign sectors in consumed and produced goods. Moreover, not only consumption in some countries relies on foreign impacts as in a consumption-based perspective, but also the economic activity in core countries related to profitable and low-impact sectors such as the automotive industry requires more impactful upstream activities such as raw materials and intermediate goods production generating scope 3 emissions. We aim to see whether upstream activities happen in Germany or abroad, and whether the value chain conforms to the smile curve.

This paper presents two footprint accounting perspectives on the embodied impacts of final goods in a given country. We illustrate it with the example of Germany and the Motor vehicles industry in 2018 and contextualise these results with time series from 1995 to 2020. These accountings are related to two partly different global value chains: 1) the global Supply system of an industry to a country (hereinafter “Supply System” – SS), which provides final products from this given industry to fulfil a country's final demand, and 2) a country's Final production system of an industry to the world (hereinafter “Final production system” - FPS), where the national industry provides final products to global markets. We unravel and compare the supply chains of vehicles "made in Germany" (Final production system) and vehicles bought by Germans (Supply system). Where relevant, we also present results for exports and imports. This paper aims to provide insight into the MVI's role in the economy and its spillover effect in upstream sectors and foreign countries via economic (salaries and working hours) and environmental impacts (GHG emissions). We identify how benefits and impacts are sectorally and geographically distributed in global production networks and which country-industries depend the most on the activity of the MVI in and for Germany.

In the following section, we explain these two footprint approaches to impacts of a given industry and their MRIOA methods. Afterwards, we present the results, which include the analysis of final demand, working time, GHG emissions and compensation of employees by regions and sectors and the resource requirements for vehicle for 2018 and the time series 1995-2020. Then, we discuss the role of Germany and of the MVI, and contextualise this work with literature both from MRIO and LCA footprinting existing results and the relationship of the diverse footprint account perspectives to responsibility.

2. Methods

2.1. Two global value chains

We consider two different but overlapping global value chains related to vehicle manufacturing and Germany: the system that generates value added and jobs due to the global final demand for "made in Germany" vehicles and the system that provides new vehicles to German society. Both systems rely on global production networks that distribute impacts and profits unevenly. More specifically, we refer to the NACE C29 section: Motor vehicles, trailers and semi-trailers, but we will use the term Motor Vehicles Industry (MVI) in order to improve readability.

In one case, we select the final demands of a country for a given industry no matter its location. We call it the "Supply system" of an industry to a country (Fig. 1). This explains how the final consumption of the country is fulfilled. The case study in this paper considers "the Supply system of Motor vehicles industry to Germany". This Supply system provides vehicles and replacement parts from global markets to German society. The impacts in the Supply system are a fraction of the total German consumption-based accounts.

The second approach addresses the domestic industry and their scope 2 and 3 impacts and dependencies. This is driven by the global final demand for an industry in a given country. We call it the "Final production system" (Fig. 1). This is specified as final (production system) because there are outputs of the vehicle industry that are intermediate parts and modules that are imported to other industries and will be part of the scope 3 for other final demands. In our case study, exported outputs are not included in the calculation if they do not return to the German MVI to contribute to the final vehicles taking part in the final demand for German MVI. This approach is similar to that generally used for measuring international fragmentation of value chains, such as in Los et al. (2015) and Timmer et al. (2015). In this paper, we quantify and make a contribution analysis of the impacts embodied in vehicles "made in Germany" that are in part exported to global markets. Motor vehicles are the main export product for Germany (2021). In a traditional consumption-based account, a part of the emissions of this industry would not appear because its final products are exported, while jobs and salaries would remain in the country and provide purchasing

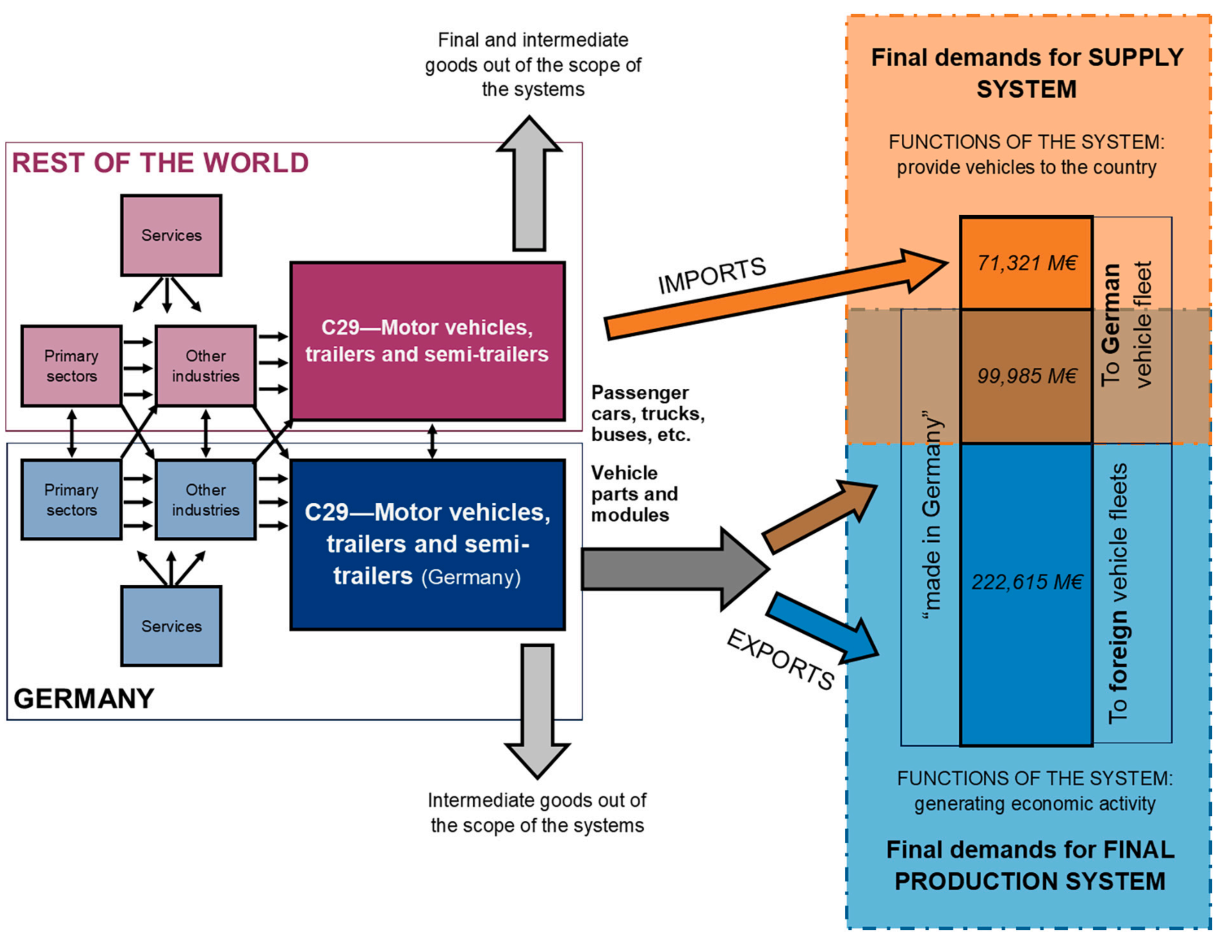

Fig. 1. Scheme of the Supply system of the German demand for Motor vehicles, trailers, and semi-trailers and the Final Production system of the German Motor vehicles, trailers, and semi-trailers (2018).

power in global markets. Final consumption is in part enabled by the value capture power of local economic activity, which at the same time depends on processes carried out elsewhere (not appearing either in the consumption- or production-based accounts). The global footprint of this system sustains the economic activity of the German MVI that generates jobs (and therefore salaries) and value added in Germany. It is not the local need for vehicles but the economic activity in their production that is most dominantly presented as the justification by governments to support automobile companies (Di Felice et al., 2021a, 2021b).

2.2. Data

We used EXIOBASE database version 3.81 for years 1995 to 2009, and EXIOBASE v3.9.6 for 2010–2020 (Stadler et al., 2018; Wood et al., 2018; Stadler et al., 2025). The use of two different versions of EXIOBASE is further discussed in the Supplementary Material. This database is a global, multiregional input-output table that contains 44 countries plus the 5 rest of the world regions. This article aims to analyse the regional and sectoral distribution of the footprints in a given year (2018). We chose the year 2018 for the more detailed analysis due to the comparability with the MuSIASEM analysis of 8 EU countries in Pérez-Sánchez et al. (2024).

We use the industry-by-industry EXIOBASE version, which includes 163 economic sectors per country and the rest of the world regions. For the analysis, we will use 3 different levels: the whole supply and final production systems (2), an intermediate disaggregation in sectors (9) and regions (3), and the top 10 for each variable and system from the complete available list of divisions (163 economic sectors) and countries/regions (49).

