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Assessing the sustainability of industrial value chains in Europe: a mapping method proposal

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ABSTRACT

Establishing sustainability policies and business strategies involves mapping environmental, economic, and social factors in an integrative way. In the academic literature, environmentally extended input-output tables have been employed to analyse the relationship between economic flows and their impacts on sustainability. These methodologies require advanced mathematical expertise and do not easily provide a graphical representation to facilitate their interpretation. To fill this gap, this paper develops a unique approach using Power Query that integrates economic, environmental, and employment data to create value chain maps. It also provides examples of the insights gained by applying the method to 12 European countries. The resulting 240 industrial value chain maps represent 94.41% of the industrial emissions in the surveyed countries. This novel and comprehensive methodology for mapping and characterising industrial sustainability in European industrial value chains (including Scope 3 emissions) provides valuable knowledge for researchers, business representatives, and policymakers to design effective sustainable strategies.

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Mapping; value chain; Europe; sustainability; triple bottom line

1. Introduction

As of 2017, anthropogenic warming had increased by approximately 1°C relative to pre-industrial baseline temperatures. This warming trend is accelerating at a rate of 0.2°C per decade (Intergovernmental Panel on Climate Change, 2022). Calvin et al. (2023) have recognised the interdependence of the climate, ecosystems and biodiversity, and human societies, the value of diverse forms of knowledge, and the close linkages between climate change adaptation, mitigation, ecosystem health, human well-being and sustainable development, which reflects the increasing diversity of actors involved in climate action. The broad consensus regarding climate change underscores the need for policymakers to prioritise the sustainability of the economy and of regions and nations in line with the United Nations' Sustainable Development Goals (Hailemariam & Erdiaw-Kwasie, 2023).

The success of society's transformation towards a more sustainable economy depends on, among other aspects, the assessment of environmental, economic, and industrial

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factors, social factors (e.g. labour practices, human rights, community well-being), and a clear, straightforward, and comprehensive mapping of factors that allows different stakeholders to assess the situation to make better decisions (Elkington, 1998).

Great efforts have been made in assessing sustainability to define objectives and targets, evaluate implications, and compare the industrial value chains of countries. However, economic, social, and environmental aspects have been only sporadically integrated and require more systematic inclusion (Bellamy et al., 2020; Mies & Gold, 2021). There is a need for mapping and analysis tools that combine various aspects from integrative and supply chain linking perspectives to promote a comprehensive assessment and evaluate the impacts of different scenarios.

Greenhouse gases (GHGs) are at the core of climate change, and it is imperative to reduce them. These emissions are released at different points in human activities, including energy generation, transportation, industrial activity, agriculture, and residential or commercial activities. These activities are interconnected through value chains, which represent the full range of activities that firms and workers perform to bring a product from its conception to its end use and beyond (Gereffi & Fernández-Stark, 2011).

Characterising industrial value chains is a challenging but necessary task to build and assess a more resilient and sustainable economy. By mapping these value chains, policymakers, business representatives, and researchers can gain insight into the complex and dynamic interactions between business models within or across value chains, as highlighted by Mubarik et al. (2021). The adoption of supply chain mapping as an apex business strategy is of foremost importance to incorporate the trio of supply chain resilience, industry 4.0, and sustainability.

Efforts to characterise industrial value chains have considered the triple bottom line (TBL) concept developed by Elkington (1998). This approach has been influential in shifting the focus of businesses from short-term financial gains to long-term sustainability. In the context of value chains, the use of TBL as a transformative framework should first consider the broader impact of industry on the environment before addressing the economic and social components of that impact.

This study focuses on emissions from industrial activities. As industry is structured in value chains, the decisions made at one level can affect or be affected by other levels. Policymakers need a global vision of the configuration of these value chains to make informed and effective decisions. Therefore, the purpose of this paper is to introduce a novel and comprehensive methodology for mapping and characterising industrial sustainability in European industrial value chains. To this end, it explains the methodology and steps that were followed and describes the application of the method to 240 industrial value chains from 12 European countries according to the distributions by quartiles of their gross domestic product (GDP). The results can inform comparative discussions of value chains and promote conclusions about the proposed method.

The paper is organised in six sections. Following this introduction, Section 2 presents the literature review, and Section 3 details the methodological approach and method of the study. Then, Section 4 provides a value chain map example, and Section 5 presents the results and findings based on a comparative analysis of sustainability profiles across countries and value chains. Finally, Section 6 offers concluding remarks and specifies the limitations of the study as well as recommendations for future research.

2. Literature review

2.1. Sustainability assessment methods

The literature has developed two main approaches to assessing sustainability: the process-based life cycle assessment (LCA) and environmentally extended input output (EEIOT) analysis. Most applications of these approaches have aimed to assess environmental impacts and mitigation actions. Integrated modelling of emissions and the economy using input-output tables has been used to assess the trade-offs between economic activities and GHG emissions (Mi et al., 2017), while input-output tables and structural decomposition analysis (SDA) have been employed to identify the drivers of energy consumption and carbon emissions (Peters et al., 2007). In the business context, the LCA method has been applied to evaluate the impact of business activities. However, to assess the sustainability impacts of the final demand in nations or industrial activities, EEIOT analysis is more appropriate (Peters et al., 2011).

While process analysis is more precise, input-output table analysis provides a more comprehensive view, which makes it more suitable for regional analysis (Rauf, 2022). Even if attempts were made to automate data acquisition through process mining (Horsthofer-Rauch et al., 2024), it would not be feasible to use LCA to analyse the entire environmental impact (emissions, materials, waste, water) of a country's industrial fabric because of the vast amount of information it would require. However, LCA allows for a more precise assessment of the impacts (e.g. improved efficiency, energy loss reduction, changes to technology or product lines) and benefits of technological improvements (Xue et al., 2021).

Input-output table analysis is an adequate tool for obtaining a comprehensive visualisation of the economic reality of a region and its impacts on sustainability through the extension of variables to environmental, material use, or employment variables. Since their introduction by Leontief (1936), input-output tables have been instrumental in reflecting the productive structures of regions and the economic relationships between different sectors and regions. Leontief (1936) also discovered that, in addition to simplifying calculations towards a system of linear equations, matrix triangulation revealed the structural characteristics of the economy they represented.

By incorporating environmental variables related to economic flows, EEIOTs make it possible to evaluate the impacts associated with the value chains of products and services (Faße et al., 2009). Interest in environmental extensions first emerged in the late 1960s with the publications of Ayres and Kneese (1969) and other researchers, and EEIOT analysis has developed significantly over the last two decades (Brown et al., 2021). Various databases, including Eora, EXIOBASE, Global Trade Analysis (GTA), and World Input Output Database (WIOD), are available to support analyses of intersectoral relationships from an environmental perspective with both regional and multiregional scopes (Owen et al., 2016).

However, the input-output matrices extended to sustainability have been mostly environmental and frequently used to analyse intersectoral relationships and their respective impacts. Studies have analysed a diverse range of variables, including energy (Casler & Wilbur, 1984), water (Hoekstra & Mekonnen, 2012), materials (Oei et al., 2020), employment (Markandya et al., 2016), land (He et al., 2024), gas emissions (Han et al., 2024), and multi-variables (Ivanova et al., 2016). At the same time, it is important to recognise that the use of input-output tables may have limitations stemming from the aggregation of different value chains within a sectoral category (Nomaler & Verspagen, 2014).

2.2. Assessing sustainability through value chain maps

There is now a widespread appreciation of the critical role of supply chains in the global economy (MacCarthy et al., 2022). The economic activity of a country is structured in value chains that serve the final demand. A value chain is composed of the full range of activities that firms and workers perform to bring a product from its conception to its end use and beyond (Gereffi & Fernández-Stark, 2011). The activities within a value chain are interdependent; therefore, an increase or decrease in activity in one phase of a value chain can affect the activities upstream. Supply and value chains are complementary views of an extended enterprise (Feller et al., 2006). In this paper, we consider both terms to represent the same network of firms.

