

## Article

# Modelling and Visualization Tools for Resource Decoupling at Meso- and Micro-Levels: Case Study in Poland

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**Abstract:** The monitoring and transition toward a circular economy, along with resource and economic decoupling, can be supported by an assessment and visualization system for material use. While resource productivity indicators and macro-level decoupling are well established, significant challenges remain at the meso-level. In particular, identifying and comparing industry branches is hindered by data access constraints and visualization limitations. To identify and visualize resource decoupling across different industrial divisions, data were collected for Poland from the Central Statistical Office. A combination of three statistical methods offers a multidimensional perspective on this research challenge. The Osanna Triangle illustrates the proportions of resources used across different manufacturing divisions, while Ward's method identifies similarities between industrial divisions. Meanwhile, correlation analysis determines the strength and direction of relationships between resource utilization and production value. This study aims to analyze resource consumption patterns across various industrial processing divisions and visualize these connections. The results can support the formulation of effective industrial policies, including targeted support for low-emission technologies in specific industrial divisions. This approach aims to optimize resource utilization, promote sustainable development, and achieve resource decoupling.

**Keywords:** environmental policy; industrial divisions; public policies; resource management; circular economy



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## 1. Introduction

With the rapid transformation and implementation of the circular economy (CE) in recent years, there is a growing need for effective monitoring at the micro-, meso-, and macro-economic levels. This requires the development of assessment and visualization systems for material use. Thanks to this, it is possible to identify areas of excessive resource consumption. Useful assessment tools in this process can be efficiency indicators. Their analysis can help reduce production costs and increase competitiveness. The study of these indicators enables companies to identify changing production conditions. The introduction of technological innovations can help reduce resource consumption. An integrated approach to monitoring resource efficiency also supports the implementation of circular economy principles and helps minimize the negative impact of industry on the natural environment.

CE is a new concept aimed at closing, narrowing, and slowing down material circulation while simultaneously achieving sustainable development goals by improving

economic and environmental performance. Therefore, it is critically important to design products that require fewer materials and consume less energy during production [1]. It is claimed that investing in research and development contributes to the creation of innovations that can facilitate the growth of the circular economy [2]. The use of appropriate measurement and analytical tools may prove helpful in evaluating the implementation of the concept and ensuring compliance with regulatory requirements. It is possible to monitor national material consumption, resource productivity, and the structure of the energy market. Material flow analysis can also be carried out. Monitoring the efficient use of resources also enables the assessment of progress in reducing the amount of waste [1]. The adoption of circular economy principles requires, above all, a pursuit of economic balance through increased material savings, particularly in industrial production [2].

In particular, studies at the meso-economic level are crucial for shaping effective public policies that facilitate the successful implementation of the CE. A systematic literature review has been conducted at the meso-level to study the configuration of the supply chain for a practical circular economy. Three supply chain configurations have been summarized: eco-industrial parks, environmental, sustainable, and green supply chains, and a closed-loop supply chain [3].

A review of the literature reveals studies analyzing water and energy consumption across various industrial divisions in China, highlighting their connection to socioeconomic development [4]. Research has also been conducted on water usage and conservation in the Colombian manufacturing industry, employing machine learning methods. These studies suggest that, to promote efficient water use and conservation in manufacturing, appropriate public policies should be developed. This includes implementing environmental regulations and standards for companies that produce textiles, metal products, and rubber and plastic products, alongside financial and fiscal incentives [5]. Other studies examine industrial divisions' interdependencies, demonstrating that basic metal production is closely linked to the manufacturing of metal products, excluding machinery [6]. Notably, major non-ferrous metals are among the most valuable resources [7]. There are also studies on the potential of biomass [8,9]; however, it should be noted that the use of biomass for energy production should take into account the aspect of natural environmental protection, particularly with regard to forests [9]. According to Lene Lange [10], a new era of bioproduction has begun, focusing on fully unlocking the potential of biomass through cascading, and optimized use of all or at least the majority of its components. This creates opportunities for the development of new business models that could enable the growth of bioproduction. This may involve the production of higher value-added products, which are more complex, based on additional stages of various processes and various streams of production for different bioproducts.

It can be observed that the circular economy is not limited to industry but encompasses all sectors of industrial processing [11]. A review of the literature and an analysis of recent studies highlight the importance of industrial symbiosis [12]. There is an increasing need to protect, restore, and revitalize ecosystems while simultaneously achieving the economic objectives of businesses [13]. This is in line with the European vision of the circular economy model, which, in this context, is viewed as a future-oriented perspective [12]. A positive growth cycle is expected—one that sustains and enhances natural capital, optimizes resource allocation, and minimizes systemic risk through the integration of policies and tools, while also considering environmental constraint [13].

Reducing raw material consumption is essential for minimizing environmental impacts, lowering resource footprints, and alleviating pressure on scarce resources, such as critical raw materials. Additionally, ensuring raw material security—measured by self-sufficiency indicators—has gained momentum in policy discussions, particularly following

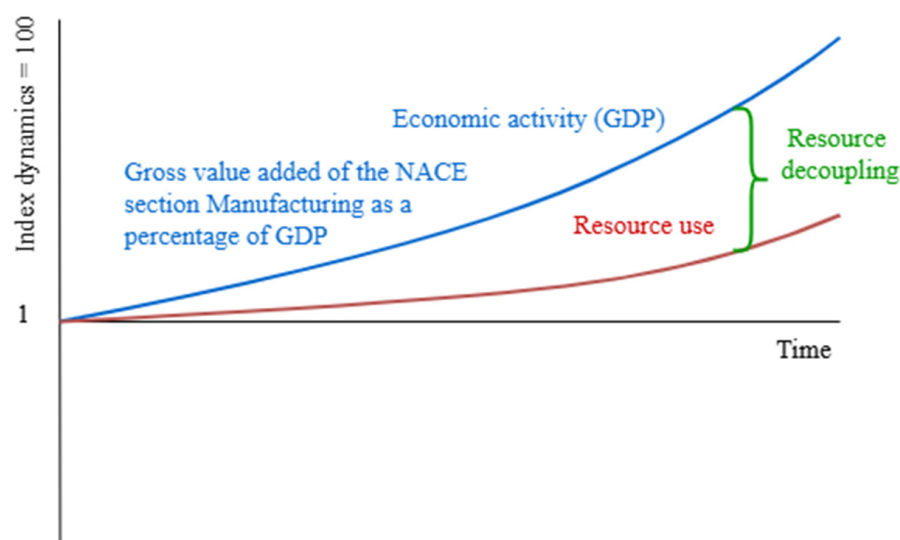
supply disruptions caused by COVID-19 and Russia's invasion of Ukraine. As highlighted in the *The Future of European Competitiveness* report by Mario Draghi, the EU's total payments for imported fossil fuels (coal, gas, and oil) reached EUR 390 billion in 2023. This was 90% higher than the historical 2017–2021 average, driven primarily by price increases, while import volumes rose by just 7% on average [14]. This highlights the significant impact of the energy market on EU economies, including that of Poland. The changes occurring between 2016 and 2023 indicate the need for action to reduce energy consumption. This underscores the growing importance of research in this area and the necessity of implementing appropriate energy policies.