Furthermore, EXIOBASE contains 3 employment skill levels per gender and 417 emission categories as environmental extensions. In this paper, we select 6 employment hours categories (hours actually worked per skill level and gender), 3 compensation of employees categories (in constant prices), 19 GHG emissions categories that were converted into CO_2 equivalent using the respective Global Warming Potentials (100-year time period). Compensation of employees includes wages, salaries and employers' social contribution. A detailed list of the selected impact categories and conversion factors is provided in SM.

The analyzed impacts are GHG emissions, working hours and compensation of employees. GHG emissions are one of the main variables for sustainability given the urgency for climate change mitigation. Working hours and employment help us explain the income capture of countries and sectors. We also analyse two ratios derived from the impacts: GHG emission rate (kgCO_{2e}/h) and hourly wages (€/h). We normalize the impacts through hours of work for enabling the comparison between systems and sectors. Instead of other typical indicators based on value added (carbon intensity, energy intensity), ratios per hour such as hourly wages and GHG emission rates are closer to biophysical and social realities (Fiorito, 2013; Pérez-Sánchez et al., 2024). Hourly wages allow us to compare the income of workers and analyse possible inequalities related to value capture, unequal exchange and the "smile curve". The GHG emission rate can be a proxy for mechanization, which depends on the type of activity but also on the level of investment and automatization. The analysis of the three variables and their ratios enables exploring whether specific activities and countries get the economic profits without contributing directly to the climate impacts.

2.3. Calculation

We estimate the embodied GHG emissions and employment (in hours and compensation of employees) in two final demands: 1) Global final demand for German motor vehicles (Final production system) and 2) German final demand for motor vehicles worldwide (Supply system). To do so, we apply a demand-driven, environmentally-extended multiregional input-output model (Miller and Blair, 2021). Mathematically, the embodied impacts of a final demand ($E_{i,c}$) can be described as follows:

$$E^{i,c} = \widehat{f^i} \cdot L \cdot y^c \quad (1)$$

where:

- i = impact i (i.e., GHG emissions, employment hours, and employment compensation),
- c = country c,
- $\widehat{f^i}$ = diagonalized intensity impact vector, in which $f^i = F^i \cdot \widehat{x}^{-1}$ = direct impact F^i by industry-country divided by total economic output x of each industry-country,
- L = Leontief inverse matrix, in which $L = (I - A)^{-1}$ where A is the matrix of technical coefficients or direct requirements matrix, and I, the identity matrix,
- y^c = final demand of country c vector, in which $y^c = Y^c \cdot 1^y$ = row-wise sum of all final demand categories for country c.

Considering the impact multipliers (M^i) as:

$$M^i = \widehat{f^i} \cdot L \quad (2)$$

then, the embodied impact of a country c final demand can be expressed as:

$$E^{i,c} = M^i \cdot y^c \quad (3)$$

Here, we choose specific final demands to unravel two supply chains related to MVI in Germany, which generate two modified versions of Eq. (3). A diagram of the blueprint of these calculations in a multiregional input-output table can be found in Fig. 2.

For the impacts of the Final production system ($E^{i,global}_{MVI-DE}$), we select the global final demand for the German motor vehicle industry $\left(y^{global}_{MVI-DE}\right)$. Then, Eq. (3) can be expressed as follows:

$$E^{i,c}_{MVI-DE} = M^i_{MVI-DE} \cdot y^c_{MVI-DE} \quad (4)$$

where MVI-DE indicates the German motor vehicle industry, i to the industry-country of production and c to the country of final demand (all countries' final demand categories). M^i_{MVI-DE} is a 7987 × 1 vector of requirements and y^{global}_{MVI-DE}, a scalar.

On the other hand, the impacts of the Supply system are calculated through the German final demand for motor vehicle industry in all countries $\left(y^{DE}_{MVI-co}\right)$. This is expressed as:

$$E^{i,DE}_{MVI-world} = M^i_{MVI-co} \cdot y^{DE}_{MVI-co} \quad (5)$$

Here, M^i_{MVI-co} is a 7987 × 49 matrix of requirements and y^{DE}_{MVI-co} a 49 × 1 vector. The country of final demand is Germany, and *co* refers to the countries whose MVI supplies Germany of final products of MVI.

3. Results

3.1. Final demands

Final Demand (FD) gives us a first hint of how the global value chains of production and consumption overlap. While Final demand is a first proxy of externalization showing the country of completion of products and services for final consumption and capital formation. These final demands are the base for the calculation of the two systems that we are going to explore in the next sections, where we unravel the global value chains related to the German final demand for MVI (Supply system) and the Global final demand for German MVI (Final production system).

The demand for German MVI has been larger than the German final demand for MVI during the whole time series (Fig. 3). In 2018, the Global FD for German MVI (322,600 million euros) was 1.88 times that

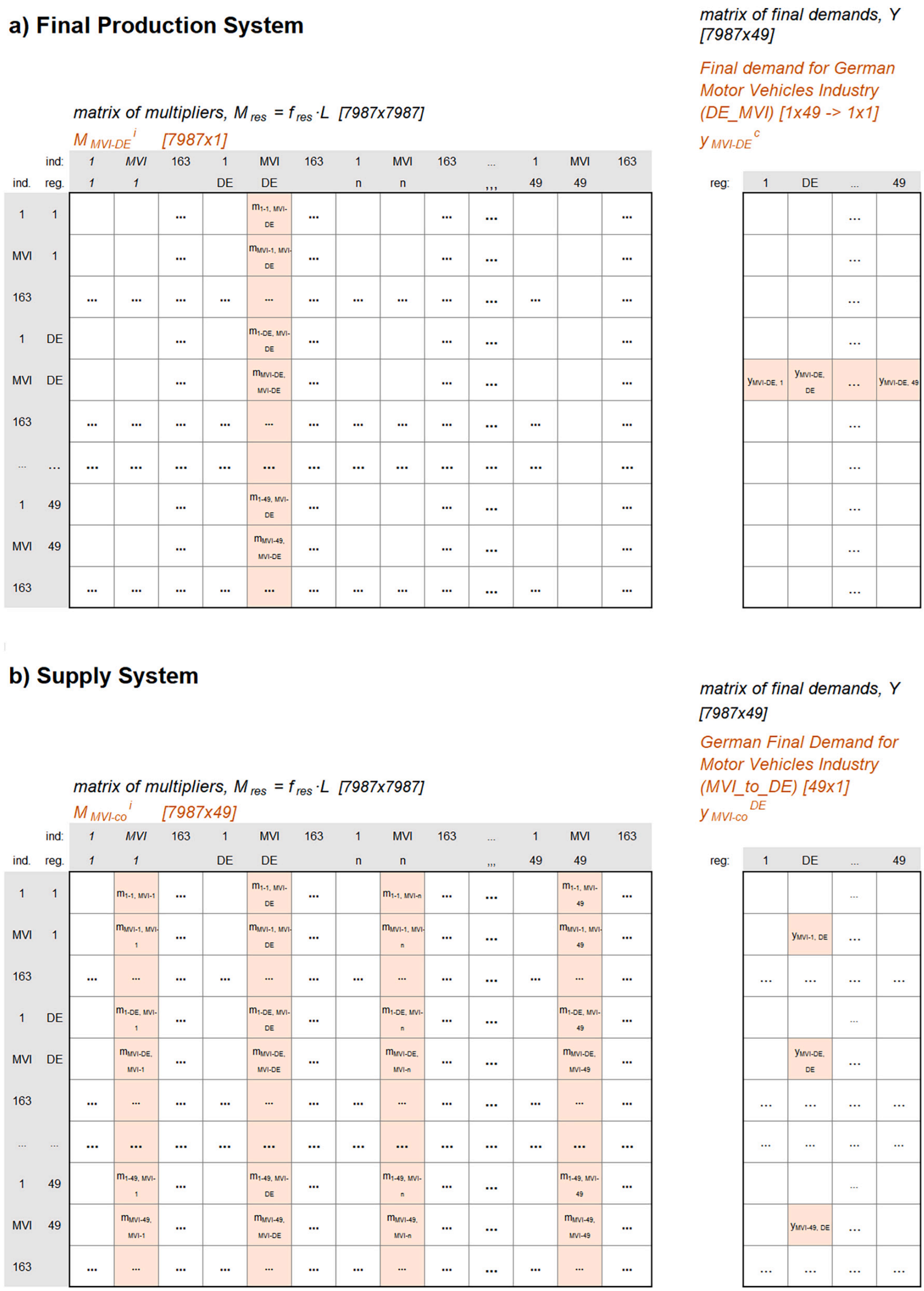

Fig. 2. Matrixes for calculating embodied impacts: matrix of multipliers (M) and final demands (Y). The elements highlighted in orange are those that play a role in the calculations of the two Systems: (a) Final production system and (b) Supply system.