Value chains are crucial for sustainability because they significantly condition environmental and social impacts through economic relationships (Ghadge et al., 2020; Li & Zhou, 2021). Supply chain sustainability refers to the shaping of a company's investment, operational, and procurement decisions to achieve positive environmental, social, and governance outcomes as well as harm reduction (WEF, 2022). Thus, value chain analysis is an effective analytical tool for understanding the interrelationships within the national economy (Kaplinsky & Morris, 2001), and the social and environmental aspects of the sustainability of regions have been increasingly integrated into analyses of global value (Gereffi & Fernández-Stark, 2011).

Insights into the creation and distribution of economic, social, and environmental values along the chain – including where, how, and by whom they are produced – are useful for business representatives and policymakers. To identify optimal interventions and leverage points to promote change, it is essential to understand the locations, methods, and agents responsible for generating and distributing these economic, social, and environmental values throughout the chain (Frederick, 2019). However, most research on the sustainability of value chains has focused on assessing the carbon footprint and methods for mitigating GHG emissions in the context of supply chain management (McKinnon et al., 2015).

By default, supply chains are complex systems that involve several processes, decision points, stakeholders, and interactions (Anastasiadis & Alebaki, 2021). A supply chain map is a visual representation of a supply chain's essential elements and can help with understanding the complexity of the supply chain (Gardner & Cooper, 2003; MacCarthy et al., 2022). The collaborative development of such a map can be one step in aligning corporate strategy with the value chain (Gardner & Cooper, 2003). While the literature has only occasionally addressed value chain mapping (MacCarthy et al., 2022), sharing such maps can improve supply chain visibility between value chain members (Christopher & Lee, 2004; Theodore Farris, 2010).

The purpose of a value chain map is to provide a visual representation of the identified chain actors and the associated product flows. According to Gardner and Cooper (2003), a value chain map should capture multiple levels of the supply chain, extend beyond logistics and manufacturing functions, and be rich in information without causing information overload. A mapped value chain encompasses the actors and their relationships as well as the economic activities at each stage and the corresponding physical and monetary flows (Faße et al., 2009). It can also include business functions, final markets, and a supporting environment (Frederick, 2019). Value chain mapping allows firms to assess and improve their sustainability (Cooper et al., 1997; Williams et al., 2013) and is necessary to manage the potential disruptions and many emerging challenges of supply chains in regard to sustainability, supply chain cyber security, technology disruption, climate change, and global shortages of critical raw materials (Ghadge et al., 2020; WEF, 2022).

At the global value chain level, industry-specific and national data can be accessed through diverse national and international entities. International trade data are similarly obtainable from organisations such as EuroStat, which provides regional data from the European Union (EU), and FAOStat, which offers industry-specific data from the agri-food sector. Economic input-output tables are instrumental in this context to systematically record the financial transactions of various industries within a given country. More detailed data can be collected by starting with a macro map and searching for major producers of materials and products in the corresponding countries (MacCarthy et al., 2022). For instance, to construct a value chain map, Anastasiadis and Alebaki (2021) obtained the necessary information from personal interviews with government officials, secondary information, and sector experts.

A good map should be interpretable and recognisable and have an easy-to-disseminate format (Gardner & Cooper, 2003). Based on micro and macro characteristics, supply chain mapping can be hierarchised from process maps (micro level) to global value chain maps (macro level). Between these two levels of detail, the value stream, supply chain, and supply network maps offer different views of inter-firm and intra-firm products, materials, and relationships (MacCarthy et al., 2022). Theodore Farris (2010) has analysed several aspects to consider when defining the form of a value chain map, including the mapping complexity and geovisualisation, which represents the magnitude of the flows of cash, goods, and information or trading relationships. The result can take the form of various kinds of maps, such as weighted or non-weighted arrow, Sankey, and geovisual maps.

As evidenced in this literature review, authors have previously addressed the need for mapping value chains, incorporating resource utilisation or environmental variables, and integrating the TBL concept into value chains using matrix-based calculation techniques, such as SDA (Foran et al., 2005). However, this article proposes a novel method that integrates various aspects, including the incorporation of sustainability by addressing environmental, social, and economic dimensions (TBL), mapping value chains in different formats (graphical and database), and applying non-conventional techniques (database combination).

3. Methodological approach

To develop a value chain sustainability mapping method based on EEIOT, several elements must be taken into consideration, including the need for reliable and comprehensive datasets that fit the mapping objectives, a sound methodology with clearly defined steps, and a mapping format that is easy to understand and disseminate.

3.1. Data sets

Following the concept of sustainability established by Elkington (1998), the data required to develop the method encompass the three dimensions of sustainability: economic, environmental, and social. To ensure the coherence of the information, and considering the availability of various datasets, the year 2020 was used as the reference year for the GDP of the selected countries, the input-output tables, and the GHG emissions. Although the emissions structure may have been affected by the pandemic in 2020, this reference year was chosen to ensure the availability of the dataset required to apply the method, which was the main objective of this study.

To realise this research, 12 EU member countries were selected using National Accounts GDP data in millions of euros (current prices) for the year 2020 from Eurostat (2020b). The countries were selected by dividing European nations into four quartiles based on GDP value and selecting three states from each quartile. The final selection consisted of the following countries (ranked in descending order by GDP): Germany, France, Spain, Sweden, Austria, Czech Republic, Portugal, Greece, Hungary, Croatia, Lithuania, and Slovenia. The purpose of using GDP criteria to segment the selected countries was to analyse whether the size of the country influenced the industrial structure and, consequently, the structure of GHG emissions.

The data on GHG emissions for each Statistical Classification of Economic Activities (NACE) sector and state for the year 2020 were sourced from Eurostat (2020a). These data correspond to emissions of GHGs in tonnes of carbon dioxide equivalents (CO_2-eq) of the following gases: carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF_6), and nitrogen trifluoride (NF_3). The NACE codes (10–12 to 35) correspond to the activities most closely related to the industrial sector and its emissions, with some appropriate groupings based on data availability.

The data on product-by-product input-output tables of the states for the year 2020 were obtained from Eurostat (2020c). For the completion of this work, economic flows in millions of units of the domestic national currency between origin and destination products were considered.

The classification of products by activity (CPA) is based on elements related to the activities defined in NACE Rev. 2. Each product was assigned to a single NACE Rev. 2 activity to determine the association of each industrial product with its corresponding sector. Data on employment and detailed economic activity (from 2008 onwards, NACE Rev. 2 two-digit level) for each country were obtained from Eurostat (2024).

3.2. Detailed method and steps

Based on Leontief's (1936) seminal work, matrix triangulation is used for comparing the economies and examining the factors influencing economic cycles and growth to reduce the computational burden and improve the economic planning and forecasting (Korte & Oberhofer, 1970). This process involves permuting the order of the rows and columns of the matrix to maximise the sum of the values under the diagonal (Simpson & Tsukui, 1965), which enables graphical and linear visualisation of the relationships between economic sectors. The degree of linearity is assessed using the quotient between the sum of the values concentrated under the diagonal and the sum of all values in the matrix. A linearity value close to unity indicates a nearly unidirectional hierarchy with minimal multi-directional dependence, such as feedback loops (Kondo, 2014).

In addition, matrix triangulation allows for graphical visualisation (without intersectoral loops) of the relationships between economic sectors, as demonstrated by Nakamura et al. (2011), Nakajima et al. (2013), and Korte and Oberhofer (1970). When the linearity obtained after triangulation is high, its representativeness of reality becomes an efficient tool.