Resource consumption levels vary significantly across the world. According to the International Resource Panel (IRP) *Global Resource Report 2024—Bend the Trend*, global material use has more than tripled over the past 50 years. The extraction and processing of material resources—including fossil fuels, metals, non-metallic minerals, and biomass—now account for over 55% of greenhouse gas emissions and 40% of particulate matter-related health impacts [15]. Therefore, decoupling has been put forward as a policy goal by the IRP, which distinguishes between two types of decoupling [16]: (1) resource decoupling, which commonly refers to the relationship between economic growth (economic activity) and the level of primary resource use; and (2) impact decoupling, which refers to the relationship between economic activity and its environmental impacts, as measured by impact and state indicators.

Resource decoupling can also be an important indicator for raw materials policy and security. Even though the EU critical raw materials list has been published since 2011 and updated every three years, the overall policy promoting sustainable production and consumption of raw materials started in 2000 [17]. In 2008, the Raw Materials Initiative was launched to establish a strategy for reducing dependencies on non-energy raw materials for industrial value chains and societal well-being [15]. The commitment of “decoupling growth from resource use” was underlined in the EU Roadmap to a Resource-Efficient Europe [18]. Since 2012, the 7th Environmental Action Programme guiding the European Commission's environmental policy until 2020, titled *Living well, within the limits of our planet* [19], has called for “an absolute decoupling of economic growth and environmental degradation.” Decoupling is still one of the key principles of the European Green Deal [20]. It is also a foundational component of the UN 2030 Agenda of Sustainable Development Goals, without which the goals themselves are unlikely to be achievable [21]. The indicators based on resource consumption compared with gross domestic product (GDP) or GDP per capita are widely used for circular economy policy and SDG reporting, i.e., Indicator 12.1.a—resource productivity provides information on whether there is decoupling of economic growth and natural resource use and, by implication, reduction of the negative impact of the economy on the environment. The resource productivity indicator is presented at constant prices as of 2010 (euro/kg), for comparison of resource productivity over time for a single territorial unit. Resource productivity in the EU economy has increased by around 44% between 2000 and 2023 [22]; however, in Poland, only in 2023 was a 12.7% increase in resource productivity index recorded compared to the previous year [23]. The concept of resource and impact decoupling is depicted in Figure 1.

At the country (macro)-level, in the report titled *Decoupling Economic Growth from Resource Consumption* [6], the concept of decoupling economic growth from the consumption of natural resources was discussed. This includes two main types of decoupling. Relative decoupling is distinguished, where resource consumption grows more slowly than economic growth, from absolute decoupling, where resource consumption decreases regardless of economic activity. To enable cross-country economic comparisons, there is a growing need for the development of appropriate indicators and the implementation of

a common analytical model. Such a framework would allow for a more accurate assessment of the effects of decoupling economic growth from resource consumption. Previous studies have predominantly focused on macroeconomic issues, while sector-specific analyses remain limited for resource consumption. Research in this area primarily relies on the Tapio decoupling [24–27] method but often lacks a detailed examination of industrial divisions. The developed Tapio model focuses on the flexibility of decoupling, showing the relationships between transport volume, carbon emissions, and economic development. Given the growing urgency to reconcile the conflict between reducing carbon emissions and fostering economic growth, decoupling has gained widespread adoption in global and local research domains. Achieving decoupling of economic growth from carbon emissions in the industrial sector is crucial for advancing towards emissions reduction goals. Consequently, research that focuses on industrial divisions is particularly important [28]. At the meso-level, both industry divisions and regions face major constraints, primarily due to limited access to detailed data about regional resource consumption. For example, analyses conducted within individual countries, based on statistical data from various sectors, often highlight the challenges of working with such data. The German economy serves as a relevant case study in this context [29].



**Figure 1.** The concept of resource and impact decoupling is depicted. Source: author’s own work based on [16].

With the increasing availability of data and indicators on a macro-scale, the number of reports and articles based on material flow analysis using Sankey diagrams published each year continues to rise, especially in the case of circular economy analysis [30]. However, at the meso-level, particularly in the case of different industries, there are more challenges due to more difficult access or the lack of detailed data (especially regarding material consumption) and the need for a clear vision, especially for identifying similarities and correlations between them. Despite the growing number of publications at the macro level, there is a clear research gap at the meso-level, particularly concerning individual industrial divisions.

The aim of this article is to analyze the relationships in resource consumption across various industrial processing divisions and visualize these connections. The division of resources at the meso-level is related to the purpose of the article, because conducting this type of analysis makes it possible to illustrate and understand the flow of consumed resources. The hypothesis posits that a research model highlighting the differentiation between industrial divisions can aid in their segmentation. This approach may help design

more precise, effective, and industry-specific public policies that promote sustainable development and efficient resource management.

The research is significant for science in an interdisciplinary context, linking fields such as environmental engineering, mining and energy, management and quality sciences, as well as political science and public administration. From a practical perspective, in the realm of political regulations and for business, knowledge in this area can help optimize the use of resources, energy, and water. It enables companies to reduce operational expenses, directly impacting their profitability. It can be useful in making strategic decisions, influencing the improvement of company competitiveness and compliance with environmental regulations. Such an approach can help in developing more precise, effective public policies targeted at individual industries, which will promote sustainable development and efficient resource management.

Poland is used as a case study to develop tools for analyzing and visualizing the examined issue, offering substantial theoretical and practical value. By applying statistical methods, such as the Osanna Triangle, Ward's clustering analysis, and Spearman's correlation analysis, the study presents an innovative approach to a multidimensional perspective on the research problem. The research results highlight similarities in resource consumption across different industrial sectors, such as the chemical and metallurgical industries.

The conducted study focuses on the visualization and assessment of resource allocation in various industrial divisions and represents a significant contribution to the development of analytical tools supporting the transition toward a circular economy. The decoupling of economic growth from resource consumption is a key challenge of contemporary sustainable development policy. In the face of increasing demand for natural resources and the requirements for reducing various types of emissions, effective monitoring and optimization of material consumption in industry are becoming essential. In the scientific literature, the issue of resource productivity at the meso-level (individual industrial divisions) and the micro-level remains insufficiently explored. The combination of three statistical methods—Osanna's Triangle, Ward's method, and correlation analysis—provides more information from a new, multidimensional perspective, useful for resource allocation in industry.