of the German FD for MVI (171,306 million euros) (Fig. 1). The German FD for German MVI was 99,985 million euros, which is the final demand common to the two systems. These are the vehicles and parts that were both produced and sold in Germany. It represents 58% of the German FD for vehicles and only 31% of the global FD for German MVI. In other words, less than half of the German demand was not fulfilled by vehicles "made in Germany" and global markets purchased two thirds of the "made in Germany" final vehicle products. Apart from Germany itself, the largest suppliers of vehicles to Germany in 2018 were France (4%), Czechia (4%), and Spain (3%), and the largest export countries were the

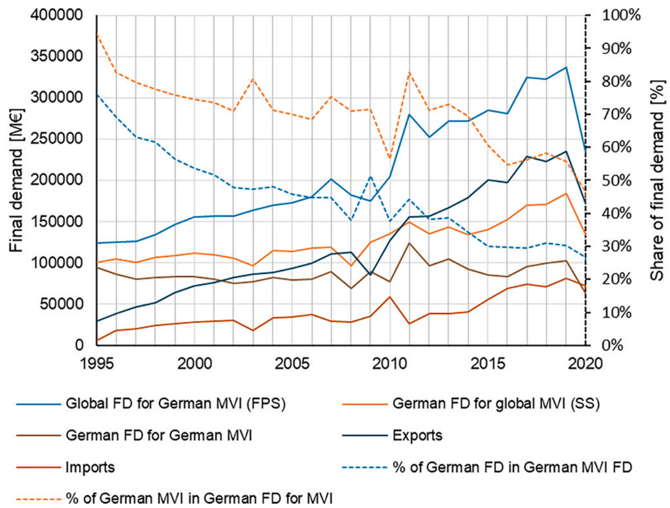

Fig. 3. Global final demand for German MVI and German final demand for MVI, and German final demand for German MVI, and the percentages of German final demand for German MVI in global final demand for German MVI German final demand for German MVI in German Final demand for MVI (1995–2020).

US (11%), China (11%) and Great Britain (5%) (see SM).

To put in context the year 2018, Fig. 3 shows the time series of final demand from 1995 to 2020. The final demand for German MVI grew during the time interval thanks to exports. German final demand for MVI also increased but thanks to imports. The German Final Demand for German MVI, the domestic demand fulfilled by domestic industry, has remained relatively constant. This makes that the percentage of German final demand fulfilled by German MVI decreased from 94% in 1995 to 56% in 2019. On the other hand, the percentage of German FD in the total FD for German MVI decreased from 76% to 34%. This is due to the high increase of exports, which more than tripled in the time interval. These monetary values correspond to a variety of products (Fig. 4). In 2018, the production of vehicles in the German MVI amounted to 4.9 M passenger cars, 6059 buses, 181,370 heavy trucks, 367,279 LCVs (European Automobile Manufacturers Association, 2019), plus other types of vehicles, parts, and services. Therefore, it mostly produces cars. In the same year, the total sales/registrations of vehicles in Germany were 3,435,778 passenger cars (ACEA, 2022), 6687 motor coaches, buses and trolley buses (Eurostat, 2025) and 321,767 lorries (Eurostat, 2015a). The total sales in Germany have been relatively steady over the time interval, between 3 and 4 M vehicles. Production outweighs the German demand for vehicles, confirming Germany's position as a net exporter both in units of products and in value (Pérez-Sánchez et al., 2024). However, the gap between production and consumption of vehicles has decreased sharply since 2017, mostly due to the decrease in production of passenger cars in Germany. While the decrease in produced vehicles started in 2017, their monetary final demand only started decreasing in 2020 (Fig. 3). The profit of some main companies also started decreasing in 2017 (Keil and Steinberger, 2024).

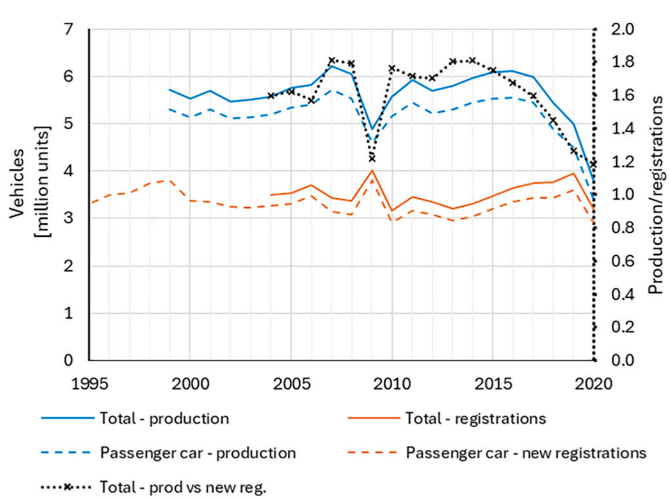

Fig. 4. Production and new registrations of passenger cars and other vehicles in Germany 1995–2010. Production data (OICA, 2021). Passenger car new registrations (European Automobile Manufacturers Association, 2019). Lorries and buses new registrations (Eurostat, 2015a, 2015b).

3.2. *Total impacts*

The footprints of Final production (FPS) were larger than Supply system (SS) in the whole time series for the three dimensions of analysis (Fig. 5 and Fig. 6). In 2018, working time in Final production was 1.3 times that in the SS. GHG emissions in the FPS were 1.4 times those of SS. The larger gap is found for compensation of employees: and vehicle production: the FPS generated 1.8 times more wages and 1.4 times more vehicles than the SS. As explained in the previous section, the global final demand for German MVI was 1.63 times the German final demand for MVI.

Fig. 6 shows the trends in time. They show a stronger interannual variability than vehicle production and monetary final demand, making it difficult to identify clear trends. First, we have to consider that 2020 was a year marked by the COVID-19 pandemic. Since this is a very exceptional year, we focus on the rest of the time interval. The clearest trends are those of compensation of employees, which increased. GHG emissions decreased slightly.

The rates (emissions and wages per hour) allow us making qualitative comparisons between the two supply chains. The largest difference comes from the average hourly rate, which was 1.35 times larger in the Final production system in 2018. The system of German Final production captured relatively more income per hour (€18.7/h (FPS)) than the system that provides vehicles to Germany (€13.8/h (SS)). Hourly wages increased over time, with FPS almost doubling from 1995 to 2020. The fundamental difference between the two systems is imports, which have almost half (€10.4/h) the hourly rate in the Final production system (€18.7/h). GHG Emission Rates were almost the same in 2018 in the two systems: 7.8 $kgCO_{2e}/h$ for FPS and 7.6 $kgCO_{2e}/h$ for SS. GHGER decreased over the period (1995–2020).

3.2.1. *Geographical distribution of the impacts*

Jobs, GHG emissions and salaries were unevenly geographically distributed in the Supply and Final production systems (Fig. 7, Fig. 8 and Fig. 9). The share of German participation in the footprints has decreased through 25-year period (Fig. 9). The exception is working time in the Final Production System, which follows a V shape. First, the participation slightly decreased until 26% in 2008 and then after 2010, it increased reaching 50% of working time in 2017 and 2020. Due to the low participation of Germany in imports, the German share in footprints is different in the two systems. Thus, we describe the regional distribution of each system separately in the next subsections.

3.2.1.1. Final production system. The economic activity generated in Germany in the FPS required intermediate parts and other inputs from other countries, with their associated embodied working time and GHG emissions. In the FPS in 2018, Germany obtained 73% of the compensation of employees, employing only 46% of the working time and emitting 37% of the GHG. While most of the income was captured in Germany, foreign countries generated most of the emissions and provided most working time for the production of vehicles "made in Germany". The generation of 104,000 million euros of salaries in Germany was related to the emission of GHG abroad (24 Mton CO_{2e} in RoEU and

			Footprint			per hour of work		per vehicle			
	Final demand	Vehicles	Working time	GHG emissions	Compensation of employees	GHG Emission Rate	Hourly Rate	Final demand	Working time	GHG emissions	Compensation of employees
year 2018	1000 M€	million	Mh	Mton CO_{2e}	1000 M€	kg CO_{2e}/h	€/h	€/veh	h/veh	ton CO_{2e}/veh	€/vehicle
Final production	323	5.6	7617	60	142	7.8	18.7	57864	1366	10.7	25554
of which exports	223		5257	41	98	7.8	18.7				
Supply	171	3.8	5740	43	79	7.6	13.8	45434	1528	11.5	21063
of which imports	71		3379	25	35	7.4	10.4				

Fig. 5. Summary table of final demand, vehicle production, footprints and resource requirements per vehicle in the Final production and Supply systems, exports and imports (2018).