As the matrix triangulation problem is NP-hard combinatorial, the ordering options are factorial in number (Charon & Hudry, 2007; Chiarini et al., 2004). While various algorithms and heuristics have been developed to address this complexity, they have not necessarily achieved optimal solutions, though some authors have proposed algorithms that can provide optimal solutions for different numbers of sectors (Chiarini et al., 2004; Grötschel et al., 1984).

In some cases, the original matrix is trimmed before triangulating the matrix. Trimming a matrix involves eliminating the contents of cells with lower values while maintaining a high degree of representativeness with respect to the initial matrix. Trimmed matrices are expected to emphasise significant interdependencies between sectors or highlight the features of production structures (Kondo, 2014). The trimming process carried out in this study guarantees 95% representativeness in the sum of the cells with respect to the original matrix – that is, after sorting the matrix cells in increasing order, the cells are eliminated until the sum of the resulting cells is reduced to below 95% of the sum of the cells of the original matrix.

Communicating EEIOT data presents unique challenges. While statistical analysts and experts may require detailed and specific terminology, business representatives, policymakers, and the public may prefer general terms (Brown et al., 2021). Because of the significant mathematical knowledge required for operations with matrices, linear programming, trimming, or triangulation and input-output matrices, they are difficult to use for people specialised in management.

Considering the objectives of this study and the limitations of existing methods, this article proposes a new approach for mapping and characterising sustainability in European industrial value chains (including Scope 3 emissions) that addresses the abovementioned gaps. Figure 1 presents the method for obtaining the value chain maps.

3.2.1. Step 1

The tables are prepared for subsequent processing. Specifically, products with CPA are associated with the corresponding NACE sectors. The input-output matrix relative to the

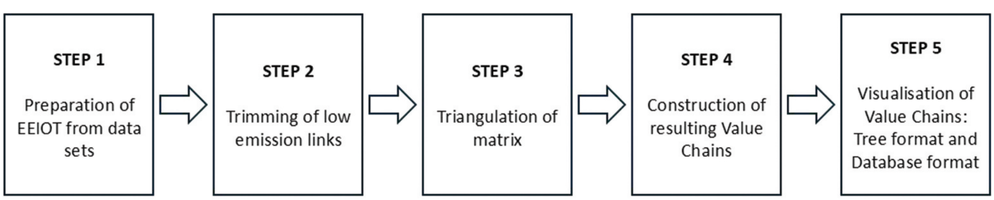

Figure 1. Value chain mapping steps.

industrial sectors for both intermediate and final consumption was extracted from the original tables obtained from Eurostat. The EEIOT is built by calculating the emissions associated with the economic exchanges between the industrial sectors, and the final demand is served in thousands of TCO_2-eq.

3.2.2. Step 2

To reduce the complexity of the model and facilitate the search for linearity between the remaining links, a trimming process is performed for emission links between sectors. With this process, the total emissions retained in the model are greater than 95% of the initial intersectoral emissions. A sensitivity analysis allows for greatly reducing the number of active links without losing the representation of the total emissions in the model.

Figure 2 depicts the relationship between the trimming percentage and the representativeness of the emissions that remain in the model. The elimination of 77.75% of the links in the case of Portugal and 90.70% in the case of Lithuania allows for maintaining the representativeness of the model above 95% of the initial intersectoral emissions. For the rest of the countries, the percentages of links to be removed fall between those two percentages. The emissions associated with the intersectoral links before the trimming process are shown in the centre of Figure 2.

3.2.3. Step 3

The order of rows and columns in the matrix resulting from Step 2 is permuted to achieve triangulation by maximising the concentration of emission linkages below the diagonal. This optimises the identification of intersectoral emission flows within the data. As discussed, the triangulation process enables the visualisation of an economy's fundamental structure and facilitates comparisons between countries, which, in this case, is

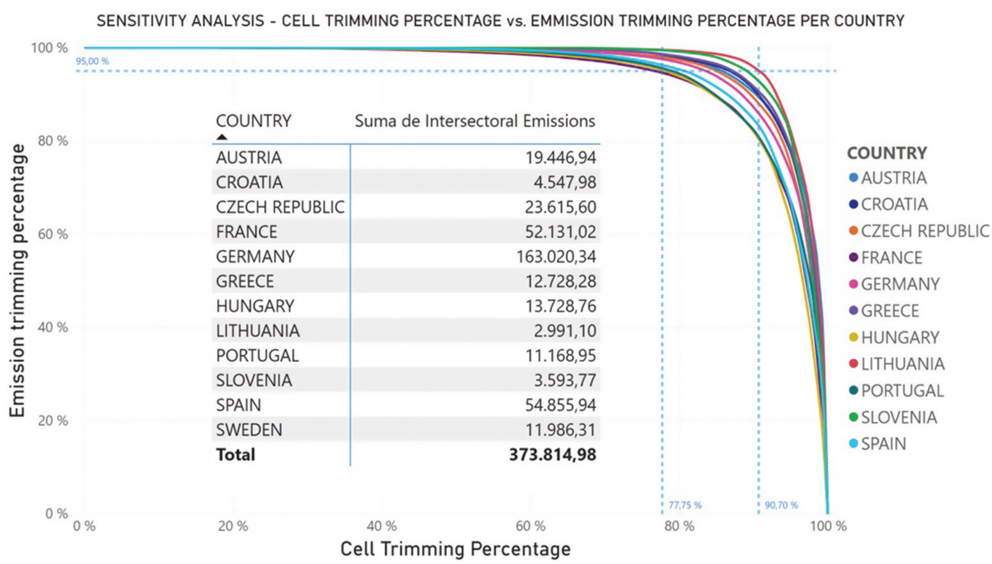

Figure 2. Comparison of the cell and emission trimming percentages for sensitivity analysis.

from the perspective of GHG emissions. The triangulation process employed in this study is rooted in the heuristic methodology proposed by Becker (1967).

Figure 3 illustrates the hierarchical arrangement of sectors during the triangulation process for various countries in order from highest to lowest GDP.

An examination of the six countries with the highest GDPs reveals a shared hierarchical structure. The sectors NACE 35 (Electricity, gas, steam, and air conditioning supply), NACE 19 (Manufacturing of coke and petroleum products), NACE 24 (Manufacturing of basic metals), NACE 20 (Manufacturing of wood and wood products), NACE 23 (Manufacturing of chemicals and chemical products), and NACE 17 (Manufacturing of paper and paper products) assume a central role in the rest of the economy in these countries from the point of view of GHG emissions. While this relevance is less pronounced in the other countries, the sectors NACE 35, 20, and 23 maintain their significance across nearly all analysed countries. For Germany, France, Spain, and Sweden, the common basic structure is further limited to five sectors (NACE 35, 19, 24, 20, and 23).

3.2.4. Step 4

After the triangulation process, value chains are constructed. To establish the fundamental structure of these value chains, the combinatorial capabilities of Power Query (Microsoft Corporation, 2024b) were employed to iteratively trace the supply chain from the final demand upstream until all relationships were captured. Building upon this initial construction, the emissions and employment associated with each generated link are allocated by calculating the proportional distributions of the emission and employment values.

To illustrate the steps of the applied method for configuring the value chain tree using the combinatorial possibilities of Power Query through Power Query M Language

Figure 3. Hierarchisation of sectors from the triangulation process.

(Microsoft Corporation, 2024a), we use data related to Germany. This method is based on two tables generated in the previous step. One of these tables, 'TablaDeEmisionesRetenidas', contains the intersectoral links retained after the triangulation process. The table consists of three columns: 'SOURCE CODE', which refers to the NACE code of the origin sector; 'DESTINATION CODE', which refers to the NACE code of the destination sector; and 'Intersectoral Emissions', which indicates the total emissions produced by the 'SOURCE CODE' sector in providing to the 'DESTINATION CODE' sector.