To identify and visualize resource decoupling across different industrial divisions, data were collected for Poland from the Central Statistical Office. The selected statistical and visualization methods were used to examine various types of decoupling in the consumption of resources, like biomass, metals, and energy (in tons), in relation to the revenue values (PLN) associated with these resources (tons) across 24 industrial processing divisions in Poland. These tools enable the assessment of dominant resources and changing proportions across different industrial divisions, as well as the identification of similarities between industrial divisions based on the usage of all analyzed resources.

These studies are of significant importance to science in an interdisciplinary context. They are also important from a practical perspective in terms of political regulations and for business. The results of this study can support policymakers in formulating effective industrial strategies, including the implementation of low-emission technologies and improving resource efficiency in various industrial divisions. Furthermore, the analyses provided can help identify industrial divisions that require priority support in the ecological transformation process. A better understanding of resource consumption patterns will enable the design of more precise economic policy instruments, such as subsidies for sustainable technologies or regulations regarding material efficiency. In reference to businesses, the results of this study can support companies in optimizing their production processes, implementing innovative, low-emission technologies, and managing resources more efficiently. Through these analyses, companies can better understand the environ-

mental impact of their activities and adapt their business strategies to the requirements of sustainable development. Businesses can also benefit from the developed analytical tools to improve operational efficiency, reduce costs, and comply with increasingly stringent environmental protection regulations.

## 2. Materials and Methods

The research presented in the article was conducted in five parts, in several stages. Initially, a review of the papers identified through Scopus, Web of Science, and Google Scholar database and international organization reports was conducted using the PRISMA framework focusing on studies from the last 15 years. In the second part of the study, a database at the meso-level was selected. Gathering such detailed data proved challenging due to its limited availability and the need for purchase, as relatively few industry-level studies are conducted with such a high degree of detail. The third stage involved an extended process of collecting a large dataset. The source data were obtained from the statistics of the Central Statistical Office (Poland). The use of data from 2016 is justified by methodological factors. Data on resource consumption in industry are subject to a lengthy process of verification and aggregation by the Central Statistical Office, due to the comprehensive nature of the collected information and the necessity of their validation. Additionally, the year 2016 pertains to a period of stable economic functioning, prior to the emergence of the coronavirus crisis associated with the global COVID-19 pandemic, which occurred in the years 2020–2022 and significantly impacted the functioning of all economic sectors, followed by the outbreak of the Russian–Ukrainian war. The use of data from this time horizon thus allows for the analysis of standard patterns of resource consumption, unaffected by economic changes resulting from these crises.

The analysis included one of the main indicators, resource productivity, which is used to assess circular economy activities [31]. Another commonly reported area is resource consumption. This indicator enables the collection of information necessary for achieving the goals and assumptions of the CE concept, which is becoming a global economic model focused on minimizing resource consumption throughout the entire value chain [32].

In the third part, during the fourth stage, these data were grouped into categories for the main resources, i.e., biomass, metals, other materials, energy, and water, within the individual 24 divisions of industrial processing (Section C) of the Polish Classification of Activities (PKD), which aligns with the European NACE Rev. 2 classification. In the fifth stage, to ensure comparability of results, resource data were converted into tons, enabling a clear and consistent representation within the framework of quantitative analysis. These actions allowed for the standardization of different data types, significantly facilitating further inferences and comparisons. Resource data (in the sixth stage) were compared with the production value expressed in monetary units (PLN), allowing for an assessment of the economic efficiency of resource utilization.

The research process was carried out in a linear manner, where each previous stage was completed before the next one began. The visualization of this process is presented in Figure 2, which helps in understanding the subsequent steps in the research process.

In the fourth part of the study, among the statistical methods, the Osanna Triangle was selected, which can be applied first due to its ability to visualize and interpret the structure of the consumption of three analyzed resources. The second statistical method applied in the research process, cluster analysis using Ward's method, enables the identification of similarities between industrial divisions in terms of the use of all analyzed resources. A complement to this method may be a heat map, which illustrates the resource intensity of the individual industrial divisions. Spearman correlation analysis serves as a supplement to the previously applied methods, demonstrating the interdependence between resource

consumption and the achieved production value by indicating significant relationships between them.