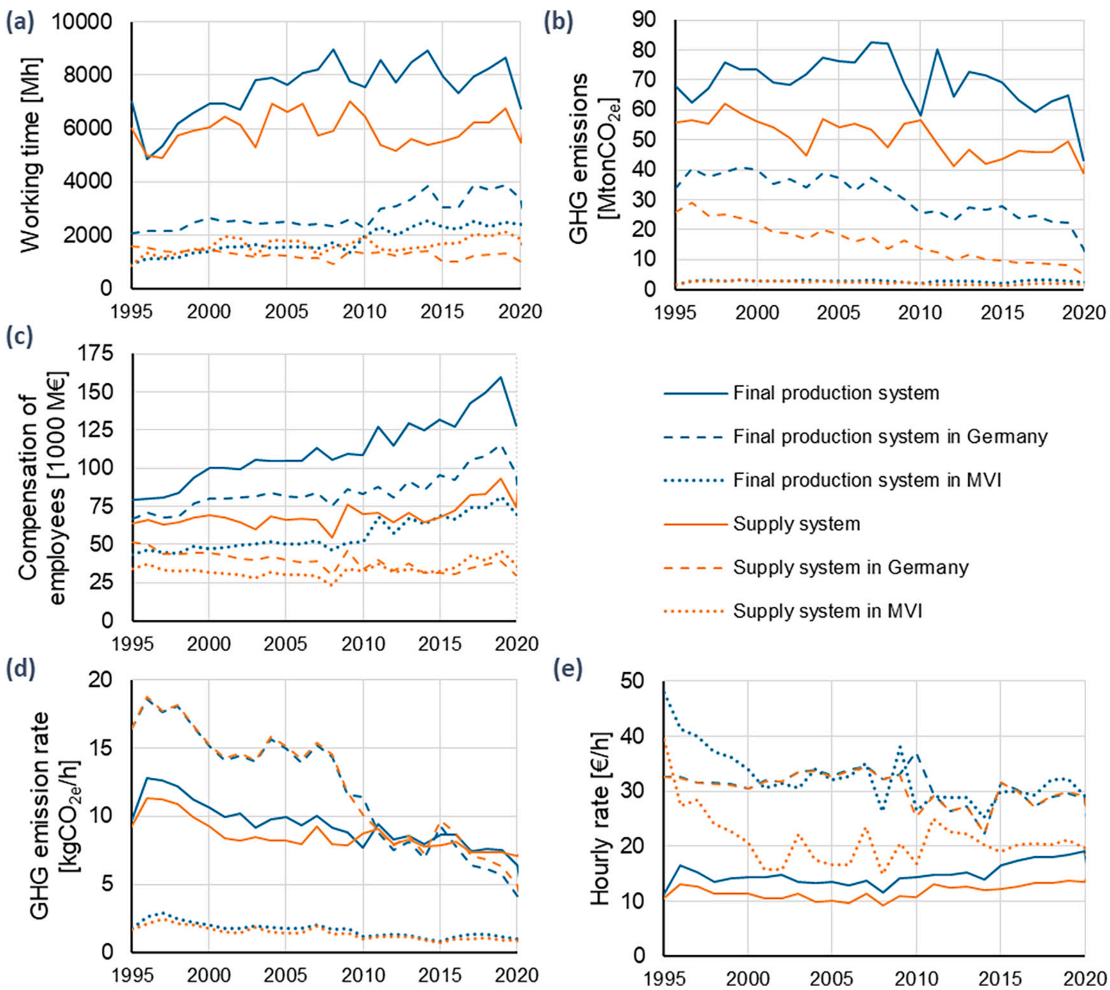

Fig. 6. Time series of (a) working time, (b) GHG emissions, (c) compensation of employees, (d) GHG emission rate and € hourly rate in the Final production (blue) and Final Demand systems (orange) and their parts in Germany (dashed lines) and the MVI (dotted lines) (1995–2020).

14 Mton CO_{2e} in RoW) for the production of "made in Germany" motor vehicles (German FPS of motor vehicles).

Despite representing 29% of the FPS working hours footprint in 2018, the Rest of the World only received 20% of the salary footprint. This region a higher GHG emission rate (9.0 kgCO_{2e}/h) than Germany. RoW had an hourly salary of €5.3/h, which is the lowest and very low compared to the FPS average (€18.7/h).

3.2.1.2. Supply system. The Supply system represents the production network of the MVI final products purchased in Germany, which includes imports. Therefore, the participation of Germany it is expected to be lower compared to the Final Production System for the three impacts, while the shares of RoEU and RoW increase. The largest difference is the compensation of employees in the EU, which almost doubles their hourly wages compared to FPS (Fig. 7 and Fig. 8). While German participation in the FPS working hours footprint (46%) doubled that in the SS (21%), Germany still got 44% of the compensation of employees in the SS. This means that the purchase of motor vehicles in Germany generated 44% of wages in Germany, disproportionately to its low contribution in terms of employment (21%) and emissions (19%). This lower participation in the SS compared to FPS is due to the limited role of Germany in imported vehicles, where it represents only 8% of compensation of employees and 3% of working time (Fig. 8c). For imported vehicles, most of the compensation of employees goes to RoEU (59%), whereas most of the GHG emissions (63%) and working time (63%) occur in the RoW.

year 2018		Working time			GHG emissions			Compensation of employees			GHG Emission Rate	Hourly Rate
System	Region	Mh	% system	%NA	Mton CO_{2e}	% system	%NA	1000 M€	% system	%NA	kg CO_{2e}/h	€/h
Final production	Germany	3513	46%	5.4%	22	37%	3.4%	104	73%	6.5%	6.4	29.5
	Rest of the EU	1398	18%	0.5%	13	22%	0.5%	24	17%	0.5%	9.3	17.5
	Rest of the World	2707	36%	0.0%	24	41%	0.0%	14	10%	0.1%	9.0	5.3
Supply	Germany	1184	21%	1.8%	8	19%	1.3%	35	44%	2.2%	7.1	29.7
	Rest of the EU	1587	28%	0.5%	12	27%	0.4%	28	36%	0.5%	7.3	17.7
	Rest of the World	2970	52%	0.1%	23	54%	0.1%	16	20%	0.1%	7.8	5.4
Imports	Germany	95	3%	0.0%	1	6%	0.2%	3	8%	0.2%	15.8	31.2
	Rest of the EU	1154	34%	0.1%	8	31%	0.3%	21	59%	0.4%	6.6	17.8
	Rest of the World	2131	63%	0.0%	16	63%	0.0%	11	33%	0.0%	7.4	5.4

Fig. 7. Summary table of impacts in the Final production and Supply systems (2018), by region of completion (Germany, rest of European Union and the rest of the world). This includes the percentage of the system per region (%system) and the percentage of the system by region by the total regional national accounts (%NA: production-based accounts of each region: Germany, rest of the EU and rest of the world).

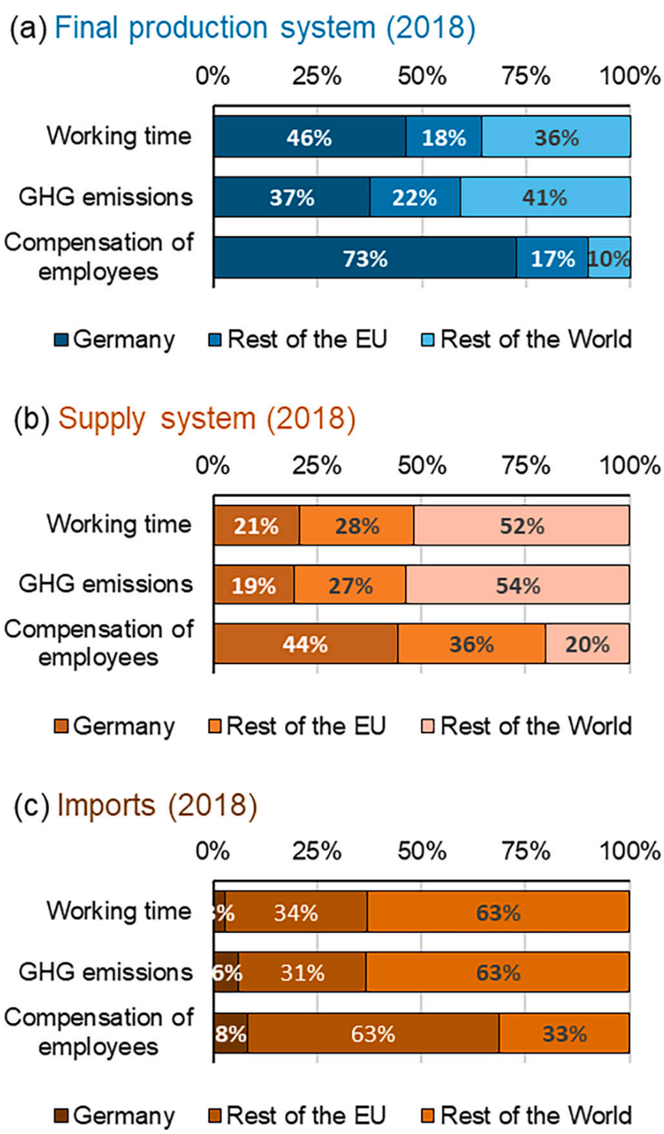

Fig. 8. Share of impacts in (a) the Final production system, (b) Supply system and (c) imports by country/region in 2018.