The second table, 'Table 2', contains the links in which each sector meets the final demand. It contains the following columns: 'Nivel 0. Origen', which refers to the NACE code of the sector serving the final demand; 'FinalDemand/FinalConsumption', in which all values are labelled 'FC' (Final Demand/Final Consumption); and 'Intersectoral Emissions', which displays the emissions produced by each sector in its direct relationship with the final demand. Table 1 presents the initial configuration of 'Table 2'.

Subsequently, the configuration of the value chain tree is carried out through an iterative process (10 iterations) to progressively construct the upstream links of the value

Table 1. Structure of 'Table 2'.

Nivel 0. Origen	FinalDemand/FinalConsumption	Intersectoral Emissions
10–12	FC	10.868,34
13–15	FC	567,46
16	FC	427,12
17	FC	2.946,77
18	FC	418,62
19	FC	21.396,46
20	FC	15.959,44
21	FC	864,84
22	FC	426,51
23	FC	29.035,54
24	FC	1.877,74
25	FC	1.030,30
26	FC	803,15
27	FC	512,62
28	FC	2.733,24
29	FC	5.391,17
30	FC	465,52
31–32	FC	795,30
33	FC	208,38
35	FC	115.480,33

Table 2. Partial configuration of value chain tree after combination for link −1 (total of 46 rows).

Nivel 1. Origen	Nivel 1. Destino	Nivel 1. Link	Nivel 0. Origen	Nivel 0. Destino	Nivel 0. Link	Intersectoral Emissions
35	10–12	35 –> 10–12	10–12	FC	10–12 –> FC	10868,34
17	10–12	17 –> 10–12	10–12	FC	10–12 –> FC	10868,34
23	10–12	23 –> 10–12	10–12	FC	10–12 –> FC	10868,34
20	13–15	20 –> 13–15	13–15	FC	13–15 –> FC	567,45
35	13–15	35 –> 13–15	13–15	FC	13–15 –> FC	567,45
null	null	null	35	FC	35 –> FC	115480,33

chain from Level 0 to Level 10. The first iteration is performed by merging ‘Table 2’ (column ‘Nivel 0. Origen’) with ‘TablaDeEmisionesRetenidas’ (column ‘DESTINATION CODE’). The corresponding code is as follows:

```
= Table.NestedJoin(#‘Columnas con nombre cambiado’, {‘Nivel 0. Origen’}, TablaDeEmisionesRetenidas, {‘DESTINATION CODE’}, ‘TablaDeEmisionesRetenidas’, JoinKind.LeftOuter)
```

Figure 4 illustrates the performed combination.

After performing this combination and reordering and renaming the resulting columns, the table is structured as shown in Table 2.

As seen in Table 2, which presents a partial view of the merge between the service to the final demand and the immediately higher upstream level in the value chain, the value chain corresponding to sectors 10–12 requires significant contributions in terms of emissions from sectors NACE 35, 17, and 23. In contrast, sector NACE 35 does not require the participation of other sectors with significant emissions to serve the final demand; therefore, it will not develop further upstream in the subsequent merges. The process used to link Level 0 and Level −1 of the value chain is progressively repeated in the following levels. Figure 5 illustrates the method of performing the merge.

Table 3 shows the structure of the resulting table after the 10 iterations.

The next step involves calculating the emissions associated with each of the retained links in the model. The process begins with the link between each sector and the final demand, for which the associated emissions are known and obtained from the original EEIOT table. The emissions associated with each of the retained links are then calculated progressively and for each upstream level as follows.

The emissions associated with a link between sector ‘x’ and sector ‘y’ within the value chain correspond to the emissions associated with the link immediately downstream in the value chain (where the origin sector corresponds to sector ‘y’), divided by the total emissions of sector ‘y’, and multiplied by the total emissions of sector ‘x’ towards sector

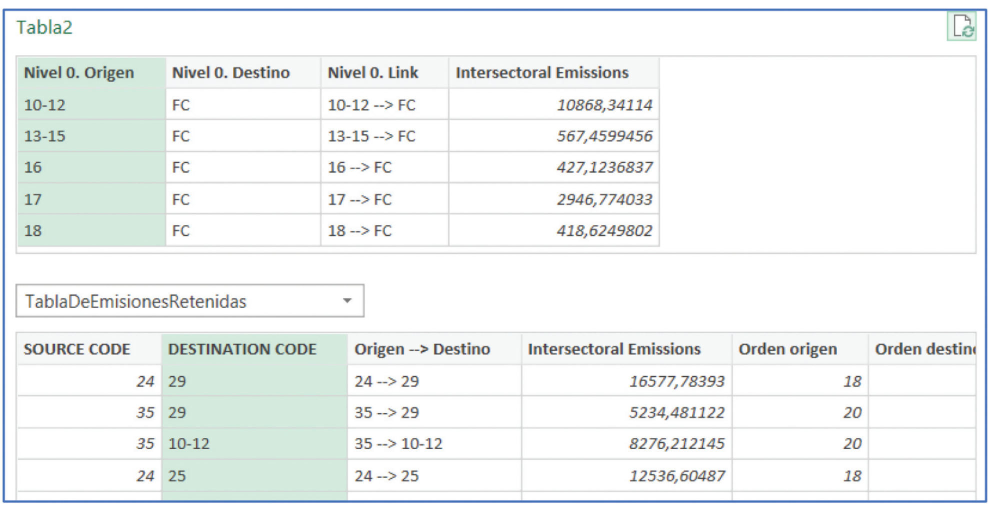

Tabla2

Nivel 0. Origen	Nivel 0. Destino	Nivel 0. Link	Intersectoral Emissions
10-12	FC	10-12 --> FC	10868,34114
13-15	FC	13-15 --> FC	567,4599456
16	FC	16 --> FC	427,1236837
17	FC	17 --> FC	2946,774033
18	FC	18 --> FC	418,6249802

TablaDeEmisionesRetenidas

SOURCE CODE	DESTINATION CODE	Origen --> Destino	Intersectoral Emissions	Orden origen	Orden destin
24	29	24 --> 29	16577,78393	18	
35	29	35 --> 29	5234,481122	20	
35	10-12	35 --> 10-12	8276,212145	20	
24	25	24 --> 25	12536,60487	18	

Figure 4. Form of combination to create links in value chain representation: final demand and link −1.

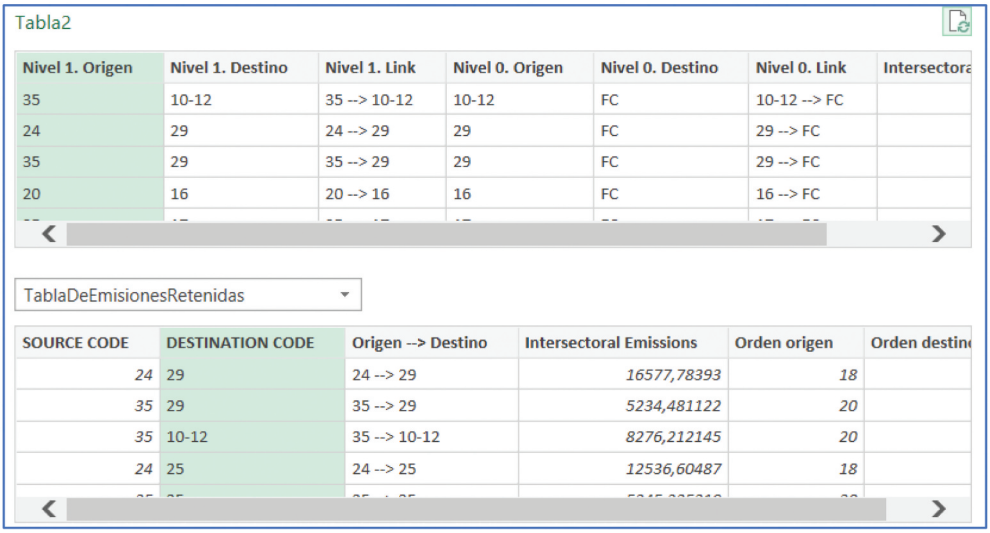

Tabla2

Nivel 1. Origen	Nivel 1. Destino	Nivel 1. Link	Nivel 0. Origen	Nivel 0. Destino	Nivel 0. Link	Intersectora
35	10-12	35 --> 10-12	10-12	FC	10-12 --> FC	
24	29	24 --> 29	29	FC	29 --> FC	
35	29	35 --> 29	29	FC	29 --> FC	
20	16	20 --> 16	16	FC	16 --> FC	