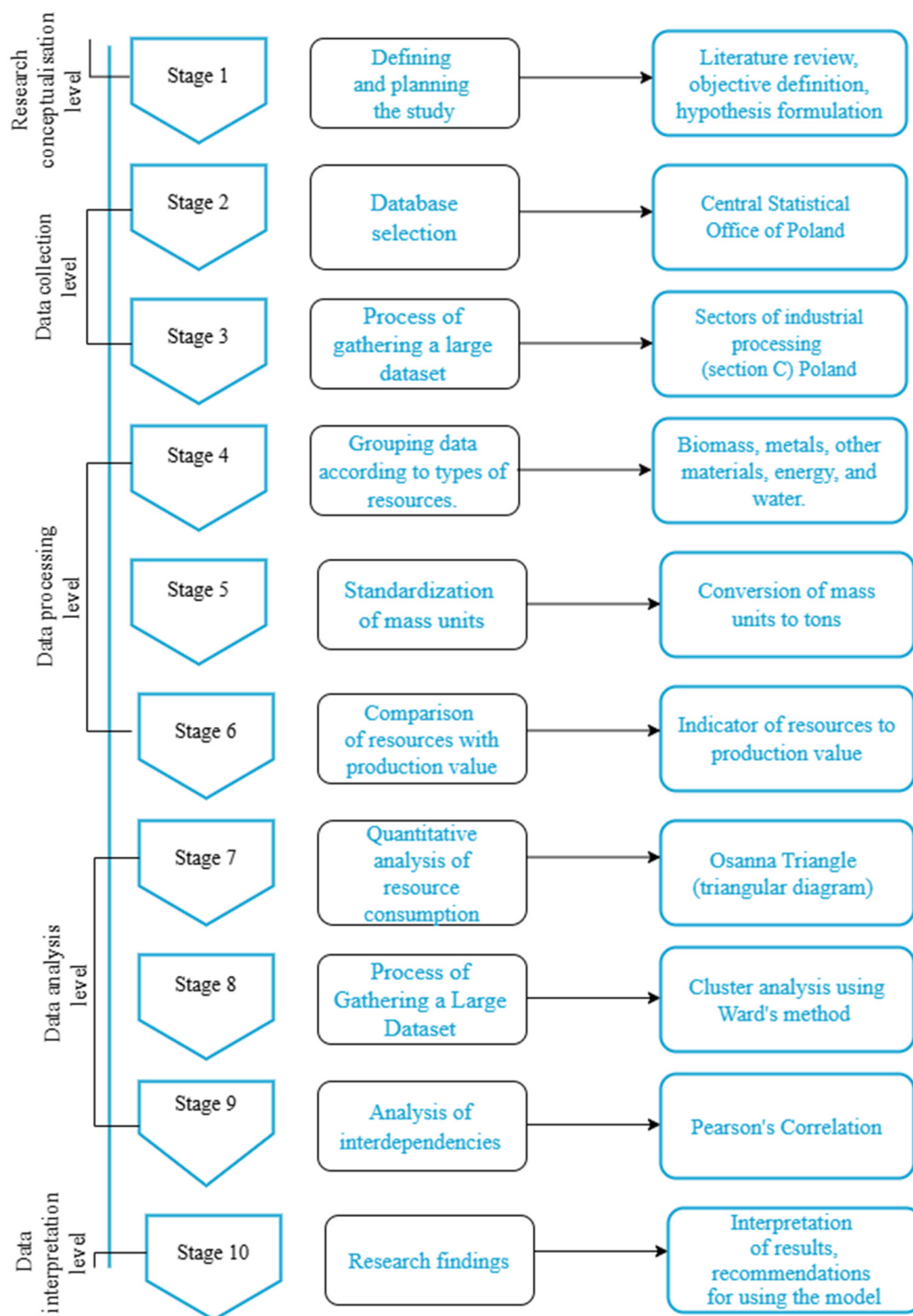


Figure 2. Research methodology. Source: authors' work.

The combination of applying these three statistical methods allows for a multidimensional view of the research problem from different perspectives. While the Osanna Triangle illustrates the proportions of resources used in individual manufacturing divisions, Ward's method reveals similarities between industrial divisions. Meanwhile, correlation analysis allows for determining the strength and direction of relationships between the resources

utilized and the resulting production value. Each of these three methods complements the knowledge gained and provides insight into the issue from a different perspective.

In the fifth, concluding part of the study, the obtained results from the data constituting the case study of Poland were analyzed and interpreted. The analysis process was based on statistical methods enabling the identification of key relationships between variables. Calculations and data visualizations were performed using Statistica statistical software (version 13.3).

Explaining the selection and use of all these three selected statistical methods, it is possible to more specifically characterize their application. This allows for a better assessment of their effectiveness. It also makes it easier to understand the results obtained using each method.

For the analysis using the Osanna triangle, three resources were selected: biomass, metals, and energy (in tons) across different industrial divisions, in relation to the revenue values (PLN) assigned to these resources (tons). The choice of this method enables the visualization of the structure of the use of these three resources in the production process within individual industrial processing divisions. This tool allows for the assessment of which resources dominate and how their proportions change across different industrial divisions. The Osanna triangle is useful for understanding the relationships between the three analyzed resources.

Thanks to this method, the Osanna triangle makes it possible to present the shares of each of these resources in the overall structure of the industrial divisions of the economy. Each point inside the triangle represents a combination of three resources used in production within a specific industrial division, and the distance from the sides of the triangle indicates the percentage share of a given component (the sum of all three resources equals 100%). The visualization helps to show how biomass, metals, and energy coexist in the analysed industrial processes. This method allows for assessing which resources are used dominantly and which play a smaller role.

In the analysis, the focus was placed on three selected resources, but it is possible to concentrate on others. It should be noted that none of the resources included in the analysis should dominate the others, accounting for nearly 100%. In this example, it can be observed that water consumption significantly outweighs other factors in the structure of resource usage. This means that its use significantly exceeds the level of consumption of other resources, such as biomass, metals, or energy. Water consumption is significantly higher compared to the other mentioned resources, and its inclusion in the analysis would lead to the dominance of this parameter, which would hinder the proper representation of proportions between the other two analyzed resources.

In the analysis of clusters using the Ward method, the grouping of 24 divisions of industrial processing was carried out based on similarities in the demand for production resources, such as biomass, metals, other materials, energy, and water. The cluster analytic procedure of grouping the divisions of industrial processing using Ward's method was used for the analysis. The successful application of this method requires the selection of a bond. In light of these requirements, one of the clustering algorithm methods was applied, specifically Ward's method, with the Euclidean distance between industrial divisions as a measure of similarity. A scatter plot was then made, which helps determine the optimal number of clusters by visualizing changes in the distances between the merged clusters. For analysis using Ward's method, a heat map was added to visualize the results.

To determine the relationship between the use of resources essential for industrial production, the Spearman correlation method was applied. The purpose of this analysis is to examine whether resource consumption is correlated across resources, that is, whether

the use of a particular raw material in industrial processing is dependent on the use of another. In addition, the value of production is included in the analysis.

To conduct an analysis of resources utilized in industrial production, collected data was organized. The specificity of individual resource types and their applications in various branches of industry were taken into account. In the process of collecting data, resources were classified according to their type, with detailed components presented in Table 1.

**Table 1.** Components of industrial processing production.

Variables	Resources	Category	Details
X <sub>1</sub>	Biomass	Forest products	Wood, wood residues, trees, shrubs, and other wood residues, sawdust, bark, etc.
		Bio-renewable Waste	Agricultural waste, wood waste from milling, urban wood waste, urban organic waste, etc.
		Energy Crops	Short-rotation woody plants, herbaceous plants, grasses, forage crops.
		Food Crops	Residues from grains and oilseed plants.
		Sugar Crops	Sugarcane, sugar beets, molasses, sorghum.
		Landfill Waste	Municipal solid waste.
		Industrial Organic Waste	Plastic waste, oil waste, leather waste, rubber waste, organic acid waste, etc.
		Algae, Kelp, Lichens, and Mosses	Water hyacinth, mushrooms, etc.
		Aquatic Plants	Algae, water weeds, water hyacinth, reeds, lichens, and mosses.
		Aquatic plants	Algae, water weeds, water hyacinth, reeds, and sedges.
X <sub>2</sub>	Metal	Primary Metals	Raw iron, steel, aluminum, copper, zinc, and lead.
		Secondary Metals	Recycled iron, steel scrap, aluminum scrap.
		Precious Metals	Silver, gold, platinum used in industrial applications.
		Industrial Metals	Metals used in construction and industry, e.g., steel, copper, aluminum.
X <sub>3</sub>	Other Materials	Non-metallic Minerals	Sand, gravel, clay, stone.
		Secondary Metals	Recycled iron, steel scrap, aluminum scrap.
		Precious Metals	Silver, gold, platinum used in industrial applications.
		Building Materials	Ceramic products, bricks, roof tiles, aerated concrete.
X <sub>4</sub>	Energy	Fossil Fuels	Coal, natural gas, crude oil.
		Renewable Energy Sources	Solar, wind, hydro, geothermal.
		Electricity	Production and distribution of electricity.
		Heat Energy	Heat generated in district heating plants.
X <sub>5</sub>	Water	Surface Water	Lakes, rivers, reservoirs.
		Groundwater	Aquifers and underground sources.
		Industrial Water Use	Industrial water for technological processes.
		Municipal Water Supply	Water for public supply.