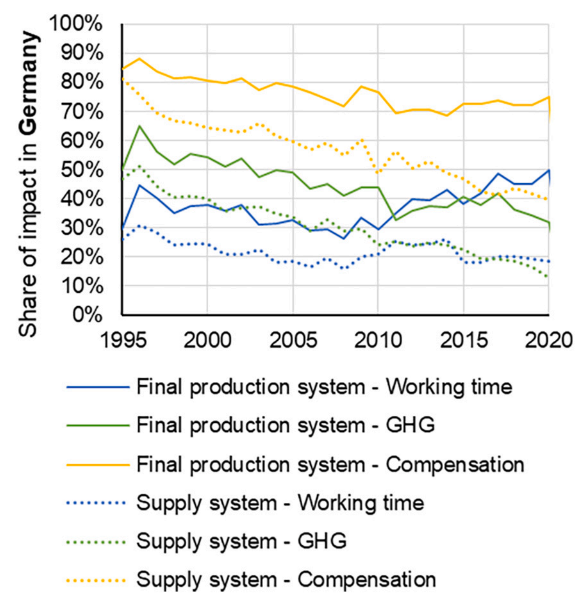

Fig. 9. Share of the three impacts in Germany in the two systems (1995–2020).

As it happened in the Final Production System, RoW was the largest contributor in terms of employment while it received the lowest share of salaries. The RoW showed the highest share in the SS footprint for GHG emissions (54%), followed by working time (52%), and the smallest for compensation of employees (20%). The role of the Rest of the EU in the SS also increased compared to the FPS. RoEU working hours (28%) in the SS even surpassed those from Germany (21%).

3.2.1.3. Rates. The rates help us understand this uneven regional distribution of impacts. In 2018, hourly wages were the same within each region regardless of the system. The largest are those for Germany (€29.5–29.7/h), intermediate for the Rest of EU (€17.5–17.7/h) and lowest for the Rest of the World (€5.3–5.4/h). In time, German hourly wages have kept constant and even slightly decreased (Fig. 6), while the average hourly wage in both systems have increased, most notably for the final production system. This shows a slight convergence trend in salaries among regions. By the end of the time interval of analysis, around half of the German final demand for motor vehicles are imports. While the role of Rest of the EU in the FPS is an upstream supplier to the German MVI, Rest of the EU is the final producer of motor vehicles in these imports and can thus capture a larger proportion of value.

GHG emission rates are a proxy of mechanization of the activities and are quite similar in most regions and systems. Imports in Germany (15.8 kg CO_{2e}/h) are the highest, while FPS in Germany is the lowest (6.4 kg

CO_{2e}/h). During the time interval, GHGER have decreased sharply in Germany from 16.4 kg CO_{2e}/h in 1995 to 4.1-4.9 kg CO_{2e}/h in 2020, with 2009 as a key turning point year. This might be related to the increasing reliance on upstream processes abroad. Another of the drivers of such decrease has been the decrease in carbon intensity of the German electricity mix, from 594 gCO_{2e}/kWh in 1995 to 312 gCO_{2e}/kWh in 2020 (European Environment Agency, 2024).

3.2.2. Sectoral distribution of the impacts

The sectoral distributions of the footprints are similar in the two systems (Fig. 10 and Fig. 12). The MVI captured in 2018 50–52% (SS-FPS) of the compensation of employees, with only 34–30% of working time and, most differently, 5% of GHG emissions. Therefore, this sector is able to capture a lot of value with very low direct impacts. The shares of MVI participation in the footprints have been quite constant with small fluctuations during the time series 1995–2020 (Fig. 11). We find two exceptions: (i) compensation of employees, which decreased about 10% during the 90s and then increased again, and (ii) working time in the FPS which started around 20% in 1995–2009 to then grow linearly reaching 35% in 2020.

Less than half of the compensation of employees generated in the systems was distributed among the rest of the sectors, as MVI obtains around 51%. Other sectors relevant for salaries were *Product industry*, *Other services* and *Offices*, with around 12% in both systems. The activities that captured most income do not emit GHG with the same intensity, having all low GHG emission rates (2 kgCO_{2e}/h or lower). All the activities that captured more salaries had either high hourly wages (such as *Office work*) or working time (*Product industry* and *Other Services*). Working time was more evenly distributed among sectors but the top-3 sectors after MVI (34–27%) were the same as the ones that received more compensation of employees: *Other services* (25–21%), *Product industry* (15%), and *Office work* (10–8%).

The sectoral distribution of GHG emissions is very different. *Basic industry* (34%) and *Utilities* (32–31%) emitted the largest shares of GHG in both systems. Therefore, an energy transition could have an important impact in climate mitigation of vehicles. At the same time, the 34% of emissions generated by *Basic industry* will be harder to abate.

Offices and Other services generated together around 8–9% of emissions. These sectors are not usually considered in Life Cycle Assessment inventories, and therefore this could give a measure of the GHG emissions in production of vehicles that are overlooked by LCA (Agez et al., 2020; Suh et al., 2004).

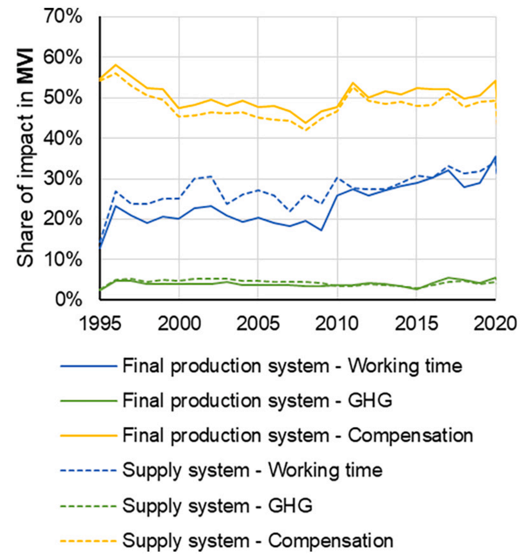

Fig. 11. Share of the three impacts in MVI in the two systems (1995–2020).

3.2.2.1. Participation of Germany in the sectors.

The participation of Germany in the sectors was uneven (Fig. 10). The share of compensation of employees that stayed in Germany was high for most activities in the Final Production System, with at least a 40% of the sectors except *Primary* and *Mining*, while in terms of working time it stayed generally below 20% except for MVI and *Other services*. The largest participation of Germany was in MVI. In this sector, the average hourly wage was also the highest (32.2€/h in FPS and 20.4€/h in the SS). In general, the largest the participation of Germany, the largest its hourly wages (except for *Other services*). Exceptions for the high participation of Germany in compensation of employees were *Primary* (8% FPS and 5% SS) and *Mining* (20% FPS and 13% SS). These two sectors also had the lowest hourly wages (€1–3/h). Our results confirm the economic geography literature that shows how Germany specialized in the final stages of production of higher-end cars with a niche demand that are sold in global markets offshoring upstream activities (Chiappini, 2012; Gerőcs and Pinkasz, 2019; Krzywdzinski, 2014; Pérez-Sánchez et al., 2024). These tasks generated income and jobs in Germany at expenses of GHG emissions and a larger amount of working time abroad in upstream