TablaDeEmisionesRetenidas

SOURCE CODE	DESTINATION CODE	Origen --> Destino	Intersectoral Emissions	Orden origen	Orden destin
24	29	24 --> 29	16577,78393	18	
35	29	35 --> 29	5234,481122	20	
35	10-12	35 --> 10-12	8276,212145	20	
24	25	24 --> 25	12536,60487	18	

Figure 5. Form of combination to create links in value chain representation link −1 and link −2.

Table 3. Partial configuration of value chain tree after 10 combinations (total of 91 rows).

Level − 4 Origin	Level − 3 Origin	Level − 2 Origin	Level − 1 Origin	Level − 0 Origin	Level − 0 Destination
35	19	20	17	10–12	FC
	35	20	17	10–12	FC
		35	17	10–12	FC
	35	19	23	10–12	FC
35	19	20	23	10–12	FC
	35	20	23	10–12	FC
		35	23	10–12	FC
			35	10–12	FC
	35	19	20	13–15	FC
		35	20	13–15	FC
			35	13–15	FC

'y'. To perform this operation, it is necessary to create columns with the required information through query merges. The corresponding M code for an example of this operation to calculate the emissions of links in Level 1 (immediately preceding the final demand) is

> #'Custom column' = Table.AddColumn(#'Column with name changed', 'Level 1. Partial Emissions', each [Intersectoral Emissions]/[Level 0. Total Emissions of Origin]*[Level 1. Total Emissions of the link]),

where 'Level 1. Partial Emissions' corresponds to the emissions to be calculated that are associated with the retained links in Level 1 of the value chain, 'Intersectoral Emissions' refers to the emissions from the immediately downstream phase in the value chain, and 'Level 0. Total Emissions of Origin' corresponds to the total emissions of the origin sector in the immediately downstream link of the value chain (in this example, the origin of the link to the final demand). Finally, 'Level 1. Total Emissions of the link' corresponds to the total emissions of the NACE sector in the origin of Link −1 when providing to destination sector Link −1.

Table 4 presents the resulting table after performing the 10 upstream iterations, reordering the columns, and removing the columns used for calculations.

Table 5 shows the result after converting the matrix structure into a database structure.

A tree structure with the associated emissions is obtained as a result. Finally, the employment associated with each retained link in the model is calculated using the following formula (an example for Link −1 is given):

> Employment associated with the link −1 = (Emissions associated with the link 0/Total emissions of the origin sector of the link 0) * Total employment associated with the origin sector of the link −1 when providing to destination sector of Link-1.

The complete and detailed programming code is available in the repository associated with this article. The authors considered several options concerning the use of column and table names to ensure the clarity and traceability of the method for both academic and practical purposes. The proposed approach utilises a significant number of tables processed through Power Query, where terms such as ‘Table 1’, ‘Table 2’, and so on serve to distinguish the tables referenced in the article’s narrative from those used within the method itself. This differentiation is critical to maintain a clear structure, as it avoids

Table 4. Partial configuration of value chain tree with emissions (thousands of TCO_2-eq) associated to links (matrix format).

Level − 4. Link	Level − 4. Emiss.	Level − 3. Link	Level − 3. Emiss.	Level − 2. Link	Level − 2. Emiss.	Level − 1. Link	Level − 1. Emiss.	Level − 0. Link	Emissions to Final Demand
35 –> 19	1,25	19 –> 20	20,18	20 –> 17	224,69	17 –> 10–12	1488,82	10–12 –> FC	10868,34
		35 –> 20	71,66	20 –> 17	224,69	17 –> 10–12	1488,82	10–12 –> FC	10868,34
				35 –> 17	1226,98	17 –> 10–12	1488,82	10–12 –> FC	10868,34
		35 –> 19	1,02	19 –> 23	16,50	23 –> 10–12	879,37	10–12 –> FC	10868,34
35 –> 19	0,27	19 –> 20	4,32	20 –> 23	48,07	23 –> 10–12	879,37	10–12 –> FC	10868,34
		35 –> 20	15,33	20 –> 23	48,07	23 –> 10–12	879,37	10–12 –> FC	10868,34
				35 –> 23	142,20	23 –> 10–12	879,37	10–12 –> FC	10868,34
						35 –> 10–12	8276,21	10–12 –> FC	10868,34

Table 5. Partial configuration of value chain tree with emissions (thousands of TCO_2-eq) associated to links (database format).

Index	Country	Link	Level − 0	Level − 1	Level − 2	Level − 3	Level − 4
1	GERMANY	35 –> FC	115480,33				
2	GERMANY	10–12 –> FC	10868,34				
3	GERMANY	35 –> 10–12		8276,21			
4	GERMANY	17 –> 10–12		1488,82			
5	GERMANY	35 –> 17			1226,98		
6	GERMANY	20 –> 17			224,69		
7	GERMANY	35 –> 20				71,66	
8	GERMANY	19 –> 20				20,18	
9	GERMANY	35 –> 19					1,25
10	GERMANY	23 –> 10–12		879,37			
11	GERMANY	35 –> 23			142,20		
12	GERMANY	19 –> 23			16,50		
13	GERMANY	35 –> 19				1,02	
14	GERMANY	20 –> 23			48,07		
15	GERMANY	35 –> 20				15,33	
16	GERMANY	19 –> 20				4,32	

potential confusion between the article's analytical discussion and the technical implementation of the methodology.

Additionally, the column and variable names were retained to align with the constraints of the software and to maintain consistency with the M programming code, a critical component of the proposed method. These names, which are sometimes abbreviations or acronyms due to software limitations, are directly utilised in the programming code, which is partially presented in the article and fully available in the supplementary repository. The inclusion of screenshots with the same terminology reinforces coherence between the tables, the method, and the associated documentation. For accessibility, the authors provided detailed explanations of each column header in English in the article to ensure that the methodology remains comprehensible to an international audience while preserving its internal consistency and traceability.

3.2.5. Step 5

The final step involves the visualisation of the constructed value chains. Two primary representation methods are employed. The first is a tree-based graphical representation depicting the value chain structure in a hierarchical format, where each node represents a specific sector, and the arrows represent the link between sectors. The total emissions and jobs associated with each link are also presented to highlight their proximity to the final demand. The second method is a database representation, which is used to organise the value chain data in a tabular format. Each row represents a specific link or connection between the sectors. The matrix includes information such as the sectors involved, associated emissions, and employment values. Table 6 presents the main advantages of each proposed representation modality.

4. Mapping examples

The application of this process culminated in a comprehensive representation of 240 value chains, with 20 value chains analysed for each of the 12 countries. This outcome holds significant value for policymakers, business representatives, and researchers because it provides a clear and intuitive visualisation of each country's emissions structure, distributed across value chains, and highlights their intricate interdependencies. The emissions captured by the constructed value chains encompass 94.41% of the

Table 6. Advantages and disadvantages of the proposed visualisation methods.