Source: authors' work.

Variable six,  $X_6$ , represents the value of production in a given industrial processing department (PLN). It reflects the scale of production activity, enables the comparison of productivity across different industry departments, and facilitates the analysis of resource utilisation efficiency. This variable was used to calculate the resource utilisation intensity index, as defined by the formula

$$I_z = Z/P \quad (1)$$

where  $I_z$  is the resource utilization intensity index;  $Z$  is the resource consumption; and  $P$  is the value of production.

The index  $I_z$  shows the amount of a given resource (biomass, metals, etc.) per unit of production value (PLN). According to the example, a result of the index equal to 0.5 tons/PLN means that, for one unit of production worth 1 PLN, there is a consumption of 0.5 tons of raw material, which defines the resource intensity of a process. This highlights the efficiency of resource utilization in the production process and enables the comparison of different industrial divisions in terms of resource utilization intensity. It can be noted that, when comparing divisions of industrial processing in a given year, inflation has no impact because values from the same period are being compared. However, if the index were to be analyzed over time (time series), inflation could be included in the analysis.

### 3. Results and Discussion

In the study, the cumulative resource consumption (in tons) was calculated in relation to the final production value (PLN) in different industrial processing departments. Subsequently, an analysis was conducted on the efficiency of resource utilization in relation to the achieved production outcomes. The share of individual categories of resources and production values in different industry departments was calculated for total resource consumption in industrial processing and final production value, presented in Table 2.

**Table 2.** Summary consumption of materials, energy, and water compared with sales (production) volume—percentage share of resource consumption.

Department Name	Consumption			Final Production Value
	Biomass, Metals, Other Resources	Energy	Water	
10. Food products	0.385	7.567	12.301	17.534
11. Beverages	0.140	1.509	4.008	1.675
12. Tobacco	0.001	0.226	0.028	0.455
13. Textiles	0.352	0.803	0.582	1.265
14. Clothing	0.010	0.183	0.055	0.867
15. Leather	0.022	0.083	0.083	0.465
16. Wood	10.600	4.425	0.901	3.218
17. Paper	13.242	6.140	14.908	3.408
18. Printing	1.797	0.435	0.000	1.297
19. Coke	0.079	9.291	5.922	4.843
20. Chemicals	6.400	16.037	50.686	5.255
21. Pharmaceuticals	0.009	0.731	0.527	1.262
22. Rubber	6.133	3.904	0.971	7.390
23. Non-metallic raw materials	23.952	8.629	1.817	4.448
24. Metals	9.128	28.308	6.005	3.966
25. Metal products	11.244	2.542	0.208	8.673
26. Computers	0.120	0.384	0.014	3.334
27. Devices	1.834	1.446	0.180	4.768
28. Machinery	1.746	1.744	0.250	3.838
29. Cars	3.050	2.909	0.125	12.454
30. Other transport equipment	0.310	0.905	0.208	1.770
31. Furniture	8.795	0.977	0.055	3.802
32. Other products	0.361	0.210	0.000	1.115
33. Repair	0.290	0.613	0.166	2.899
Total	100.000	100.000	100.000	100.000

Source: own calculations based on Statistics Poland data. Data for Section C of NACE, Poland.

The analysis of resource consumption across various industrial divisions processing shows that the use of biomass, metals, and other raw materials is highest in the industrial division engaged in the production of non-metallic raw materials, accounting for as much as 24%. The lowest consumption of these resources is observed in the tobacco industry. Energy is most intensively used by the metallurgical industry, which accounts for 28% of its total consumption. Conversely, the lowest demand for energy is recorded in leather production. When it comes to water consumption, it is utilized to a significantly greater extent in the chemical industry than in any other industry, accounting for as much as 51% of total water usage in industrial processing. The industrial division with the lowest water consumption is that involved in miscellaneous production, specified as “other products”.

The analysis of resource, energy, and water consumption intensity offers a unique perspective on resource utilization. It provides insights into the efficiency of production processes across different departments and their environmental impact. This allows for the identification of areas where efficiency can be improved and energy and water consumption can be reduced. The value of the resource intensity indicator reflects the demand for resources within these production processes. The results of the resource intensity indicators for individual divisions of industrial processing are presented in Table 3.

**Table 3.** Resource utilization intensity index (tons/th. PLN).

Department Name	Biomass	Metals	Other Resources	Energy	Water
10. Food products	0.55	0.01	0.25	10.63	451.70
11. Beverages	0.84	0.00	2.26	22.19	1540.82
12. Tobacco	0.10	0.00	0.00	12.26	39.29
13. Textiles	0.94	0.46	8.93	15.63	296.48
14. Clothing	0.20	0.00	0.22	5.20	41.19
15. Leather	1.10	0.01	0.68	4.41	115.13
16. Wood	120.45	0.97	1.05	33.87	180.36
17. Paper	142.01	0.02	2.45	44.38	2816.98
18. Printing	51.40	0.09	0.02	8.26	0.00
19. Coke	0.00	0.02	0.58	47.25	787.21
20. Chemicals	0.32	0.06	44.91	75.17	6210.85
21. Pharmaceuticals	0.05	0.00	0.22	14.26	268.92
22. Rubber	2.02	1.10	27.73	13.01	84.58
23. Non-metallic raw materials	2.06	3.19	194.97	47.79	263.01
24. Metals	0.47	74.07	11.04	175.82	975.00
25. Metal products	1.37	46.46	0.37	7.22	15.44
26. Computers	0.19	0.49	0.66	2.84	2.68
27. Devices	0.74	9.39	4.17	7.47	24.35
28. Machinery	0.57	15.86	0.49	11.19	41.88
29. Cars	0.37	8.22	0.52	5.75	6.45
30. Other transport equipment	0.36	5.96	0.19	12.60	75.68
31. Furniture	83.80	1.84	0.37	6.33	9.39
32. Other products	7.24	2.84	1.95	4.65	0.00
33. Repair	0.84	2.79	0.08	5.21	36.96

Source: own calculations based on Statistics Poland data. Data for Section C of NACE, Poland.