2018		Working time			GHG emissions			Compensation of employees			GHG Emission Rate	Hourly Rate	GHG emissions per €
System	Sector	Mh	% system	% in DE	kton CO_{2e}	% system	% in DE	M€	% system	% in DE	kg CO_{2e}/h	€/h	kg CO_{2e}/€
Final production	Primary	409	5%	1%	2046	3%	12%	370	0%	7%	5	0.9	5.52
	Mining	53	1%	2%	4272	7%	1%	599	0%	0%	81	11.3	7.13
	Basic industry	628	8%	18%	20020	34%	38%	10621	7%	44%	32	16.9	1.88
	Product industry	1161	15%	27%	1723	3%	28%	15957	11%	50%	1	13.7	0.11
	Motor vehicles ind.	2316	30%	72%	3102	5%	79%	74539	52%	89%	1	32.2	0.04
	Utilities	47	1%	34%	19131	32%	45%	776	1%	61%	410	16.6	24.64
	Transport	371	5%	23%	3894	7%	16%	4697	3%	42%	11	12.7	0.83
	Other services	1903	25%	53%	4539	8%	39%	17629	12%	67%	2	9.3	0.26
	Office work	731	10%	42%	882	1%	47%	17277	12%	62%	1	23.6	0.05
Supply	Primary	353	6%	0%	1592	4%	6%	303	0%	4%	5	0.9	5.26
	Mining	46	1%	1%	3589	8%	1%	487	1%	0%	77	10.5	7.36
	Basic industry	529	9%	9%	14622	34%	21%	7188	9%	28%	28	13.6	2.03
	Product industry	889	15%	14%	1277	3%	15%	9780	12%	33%	1	11.0	0.13
	Motor vehicles ind.	1952	34%	27%	2176	5%	36%	39774	50%	53%	1	20.4	0.05
	Utilities	36	1%	16%	13484	31%	24%	450	1%	38%	377	12.6	29.95
	Transport	243	4%	12%	2845	7%	9%	2594	3%	27%	12	10.7	1.10
	Other services	1231	21%	27%	3206	7%	19%	9488	12%	42%	3	7.7	0.34
	Office work	462	8%	23%	548	1%	26%	9080	11%	41%	1	19.7	0.06

Fig. 10. Impacts and rates in the Final production and Supply systems (2018), by sector. This includes the percentage of the sector in each system (%system) and the percentage of the sector in the system that happens in Germany (% in DE).

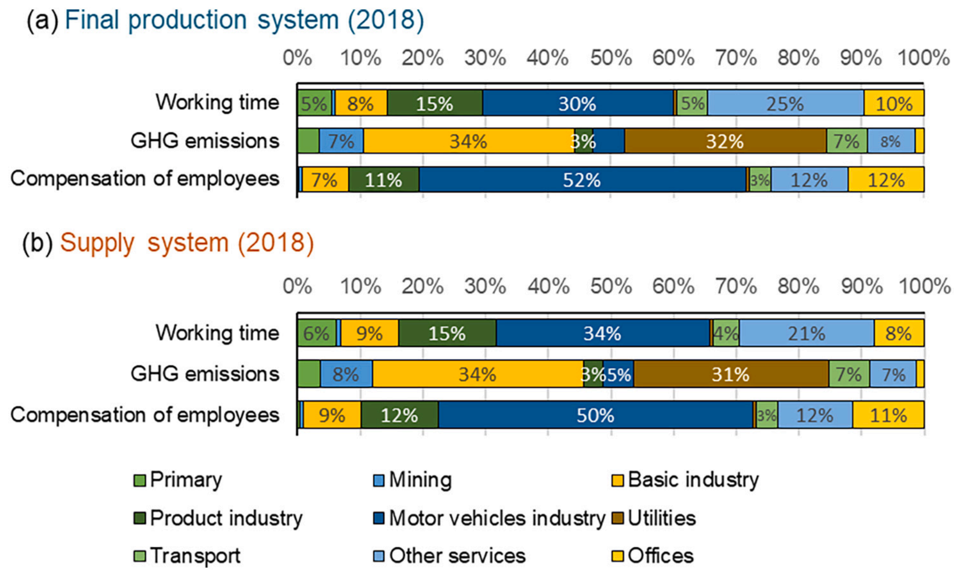

Fig. 12. Share of impacts by sector in the (a) Final production system and (b) Supply system of motor vehicles to Germany and in 2018.

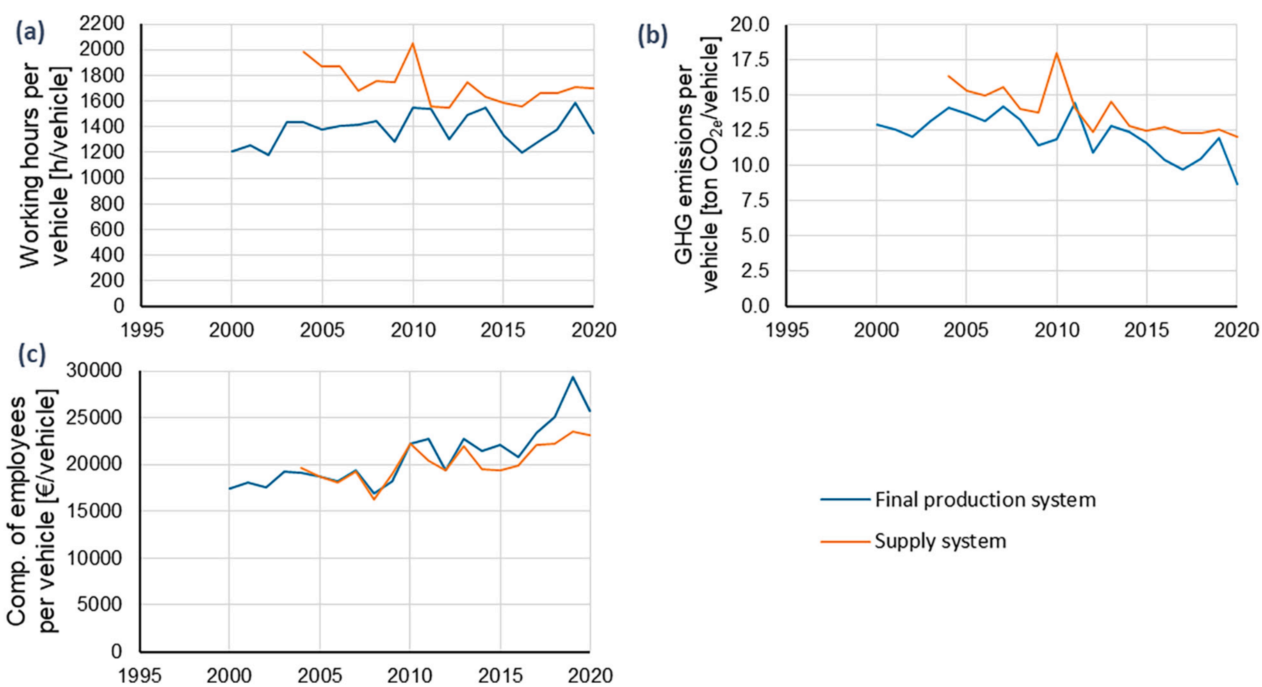

Fig. 13. Resource requirements per vehicle (2000–2020): (a) working hours, (b) GHG emissions and (c) compensation of employees.

activities.

3.2.3. Resource requirements per vehicle

Fig. 13 shows an estimation of the resource requirements per vehicle by dividing the footprint per the number of vehicles produced in each system. The trends and values of footprint requirements per vehicle are similar in both systems. The Supply system has slightly higher working hours and GHG emissions per vehicle. In 2018, the production of a "made in Germany" vehicle generated 10.7 ton CO_{2e} (of which 4 t in Germany), and €25,554 (€18,597 in Germany), and required 1366 h of work (630 h in Germany). The differences in hourly rates (a proxy of labour productivity) in SS and FPS are very large compared to the small differences in physical vehicle productivity, where both systems have a similar number of working hours per vehicle.

To contextualise these values, the working time footprint of a vehicle in Germany is equivalent to the annual workload of the average German worker (Pérez-Sánchez et al., 2024). If all workers across the production chain of "made in Germany" vehicles were paid the average German salary (€29.5/h), the total embedded salary cost per vehicle would amount to €40,297.

The carbon footprint of vehicle production is in the range provided by Life Cycle Assessment in Buberger et al. (2022), where our results for 2018 are similar to a Mercedes-Benz C 300, a Diesel PHEV car of 2060 kg. However, for most of the rest of the time interval and the two systems, our results are higher. This could be explained by the fact that we have a product mix with passenger cars and larger vehicles (with larger impacts) and other parts for maintenance of the current fleet. Cars represented 91% of vehicles produced in Germany in 2018 (Fig. 4). Moreover, MRIO-based footprints include service sectors, accounting for about 9% of the GHG emission footprints in this paper, that are typically excluded from Life Cycle Assessments. At the same time, the embodied impacts of production capital such as factories are not included in IOT-based footprints. As such, the resource requirements per vehicle presented should be interpreted as a first approximation for cars, likely on the higher end.