Visualisation method	Advantages	Disadvantages
Tree-based graphic	Intuitive to interpret Better conveys the complexity of value chains Effective for analysing a single value chain Provides ready-to-use information	Limited to visualising one value chain at a time Not suitable for deriving indicators
Database format	Allows storage of all value chains for all countries in a single table Facilitates the extraction of value chain indicators Enables an easy comparison of value chains across countries Simplifies the integration of employment and economic transaction data with emissions data	Requires database processing to generate useful insights Lacks visual and intuitive appeal

total industrial emissions, thus exhibiting a high degree of representativeness, which ensures that most emissions are accounted for and analysed within the study's framework.

Furthermore, the employment associated with each retained link in the value chains was also obtained. The results therefore hold strong suggestive power for informing decision-making and policy proposals. The obtained information provides a solid foundation for the assessment of Scope 3 emissions associated with the companies' activities.

Figure 6 provides an illustrative example of a tree-based representation of the value chains of 'Food, beverage, and tobacco products' in Spain. This graphical depiction clearly presents the emissions associated with the activities of sectors 10–12 in meeting the final demand. In addition, it highlights the upstream sectors that are involved and the emissions that are associated with each stage of the value chain. Each horizontal segment is defined by the origin sector, destination sector, and total emissions related to that exchange. The method used in this study produced 240 value chain maps with the same structure as that depicted in Figure 6.

As discussed later, this representation facilitates the evaluation of emission proximity to the final demand.

Table 7 provides an excerpt of a data matrix representation of value chains. It highlights the structured organisation of the value chain data, which enables a comprehensive analysis and identification of patterns and relationships. It shows a backwards tree of the relationships with other sectors and the related emissions, economic activity, and associated employment of the economic exchanges at every step. The links are presented hierarchically (link -x) depending on their closeness to the final demand, and the total emissions at each level are calculated.

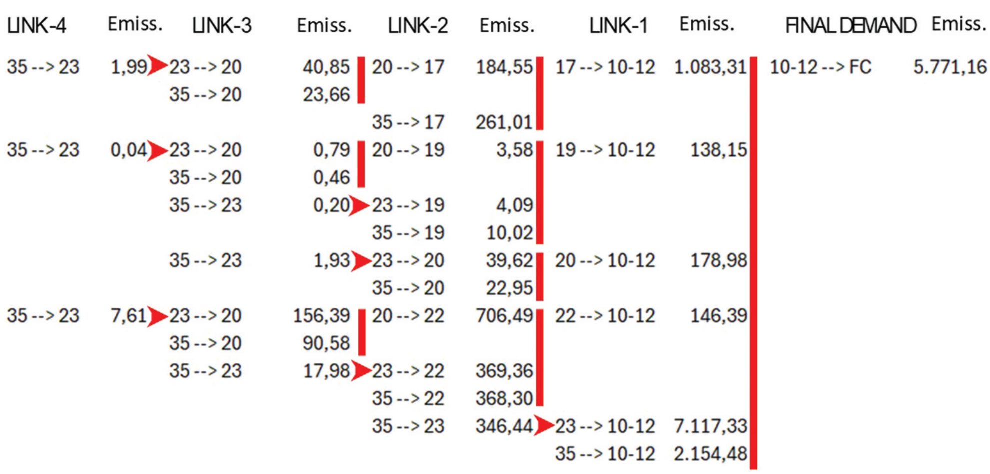

Figure 6. Example of a tree representation of the GHG emissions (thousands of TCO_2-eq) in the value chains of 'food, beverage, and tobacco products' in Spain.

Table 7. Partial extract of a database representation of the value chains of 'food, beverage, and tobacco products' in Spain with TBL sustainability variables: emissions (thousands of TCO_2-eq), economic activity (millions of euros), and employment (jobs).

COUNTRY	Link	Final Demand	Link −1	Link −2	Link −3	Link −4	Employment	Economic activity
SPAIN	10–12 –> FC	5.771,16					521.500	72.430,60
SPAIN	35 –> 10–12		2.154,48				6.252	2.867,17
SPAIN	17 –> 10–12		1.083,31				16.691	2.999,31
SPAIN	35 –> 17			261,01			757	347,35
SPAIN	20 –> 17			184,55			2.100	139,71
SPAIN	35 –> 20				23,66		68	31,49
SPAIN	23 –> 20				40,85		193	7,53
SPAIN	35 –> 23					1,99	6	2,65
SPAIN	19 –> 10–12		138,15				232	115,39
SPAIN	35 –> 19			10,02			29	13,34
SPAIN	20 –> 19			3,58			40	2,71
SPAIN	35 –> 20				0,46		1	0,61
SPAIN	23 –> 20				0,79		3	0,15

5. Results

Table 8 presents the distribution of emissions from the analysed countries ordered according to GDP. The table shows the emissions associated with each position in the value chains and the percentage of emissions at each position that contributed to the total emissions of each country.

Generally, in all countries except Sweden, Austria, and Croatia, it is observed that most emissions occurred in the final stage of the value chains – that is, the stage immediately preceding the delivery of products or services to the final demand. Furthermore, the percentage of emissions represented in the final two stages (Final Demand and Link 1) range from 78.28% (Slovenia) to 97.95% (Croatia). Considering the last three stages of the value chains, the percentage ranges from 94.30% (Hungary) to 99.93% (Croatia). It can be concluded that considering the three final stages of the countries' value chains can lead to an accurate and highly representative picture of the emissions profile and, consequently, of the areas in which actions should be taken to reduce them.

The representations obtained in this research allow for the characterisation of countries based on the configuration of their value chains and the associated emissions and employment. Using the methodology presented above, nine indicators related to value chains are proposed to characterise countries in terms of their emissions, employment, and economic activity. The proposed indicators are as follows.

- Complexity (number of links): Number of 'links' (intersectoral economic relationships) representing the value chains of a country from the point of view of emissions.
- Proximity (links): Average proximity or distance of emissions with respect to the final demand. Values range from 1 to 7. The closer the value is to 1, the closer the emissions are to the final demand. A value of 1 means that all emissions generated in that country occur in the industrial sector, which directly supplies the final demand.
- Dispersion (standard deviation): Dispersion of emissions within a country's value chain. The smaller the value, the more concentrated the emissions are in certain

Table 8. Emissions (thousands of TCO2-eq and percentage of total of country) by country and position in value chains.

Country		GERMANY	FRANCE	SPAIN	SWEDEN	AUSTRIA	CZECH REP.	PORTUGAL	GREECE	HUNGARY	CROATIA	LITHUANIA	SLOVENIA
Link −6	Emiss		0		0	0				1			
	%	-	*0,00*	-	*0,00*	*0,00*	-	-	-	*0,00*	-	-	-
Link − 5	Emiss.	0	0	1	0	7		0		13			
	%	*0,00*	*0,00*	*0,00*	*0,00*	*0,02*	-	*0,00*	-	*0,06*	-	-	-
Link −4	Emiss.	30	5	74	12	48	1	8	0	175	0	1	
	%	*0,01*	*0,00*	*0,08*	*0,07*	*0,16*	*0,00*	*0,04*	*0,00*	*0,79*	*0,00*	*0,01*	-
Link −3	Emiss.	1.656	464	1.925	196	451	822	295	44	1.065	5	31	146
	%	*0,46*	*0,49*	*1,97*	*1,17*	*1,50*	*1,52*	*1,38*	*0,12*	*4,84*	*0,06*	*0,46*	*2,09*
Link −2	Emiss.	26.472	9.039	11.463	2.497	4.252	6.756	2.245	2.690	3.513	153	508	1.373
	%	*7,42*	*9,55*	*11,75*	*14,93*	*14,10*	*12,47*	*10,49*	*7,65*	*15,98*	*1,99*	*7,39*	*19,64*
Link −1	Emiss.	116.507	32.709	33.446	7.641	13.002	13.448	7.114	7.777	7.183	3.778	2.108	1.691
	%	*32,65*	*34,56*	*34,27*	*45,68*	*43,13*	*24,83*	*33,25*	*22,12*	*32,67*	*48,97*	*30,65*	*24,17*
Final	Emiss.	212.209	52.423	50.689	6.379	12.387	33.142	11.732	24.646	10.039	3.778	4.229	3.784
Demand	%	*59,46*	*55,39*	*51,94*	*38,14*	*41,09*	*61,18*	*54,84*	*70,10*	*45,65*	*48,98*	*61,49*	*54,10*

phases within the value chains of a country, as indicated by proximity to the final demand indicator.