It can be noted here that different resources have different physical properties and, despite the conversion of all units of measure to tons for conventional comparability of data, methodological issues must be kept in mind. Although energy (measured in kWh/MJ) is not physical, it can be methodologically converted into fuel equivalents, such as tons of oil equivalent (TOE), which is an international unit of energy. However, it is important to recognize that these conversions involve certain assumptions and approximations.

Analyzing the descriptive statistics, it can be observed that, among the selected resources, biomass has the highest significance in obtaining production value in the paper industry (142.0100 t/th. PLN), and the lowest in the coke industry (0.0021 t/th. PLN).

The average is 17.4165 t/th. PLN, and the median is 0.7870 t/th. PLN. The standard deviation is 40.1780 t/th. PLN. When it comes to the consumption of metals, the highest significance is in obtaining production value in the metallurgical industry, while this is minimal in the clothing industry. The average consumption is 7.2431 t/th. PLN, the median is 0.7275 t/th. PLN, and the standard deviation is 17.2690 t/th. PLN. Energy is required in all industrial processing divisions, thus playing a significant role in obtaining production value. The highest energy demand occurs in metal production (175.8193 t/th. PLN), and the lowest in computer production (2.8354 t/th. PLN). The average is 24.7232 t/th. PLN, while the median is 11.7248 t/th. PLN. The standard deviation is 37.0270 t/th. PLN. To an even greater extent, water is utilized in certain industrial divisions. The chemical industry requires as much as 6210.8500 t/th. PLN, whereas the printing industry practically does not utilise water at all. The average is 595.1818 t/th. PLN, the median is 80.1311 t/th. PLN, and the standard deviation is as high as 1358.5820 t/th. PLN, which indicates significant variability in water usage across individual industrial processing divisions. The results of these calculations, in the context of resource intensity, show to what extent each industrial division utilizes individual resources to obtain production value.

The analysis using statistical methods began with the application of the Osanna triangle, shown in Figure 3.

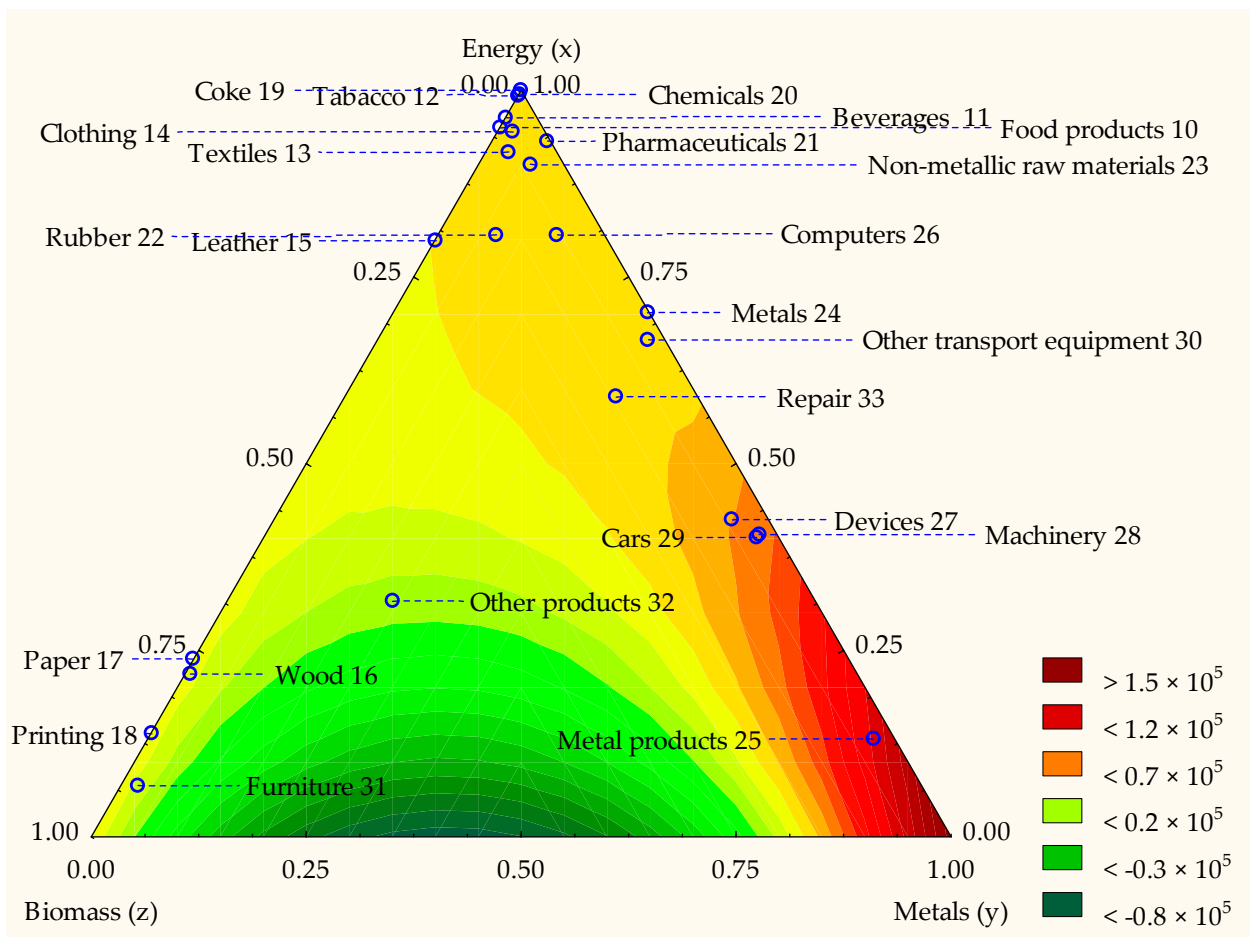


Figure 3. Ossana’s Triangle. Source: authors’ work.

A special cubic function was selected for the analysis, which allows for the representation of nonlinear phenomena. In this case, the efficiency of the use of biomass, metals, and energy in relation to the value of production can be assessed. A cluster of points indicates similar structures of raw material consumption by industrial processing departments.

A contour chart shows how variables (biomass, metals, energy) influence production efficiency. A positive coefficient indicates that the given variable increases production efficiency, while a negative coefficient indicates a decrease (according to the legend of the chart). Therefore, a special cubic function can be used to model the relationship between resource size and production value. This function is described by the following Formula (2):

$$F(x, y, z) = a_1x + a_2y + a_3z + b_1xy + b_2xz + b_3yz + c_1xyz \quad (2)$$

where  $x$  is biomass;  $y$  is metals; and  $z$  is energy.