4. Discussion

4.1. Regional distribution: the role of Germany

The industry and country that carries out the final stage of production is what uses to be identified as the "producer" of the vehicles. However, significant impacts abroad were necessary to produce vehicles "made in Germany". Germany got most compensation of employees while it relied on work and emissions abroad.

Through its Final production system, Germany provided vehicles to world markets with high wages, while the German society increasingly purchased a larger share of vehicles manufactured abroad with lower salaries. The Final production system was more centered in Germany, while the Supply system relied more on foreign processes and impacts due to the role of imports. The differences in hourly wages and participation by country and sector determine the differences in the average hourly wages in each system. Germany designs, assembles and sells higher-end vehicles with limited global demand (Chiappini, 2012; Gerőcs and Pinkasz, 2019; Gracia and Paz, 2017; Krzywdzinski, 2014; Pérez-Sánchez et al., 2024). Therefore, Germany's role in the global system is not generalizable to other countries.

We also see a dual role and performance of the Rest of the EU. When it participates as an upstream supplier for the German Auto industry, it has a smaller share of wages than as an importer of final vehicles for German consumption. In that case, it has 50% more of wages than as a supplier of intermediate parts. Throughout the period of analysis (1995–2020), the supply system of motor vehicles to Germany has remained smaller than the final production system, an expected outcome given Germany's role as a net exporter of vehicles.

To capture the full economic activity related to domestic motor vehicle use, we should include the sector *Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motor cycles parts and accessories*, 21% of which is already considered within the FPS footprint and 7% in the SS footprint. This sector directly employed 3562 Mh, generated 2.5 Mton CO_{2e} and €27,422 million of compensation of employees in 2018 according to the Exiobase satellite accounts (Merciai and Schmidt, 2018; Stadler et al., 2018; Stadler et al., 2025). Therefore, we see that apart from the work in MVI and upstream processes, sales and maintenance are important for employment. Further work could consider this sector in a consumption-based perspective to make a more complete metabolic assessment of mobility in Germany. The emissions of these sale and maintenance ancillary sectors are very small, but while the supply system GHG emissions footprint was of 43 Mton CO_{2e} in 2018, the direct emissions of road transport in Germany in the same year were 167 Mt CO_{2e} (German Environment Agency, 2025). Therefore, the footprint of GHG for production of motor vehicles are significant compared to the direct operational emissions of German motor vehicle fleets.

4.1.1. Comparison to existing literature

Our results are consistent with historical analyses of the evolution of the spatial division of labour and core-periphery relationships between Germany and Eastern European Countries (Gerőcs and Pinkasz, 2019; Krzywdzinski, 2014; Lung, 2004). To the best of our knowledge, the most common approach of consumption-based impacts (here Supply system) has not been used for sectoral contribution analysis and the geographic distribution of its global value chain impacts for the MVI before. Existing comparable results are in the line of the Final production system (vertically integrated production of German Motor vehicles) and its regional distribution. Los et al. (2015) and Timmer et al. (2015) calculated that the local value added content in final goods from the transport equipment industry in Germany was 66% in 2008 and 79% in 1995. We have not calculated value added, but we can use compensation of employees as a proxy for comparison: German salary content was 85% in 1995 and 72% in 2008. These values are also similar to the local unit labour costs in Gracia Santos et al. (2024) (80% in 2007) for the German automotive industry in 2007.

Timmer et al. (2015) also indicate that 19% of the value added of final output value in Germany was generated within the rest of Europe in 2008. In this paper, we calculated that 13% of compensation of employees was generated in the RoEU in 2010. Fana and Villani (2022) calculated with WIOD that the foreign labour in the final exports of automotive supply chains of Germany in 2007 and 2014 was right above 55%. Our results for final production of German MVI are 70.5% (2007) and 56.9% (2014).

4.2. Sectoral distribution: the role of the motor vehicles industry

Both systems had a similar sectoral distribution of impacts, where MVI took half the compensation of employees while it emitted only around 5% of GHG emissions in the whole time interval of analysis. While most compensation of employees stayed in MVI, GHG emissions were produced in *Utilities* (which includes the electricity system and most importantly, coal electricity in this case (see SM)), and *Basic industry* (generally hard-to-abate sectors related to material refining and transformation).

MVI showed a high salary generation capacity at a relatively low emission intensity and job requirements, making it a paradigmatic example of the smile curve, where value capture is concentrated in engineering and other office activities, and the final assembly of some products. This may be a sign of the control that the Original Equipment Manufacturers have over the suppliers in the value chain, and the possibility of assigning higher value added to their products (Frigant, 2011). Hourly wages depend on the sector, but also on its location: in general, the higher share of activity within Germany, the higher hourly wages.

4.3. Footprints, environmental and social responsibility

Existing literature has reflected on how footprint accounting assigns responsibility to producers and consumers, linking it with different policy approaches (e.g., production-based accounting to the producer-pays principle) (Munksgaard and Pedersen, 2001; Steininger et al., 2016; Tukker et al., 2020) and proposing alternative footprint indicators such as those based on value added and income (Liang et al., 2017; Marques et al., 2012; Piñero et al., 2019) and shared responsibility metrics (Cadarso et al., 2012; Lenzen and Murray, 2010; Marques et al., 2012; Rodrigues and Domingos, 2008). These studies have predominantly focused on national footprints.

In this article, we provide a sectoral analysis of MVI by comparing two different producer and consumer footprint approaches. Our approach includes the upstream emissions necessary for the manufacturing of the final products exploring their backward linkages. Since both footprints are related to a relatively similar set of final products related to MVI and Germany following the consumption-based logic, they can be compared and in fact overlap. The footprints driven by two different final demands presented in this paper can inform different policy approaches to tackle social and environmental sustainability and supply risk. Further work could assess specific policies and systemic change through scenarios.

However, the footprints of the motor vehicles industry unraveling the upstream production chains are not enough for assessing environmental sustainability. The production of motor vehicles sustains the reproduction of fleets in Germany and commits future GHG emissions of their use. This kind of responsibility of the Motor Vehicles Industry is not integrated in the sectoral footprints we quantified here, but we have also provided some first data. The supply system footprint represents only around 25% of road vehicles production and use emissions in Germany due to the centrality of internal combustion vehicles (ICEV), as shown in Section 4.1, which is in the line of previous LCA analyses of vehicles (Wolfram et al., 2020; Bauer et al., 2015). And therefore, for assessing the whole environmental implications of motor vehicles, a broader perspective is needed where both manufacturing, repair, sales and use of vehicles and construction of roads and other infrastructure are included. The footprints in this paper include sectoral and regional hotspot analysis that show the potential for decreasing emissions in manufacturing through, for example, a renewable electricity mix. An ICEV produced with a lower carbon-intensity electricity mix will have a lower product carbon footprint. However, this action alone will have a limited effect on the overall sustainability of the system, since it won't decrease the operational emissions, which are very large in the case of ICEVs. The main objective of the paper was to explore the unequal exchange relationships and smile curve related to consumption and production, which entail a larger share of GHG emissions and working hours with fewer income returns in certain sectors and regions.

Consumption-based accounts help understand the impacts of final consumption, but miss part of the impacts due to the economic activity that provides income to support this consumption (both locally and abroad). About two thirds of the German MVI final production footprint in 2018 were caused by exports. Therefore, in a consumption-based approach these 2/3 of impacts would be allocated to the countries where these vehicles are purchased and only 37% is included in production-based German accounts. Consumer footprints tell part of the story. Citizens have a relative degree of agency over their mobility decisions, which include purchases of vehicles. However, the German MVI has even more power over the supply chain through the selection and conditions of suppliers and shapes the future use of those vehicles and their operational emissions with decisions such as design (size, materials, etc.), and type of powertrain and fuel.

The supply chain is unveiled through the FPS footprint, where we have seen the unequal distribution of salaries, employment and GHG emissions, which confirms the existing literature on the smile curve, allocating more value to design and assembly compared to intermediate materials and parts, and unequal exchange, which shows how specific countries capture more value. Not only is final consumption based on unequal exchange, but also the production of these higher-end and niche products and its associated large economic profits in Germany are sustained on global production networks based on inequality. Germany and MVI capture most of the salaries and produces local well-paid jobs, while GHG and lower-paid jobs are generated elsewhere. Having control over the final product and the symbolic power of the brands is key to having control over the value that is added in this final step of production. The MVI has a special position compared to other industries due to path dependencies sustained by the large amounts of knowledge and infrastructure necessary for the production of vehicles. We see also how the SS and FPS supply the same products, having a similar percentage of passenger cars in their product mix in 2018 (89%). However, they hold different levels of income capture power, shown by the different salary per hour rates and the final demand per vehicle. Our results support the existing literature identifying MVI as a core industry. Moreover, the influence of MVI reaches its peak in Germany thanks to the path dependency of MVI and the specific reputation for German quality manufacturing and engineering. This allows the German MVI to capture more value than other MVIs (for example comparing the rates of the final production and supply systems).