- Total emissions (thousands of TCO_2-eq): The GHG emissions generated to produce what is necessary to meet the final annual demand of the country.
- Employment: Number of jobs related to the analysed industrial sectors.
- Employment intensity (emissions per job): Emissions generated by the value chains of a country per job, which allows for the identification of value chains where potential reductions in activity and emissions would have greater impacts on employment.
- Economic activity intensity (emissions/GDP): Emission intensity per unit of economic activity generated.
- Emissions due to the energy sector (%): Emissions produced by energy production over the total emissions retained in the model.

Considering these variables, Table 9 presents the indicators associated with the value chains of each country.

Based on the characterisation of the countries, a correlation analysis between the descriptive variables was performed. Table 10 shows the correlations between the variables.

In addition to the obvious correlations derived from the countries' own dimensions in terms of economic activity (GDP, employment, and emissions), the analysis of the results led to interesting conclusions regarding the rest of the variables.

A correlation was found between the variables of proximity and complexity (*Pearson's* $r = 0.73$) and between the variables of proximity and dispersion (*Pearson's* $r = 0.74$). Thus, in countries where emissions occurred in stages closer to the final demand, both the model complexity and the dispersion of emissions across different value chains increased. Greater complexity of the network of links required to describe a country's emissions corresponds to a higher number of participants and more intricate relationships between them across various interactions that can be affected by emission reduction policies. Conversely, when complexity is lower, fewer stakeholders are needed to affect a significant change in emissions.

Table 9. Characterisation of European countries based on the configuration of their GHG emissions (thousands of TCO_2-eq) within their value chains.

Country	Complexity	Proximity	Dispersion	Total emissions	Employment	Employment intensity	Economic activity intensity	% emissions due to energy sector
GERMANY	183	1,49	0,65	356.873	8.580.100	0,042	144,24	49,20
FRANCE	269	1,55	0,68	94.640	3.295.100	0,029	40,83	22,88
SPAIN	209	1,64	0,77	97.597	2.518.000	0,039	87,22	28,62
SWEDEN	534	1,79	0,74	16.726	524.900	0,032	34,81	28,86
AUSTRIA	246	1,77	0,76	30.147	699.200	0,043	79,15	19,37
CZECH REP.	106	1,54	0,77	54.169	1.456.300	0,037	251,01	69,23
PORTUGAL	268	1,59	0,73	21.393	841.900	0,025	106,69	34,79
GREECE	80	1,38	0,63	35.156	403.000	0,087	213,05	54,48
HUNGARY	428	1,83	0,93	21.988	994.800	0,022	159,43	50,96
CROATIA	125	1,53	0,54	7.714	310.900	0,025	151,42	40,90
LITHUANIA	86	1,47	0,65	6.877	222.000	0,031	137,89	23,36
SLOVENIA	80	1,70	0,85	6.995	257.600	0,027	148,68	63,08

Table 10. Correlation analysis of the variables characterising the countries.

	Complex.	Proximity	Dispersion	Total emiss.	Employm.	Employm. intensity	Economic activity intensity	% emiss. due to energy sector	GDP
Complexity	1,00								
Proximity	0,73	1,00							
Dispersion	0,40	0,74	1,00						
Total emissions	− 0,07	− 0,29	− 0,19	1,00					
Employment	− 0,01	− 0,24	− 0,16	0,99	1,00				
Employment intensity	− 0,34	− 0,51	− 0,32	0,13	0,03	1,00			
Econ. activity intensity	− 0,37	− 0,06	0,09	− 0,39	− 0,42	− 0,17	1,00		
% emiss. from ener. Sect.	− 0,36	− 0,16	0,25	0,09	0,05	0,18	0,48	1,00	
GDP	0,12	− 0,19	− 0,19	0,83	0,88	− 0,00	− 0,58	− 0,23	1,00

A negative correlation (*Pearson's* $r = -0.58$) was observed between the variables of GDP and economic activity intensity. Therefore, countries with a higher GDP emit fewer GHGs per unit of economic activity. A less significant negative correlation was also found between employment intensity and proximity (*Pearson's* $r = -0.51$), which suggests that GHG emissions per job are higher when emissions are closer to the final demand.

A clustering analysis was performed for the countries included in the study using the defined variables for which the most significant correlations were observed: complexity, proximity, and dispersion. Based on the results, three groups of countries were formed according to the characteristics of emissions in their value chains, as shown in Table 11.

The clustering process incorporated a comprehensive sensitivity analysis to determine the most suitable number of clusters for the dataset. This approach was critical to ensure robust and meaningful clustering outcomes. The silhouette method was employed to determine the optimal number of clusters. An analysis was performed by varying the proposed number of clusters, and the results are presented in Table 12.

The number of clusters that maximised the silhouette value was three, yielding a silhouette index of 0.360. This result supports the validity of the clustering and confirms moderate intra-cluster cohesion and inter-cluster separation. Table 13 presents the statistical variables resulting from the clustering process.

Table 11. Clustering of countries according to the correlated variables.

Cluster No.	Countries	Clustering variables
1	Sweden and Hungary	Countries characterised by a very high complexity of emissions in the model, relative farness of emissions from the final demand, and high dispersion of emissions from the point of view of distance to the final demand
2	Austria, France, Spain, Portugal, Slovenia, and Czech Republic	Countries characterised by an average complexity, proximity, and dispersion
3	Lithuania, Croatia, Germany, and Greece	Countries characterised by very low complexity, with emissions close to the final demand and very limited dispersion of emissions from the point of view of distance to the final demand

Table 12. Sensitivity analysis of clustering process. Silhouette index vs. number of clusters.

Number of clusters	Silhouette
2	0,350
3	0,360
4	0,27
5	0,23
6	0,22

Table 13. Statistical characteristics of the clustering process.

K-Means Clustering					
Clusters	N	R^2	AIC	BIC	Silhouette
3	12	0.732	26.840	31.200	0.360
Cluster Information					
Cluster			1	2	3
Size			2	6	4
Explained proportion within-cluster heterogeneity			0.223	0.585	0.192
Within sum of squares			1.970	5.168	1.697

Table 13 provides a detailed summary of the k-means clustering results for the optimal configuration of the three clusters. The total number of observations (N) analysed was 12. An R^2 value of 0.732 was obtained, which indicates that 73.2% of the variance in the dataset is explained by the clustering. This high R^2 value underscores the strong explanatory power of the clustering model.

The mapping of value chains within the countries' industrial ecosystems that was realised in this research also allows for the characterisation of value chains. For example, in Figure 7, the distribution of the value chains of the 20 selected countries (240 value chains) is plotted according to their complexity and employment intensity.