This method can be used for optimizing production processes, resource planning, and understanding the interactions between key factors affecting performance. This allows better adaptation of resource allocation to changing production needs. It also enables identification of areas of lower efficiency, allowing streamlining and improvement of production results.

Next, a heatmap visualization was used in combination with the Ward method, illustrated in the dendrogram. In this analysis, all available data on the consumption of biomass, metals, other materials, energy, and water were taken into account, and the values of the obtained final output for the 24 industrial processing divisions were considered. Using a heat map for analysis, combined with Ward's method, can provide accurate information on which departments are similar in terms of the analysed characteristics. The heat map model is used to illustrate (estimate) the main components consumed in production versus the final value for industrial processing departments. The dendrogram presents a hierarchical clustering of industrial departments in terms of the variables analysed. Data for analysis were standardized by Formula (3):

$$z = (x - \mu) / \sigma \quad (3)$$

where  $z$  is standardized value;  $x$  is calculated value;  $\mu$  is arithmetic mean; and  $\sigma$  is standard deviation.

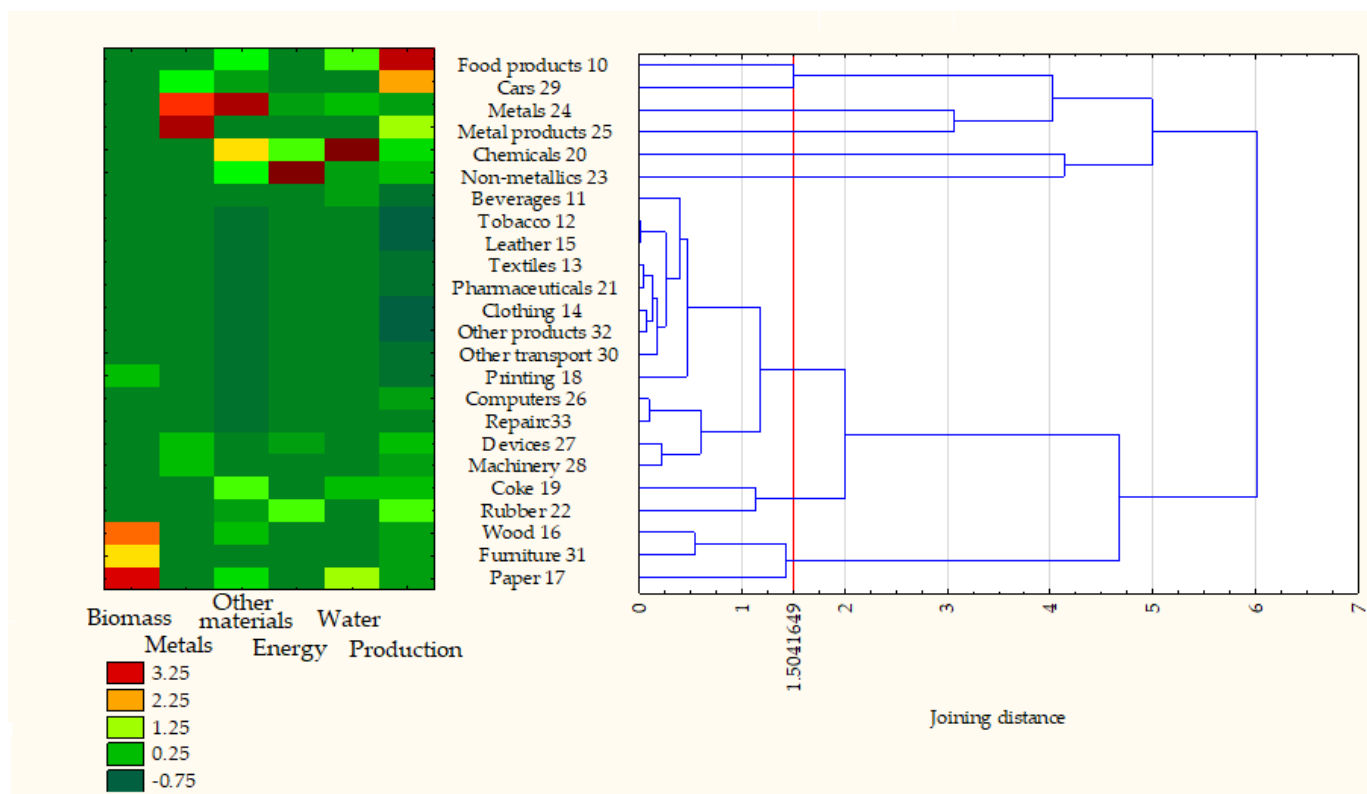
Standardization is a type of normalization that enables the comparison of different units of measurement and allows for the simultaneous consideration of all variables in the grouping process. This is particularly necessary when combining all data on resource utilization and final production values across all industrial processing departments. One can see whether high production value is associated with high resource consumption, or whether some industrial divisions are able to generate high value with relatively lower resource consumption. A comparison of the two methods is shown in Figure 4.

On the heat map, each row represents a different industrial division, and the color in a cell shows how intensively a particular division uses a particular resource compared to the average of all industrial processing divisions. The paper-producing branch of the industry consumes the most biomass (red color), indicating very high use of this resource compared to other industrial processing divisions. Values below the average are shown as negative. The more negative the value (darker green), the more a given resource consumption is below the particular division average. Looking at the heatmap, it can also be seen that the food products industry generates a high value of output, compared to other industrial divisions. The result is significantly above the average performance of all industrial processing divisions. The department is the largest in economic terms, specifically in terms of the value of goods produced, compared to other divisions of industrial processing.

In searching for departments with a similar level of resource utilization and achieved final production value, an agglomerative Ward method analysis was conducted using Euclidean distance, which is the geometric distance in multidimensional space, calculated using Formula (4):

$$d(x, y) = \left( \sum_{i=0}^n (x_i - y_i)^2 \right)^{\frac{1}{2}} \tag{4}$$

where  $d(x, y)$  is the Euclidean distance between points  $x$  and  $y$  in an  $n$ -dimensional space;  $x_i$  is the value of the  $i$ -th coordinate of point  $x$ ;  $y_i$  is the value of the  $i$ -th coordinate of point  $y$ ; and  $n$  is the number of dimensions of the space.