However, this position can shift quickly. The sustainability transition which could entail electrification and sufficiency measures such as smaller and fewer vehicles poses risks for the German MVI, stuck on the production of high-end and large vehicles with fossil-based engines. These risks also extend to its suppliers. Despite having lower returns on economic activity than Germany, periphery supplier countries to the German MVI also depend on this economic activity and can suffer losses with a change of consumption patterns or policy cutting demand of the kind of motor vehicles that Germany produces. However, in our dependency results (see SM), we have seen that this effect is relatively small. For example, the 9% of the activity of Hungarian MVI depends on the production of "Made in Germany" vehicles in 2018. In the last years, vehicle production has decreased substantially in Germany and therefore further work when data is available is needed for unraveling the new international automotive industry context with the rise of China as an EV powerhouse.

4.4. Uncertainties and limitations

The ambition to analyse the division and country sector as much as possible has drawbacks and limitations given by how MRIO tables are constructed. These assume industry homogeneity, meaning that any euro of final demand and intermediate products in a sector in a country will generate the same impacts and profits, even though there is a large diversity of activities and products within a sector-industry (André et al., 2024; Timmer et al., 2015). The different subsectors in the MVI (manufacturing of vehicles, parts and bodies) have different multipliers, and the differences between intermediate parts and final goods is important, as shown in Pérez-Sánchez et al. (2024). Even within the same subsector, we might find a broad variety of products and their qualitative characteristics. We know that vehicles are of different types, segments, and powertrains, and it is uncertain how a more expensive vehicle generates a proportionally larger impact. It is possible that the exported and locally consumed vehicles and parts have different characteristics and that this is not reflected in the calculated resource use. For example, we can see in Fig. 5 how hourly wages and GHG emission rates are the same for the Final Production System and exports. The effects of this assumption have been assessed in literature. The effect of the import proportionality assumption is larger when assessing industrial footprints than in national consumption-based accounts (Schulte et al., 2021). Also, when comparing EEIO with more bottom-up and detailed (but yet not fully comprehensive) Life Cycle Assessment to calculate of carbon footprints of products, significant differences have been found (Steubing et al., 2022). Environmental extensions have been found as having major influence in uncertainty in GMRIOs (Cazcarro et al., 2025; Moran and Wood, 2014; Owen et al., 2014; Tukker et al., 2018). Therefore, the paper's results must be considered as a first approximation.

This double approach can be operationalized via Leontief matrixes in this specific sector because it manufactures products for capital formation and because Germany is focused on the production of vehicles, unlike other countries that are more specialized in intermediate parts for assembly in other countries (Frigant and Miollan, 2014; Gracia and Paz, 2017; Pérez-Sánchez et al., 2024). Therefore, these latter countries would mainly appear as scope 3 for other Motor vehicles industries. The final demand does not necessarily include only final goods but also replacement parts. The calculation will not capture a part of the activity of this industry: the one that does not devote or is related to the production of goods for final consumption but to intermediate parts for other foreign industries and thus would be part of Final product systems from other countries and even industries. As shown in the SM, 25% of German MVI does not appear in the Final production system. This part is also supplied by upstream industries that we will not be able to analyse. This could be considered a limitation of the approach, but the scope of this paper is not to quantify the total weight of the industry in Germany. We aim to quantify the impacts of final motor vehicles for local consumption and locally produced.

Our results end in 2020, a year profoundly marked by the COVID-19 pandemic. Our intention was to examine long-term historical trends prior to this disruption. The COVID-19 pandemic, together with the rapid rise of the Chinese electric vehicle manufacturers have reshaped the market. Consequently, our 1995–2020 results should not be extrapolated. Exiobase 3.9.6 is based on supply and use tables only until 2020 and provides projected values until 2022, but these will most likely not capture the COVID-19 aftermath and the surge of Chinese auto industry. Nonetheless, this work offers valuable insights into the recent evolution of Germany's automotive industry.

5. Conclusions

We calculated through Multi-Regional Input-Output Analysis the labour, salaries and GHG emission footprints and their regional and sectoral distribution of two global value chains: the vertical integration of a sector and derived from its global final demand (Final production system), and the footprint derived from final consumption in a given country (Supply system). We used the case study of the Motor vehicles industry in Germany in 1995–2020. This enables us comparing the footprint of the product as a generator of income to the country and as a good for local consumption.

Emissions, salaries and working time are unevenly distributed among countries and sectors in the global value chains of final production and consumption of Motor Vehicles industry in Germany. The sectoral distribution of the footprints were similar in the two systems. Salary generation was led by the Motor vehicles industry, getting half of the compensation of employees in both systems but emitting only 5% of GHG. In terms of regions, the German motor vehicles industry generated salaries locally while it outsourced the lower value-added and more labour and emission-intensive activities. "Made in Germany" vehicles were produced in fact only partially in Germany, with 46% of working time and 37% of GHG emissions in 2018. We can see thus not only carbon leakage, but also to a form of "working time leakage". Despite this high degree of externalization of impacts and jobs, most of the employees' compensation remained in Germany (73%). Regarding the footprint of the vehicles purchased in Germany, the Rest of the EU took the core role, but didn't reach the German hourly salaries, while the Rest of the World provided proportionally even more working time and emissions.

Therefore, Germany's MVI represents an archetypal case of a core country and industry that captures a disproportionate share of value through design, engineering, and branding while offshoring emission- and labour-intensive stages of production. The social and environmental responsibility goes in different directions, represented by the two footprint approaches in this paper. The German MVI bears responsibility as a powerful buyer of intermediate products, setting the terms of transactions with suppliers. This is sustained by the high reputation of "Made in Germany" products, the path dependency of complex engineering projects such as cars (spanning knowledge-based patents and physical manufacturing infrastructure), and the unequal exchange conditions of the global economy. These factors make it difficult for developing countries to enter or capture significant market share in high-value segments of the automotive industry. However, China has already seized a large share of production, challenging the German long-held leadership in the industry, also due to their wager on electric mobility. The German MVI also has downstream responsibility over vehicle design and type of powertrains that are offered in the market. Currently, it sustains not only the "automotive system" but most specifically locks-in the fossil-fuelled private car system generating GHG emissions out of the scope of the footprints presented in this paper. The resistance to change to alternative powertrains in the German explains partially the shift of demand of German vehicles that challenges this important source of income for the country.

At the same time, citizens and other vehicle users also have a certain degree of power over their consumption. They define the supply system footprint and the size and composition of vehicle fleets over time. Our results show how the footprint of GHG emissions in vehicles purchased in a year in Germany are around one third of the direct GHG emissions of road transport in Germany. This consumption is more based on foreign impacts due to imported vehicles. This paper also provides footprints per vehicle, being this a first approximation of resource requirements per car (considering the product mixes). The GHG emissions per car align with existing life cycle assessment (LCA) results in the literature, decreasing during the time of analysis to around 12–10 ton CO_{2e} per vehicle. Notably, producing a single vehicle in Germany requires approximately 1400 working hours, the equivalent of one year of labour by a German worker. These results can contribute to assess sufficiency, resource requirements of a good life or decent living standards including time use and based on detailed activity levels, for example discussing how many cars are necessary for a good life and its concomitant impacts in production (Druckman and Jackson, 2010; McElroy and O'Neill, 2025; Millward-Hopkins et al., 2025, 2020; Rao et al., 2019; Streeck et al., 2025). These results can also be of interest for the rising field analysing capital formation footprints in MRIO (Södersten et al., 2020, 2018; Wang et al., 2023).

This analysis provides a triple bottom line perspective of global production networks, the uneven distribution of impacts and profits and two diverse ways to account for responsibility and footprints for the German automotive industry. In this paper, we have seen how through 1995 to 2020 the German Motor vehicles industry has produced higher value added export items for final consumption relying largely on cheaper foreign labour and embodied GHG emissions in intermediate parts. This generated an income that is based on GHG emissions that do not appear completely in traditional production- or consumption-based accounts of final consumption of Germany. These different approaches to the impacts of a given industry in a country disaggregated by countries and sectors can help governments examine the effects of national legislation on local and foreign economies and how external agents can increase risks to local industries and provisioning.

CRediT authorship contribution statement

Laura À. Pérez-Sánchez: Writing – original draft, Software, Methodology, Formal analysis, Conceptualization. **Glenn A. Aguilar-Hernandez:** Writing – review & editing, Software.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2026.02.011.

Data availability

Data is available at Zenodo https://doi.org/10.5281/zenodo.18876540

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