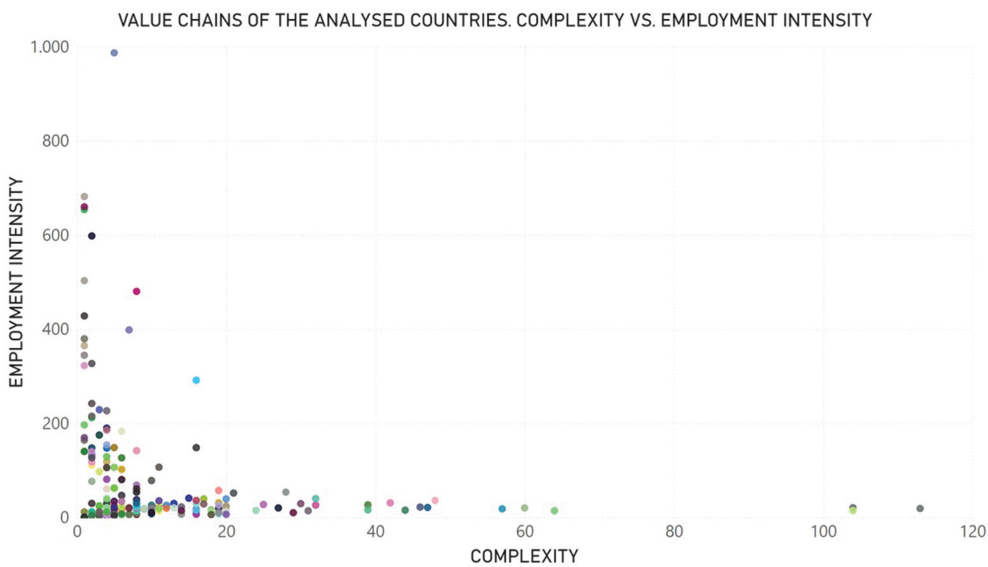

Figure 7. Value chains of the analysed countries plotted according to their complexity and employment intensity.

One group of value chains features a low level of complexity and employment intensity and a high number of members. Value chains outside of that group have either high complexity and low employment intensity or low complexity and high employment intensity. None of the value chains have both high complexity and high employment intensity.

6. Conclusion

This article has developed a method for obtaining representations of industrial value chains. The method incorporates three dimensions of sustainability in accordance with the TBL concept developed by Elkington (1998). Countries, regions, and cities that have not already done so will need to adopt extensive strategies to become more sustainable, lower their emissions, and progress towards carbon neutrality (Yao et al., 2022) while becoming more competitive and ensuring the wellbeing of their societies. Transforming industrial sectors and all value chains is essential to achieve these sustainability goals.

To evaluate strategies and decisions, business representatives and policymakers must consider both regional and global value chains in their long-term approaches. Economic, technological, and societal trends highlight the importance of understanding and managing supply chains, which emphasises the need for accurate mapping solutions.

The issue of sustainability and the impact of industries is a global problem. While the integration of companies into global value chains may be common in certain sectors, the scope of action of companies and governments is more direct within the territories where they operate. Thus, the availability of maps detailing the sustainability of a country's industrial value chains and its comparative position is essential.

This research applied a method for modelling the sustainability of value chains from a TBL perspective resulting from economic interactions between sectors within value chains to meet the final demand. This method integrates EEIOT, matrix filtering, and triangulation steps. For each analysed value chain, we developed a hierarchical model that includes links and a distribution of the emissions based on their proximity to the final demand.

The resulting graphical representation of exchange links and associated employment plus the original economic flows provides a clear understanding of the complexity of each value chain, the impacts of changes in a sector's final demand on other sectors, and the distribution of emissions along the value chains, with only a minor loss of representativity.

Based on the results of the mapping process, 20 value chains from 12 European countries (240 in total) were analysed. Through triangulation, it was observed that countries with higher GDPs had similar hierarchical structures of sectors, which became less pronounced as GDP values decreased. Moreover, a set of characterisation variables was proposed, and the potential correlations between them were examined.

In view of the work performed for the proposal of this method, the following points can be considered.

- The method is grounded in recognised data sources and existing methodological approaches and is designed to be interpretable, recognisable, and easy to disseminate. The comprehensive approach integrates EEIOTs with techniques such as matrix triangulation and trimming to provide a detailed and accurate mapping of GHG emissions across value chains in Europe.

- The novelty of this method lies in its ability to combine reliable and comprehensive datasets with a robust and systematic methodology, which ensures that the resulting value chain maps are not only accurate but also highly representative of the industrial emissions in the surveyed countries. The method's clear and systematic steps enhance its replicability and transparency and make it a valuable tool for policymakers, researchers, and industry stakeholders.
- The testing and validation of the method demonstrate its effectiveness in providing detailed insights into the emissions and employment associated with each stage of the value chain. The hierarchical visualisation of value chains along with the integration of socioeconomic factors allow for a comprehensive assessment of the environmental and economic impacts of industrial activities.
- With its clear and intuitive format, the method facilitates the communication of complex data to a broad audience, which enhances the usability and impact of the information.
- The article provides a series of indicators that, when applied to the resulting value chains, allows for the characterisation of the value chains as well as their emissions, employment, and economic activity. Such indicators can support comparative studies of countries and value chains or longitudinal studies.

In summary, this research has introduced a novel and comprehensive methodology for mapping and characterising industrial GHG emissions in European value chains. It has addressed significant gaps in existing tools and provided a robust framework for assessing the sustainability of industrial activities, thereby contributing to the broader goal of achieving a climate-neutral economy. The mapping results are useful for business, policy, and research.

From a corporate perspective, the method enables the visualisation of information about the impact of industrial activities upstream, specifically their economic, environmental, and employment-related effects. The method provides especially relevant information on Scope 3 emissions, including both emissions produced at the suppliers' facilities and those associated with the energy consumed by them.

From a policy perspective, the results offer policymakers a representation of GHG emissions across various stages of the value chain and precedence relations among them, which can support an assessment to identify value chains with the highest contributions to emissions and the dependencies of emissions within each value chain. For example, it enables an evaluation of the impact of emissions in different industrial sectors due to potential decreases or increases in demand. In addition, it can help assess the impact of technological changes and may allow for quantification of the impacts of such changes on employment and the number of affected sectors.

From a research perspective, the results of this study can enable the characterisation of environmental effects, economic flows, and employment associated with each value chain per country and collectively across countries. Three clusters were defined to group countries according to the proximity of emissions to the final demand, the complexity of emissions within the value chains, and the dispersion relative to the distance from the final demand. The treatment of the variables also facilitated clustering of the 12 countries based on proximity, dispersion, and complexity.

7. Limitations

This research offers valuable insights for decision-makers to analyse and compare the sustainability implications of industrial value chains through the proposed methodology. Nevertheless, several limitations must be mentioned.

One limitation arises from the inherent nature of input-output tables. On the one hand, the level of sectoral aggregation complicates the precise identification of sustainability impacts at the level of specific companies or corporations. On the other hand, the use of average values in the allocation process of the analysed variables can lead to compensation between sectors. Because of these limitations, this method, and the use of input-output tables, requires further refinement if it is to be applied by decision-makers within industrial corporations. However, the aggregated values provided by this approach can be highly suitable for analysis by policymakers.

In addition, for data availability reasons, the methodology was applied to data from 2020. This decision likely did not significantly affect the method itself, which was the primary focus, but it might have influenced the resulting value chain maps. Nevertheless, the use of such data provides the opportunity to replicate the analysis with more recent datasets in the future to assess the actual impact of the pandemic on the sustainability of value chains.

8. Future research

To build on this research, future studies could include a cross-sectional analysis of a sector's value chain in different countries, the creation of multi-regional maps, or a specific sensitivity analysis of the impacts of sustainable strategies on various sectors.

The automation of the process used to generate the maps also represents a potential avenue for future research. In this study, the methodology had a semi-automated nature. Future work could consider fully automating this process. It would also be interesting to propose a process for the application of the method by policymakers or industry representatives to inform decision-making and incorporate sensitivity analysis.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

Upon publication of this article, the M programming code, the data that were used, and the maps will be available in a data repository in a database format including environmental, social, and economic variables.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT to improve the language and readability. The author(s) reviewed and edited the content as needed after using this tool/service and take(s) full responsibility for the contents of the publication.

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