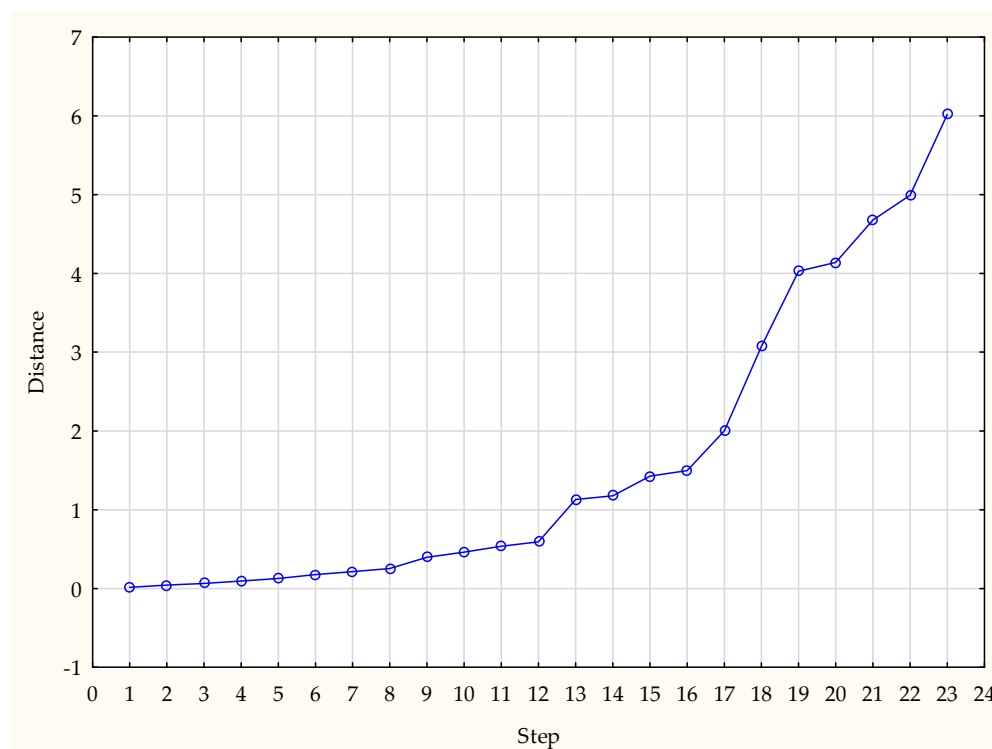


**Figure 4.** Heat map and dendrogram of Ward’s method. Source: authors’ work.

The dendrogram shows that, within each group, industrial divisions exhibit similar patterns of resource consumption and production, indicating that they have a similar structure and approach to resource management. This allows for the identification of groups of industrial division that use similar technologies, production processes, or have comparable demand for energy, water, and the other resources analyzed. First, the departments in group one (Group I) were distinguished, characterized by different characteristics of activity. The food, automotive, metal, chemical, and non-metallic product industries are distinct due to their unique characteristics. Varied use of resources is confirmed by the heatmap, which illustrates the varied intensity of using different categories of resources. Group two (Group II) consists of industrial processing divisions with similar resource utilization. These include the beverage, tobacco, leather, textile, pharmaceutical, clothing, transport and printing products. The cohesion of this group is due to similarities in resource utilization and the generated final production value. A distinct third grouping (Group III) is made up of departments of a technical nature (computer manufacturing, repair activities, equipment and machinery manufacturing), which are classified separately from industries based on natural resources. A separate but related fourth group (Group IV) consists of the coke and rubber industries. Their proximity in classification is due to similar requirements for the use of production materials, energy and water. This indicates that they significantly burden the natural environment in terms of resource consumption in production processes. The last

fifth group (Group V), including wood, furniture, and paper production, is characterized by a relatively low level of energy and metal consumption, which determines their similar environmental profile. These identified groups were obtained using a scree plot, allowing for their objective identification rather than merely subjective assessment, providing the possibility of more precise conclusions. The red line on the dendrogram indicates the cutting level, which divides the data into areas, allowing for the identification of five main groups of industrial processing departments. Based on the scree plot, a possible grouping point was observed.

The scree plot for hierarchical clustering using Ward's method is shown in Figure 5.



**Figure 5.** The scree plot for hierarchical clustering using Ward's method. Source: authors' work.

The two methods used—Osanna's triangle and cluster analysis using Ward's method—make it possible to identify groups of industrial departments in terms of their similarity in resource consumption and output value obtained, but each provides different analytical information. Osanna's triangle allows a precise visualization of the proportions between the three selected resources, enabling an accurate assessment of their interrelationships across industry divisions. Ward's method, on the other hand, through hierarchical cluster analysis, offers a comprehensive grouping of industry divisions taking into account all the analyzed variables simultaneously, allowing the identification of similarities in a multidimensional feature space. The complementary application of the two methods provides both detailed insights into the structure of the use of selected resources and a comprehensive picture of similarities between industrial divisions.

Complementing the analyses performed, the Spearman correlation method can be used to determine the strength and direction of the relationship between the variables under study. This method allows the quantification of interrelationships, in this case between individual resources and resources and production value, providing additional information about the nature of their relationship. Analyses were carried out for the entire industry without breaking it down by department. The Spearman correlation was used because the variables do not meet the normality assumptions required for parametric tests. The

correlation coefficient values marked in red indicate statistical significance with  $p < 0.050$ . The results of the Spearman correlation analysis are shown in Table 4.

**Table 4.** Spearman’s correlation coefficients.

Variable	Biomass	Metals	Other Materials	Energy	Water	Production
Biomass	1.000	0.421	0.339	0.346	0.104	0.428
Metals	0.421	1.000	0.387	0.437	0.041	0.603
Other materials	0.339	0.387	1.000	0.763	0.849	0.794
Energy	0.346	0.437	0.763	1.000	0.692	0.670
Water	0.104	0.041	0.849	0.692	1.000	0.516
Production	0.428	0.603	0.794	0.670	0.516	1.000

The correlation coefficient values marked in red are significant with  $p < 0.050$ . Source: authors’ work.

They show that the higher the value, the stronger the relationships, and all values marked in red are statistically significant. The strongest relationships are observed between resource consumption in the categories of other materials, water, and energy, which are also statistically significant, indicating a high level of interdependence. All resources have a significant relationship with production value, with the strongest significant correlations being observed for other materials, energy, and water. In contrast, weak correlations that are not statistically significant are between the use of biomass, other materials, energy, and water.

The results of the study confirm the hypothesis and show that the research model illustrating the differentiation between industrial divisions can support resource segregation. Measurement and visualization tools can be used to analyze industrial divisions. The analysis of resource consumption, such as that of energy, water, and others, involves identifying the extent of their use in industrial processing divisions. This helps determine which industrial divisions require the most, taking into account the efficiency of their utilization. By analyzing differences in resource consumption intensity across various industrial divisions, the model can assist in better matching resources to the actual needs of each industrial divisions, which increases efficiency and reduces waste. These tools allow for continuous monitoring of production process performance in individual industrial divisions.

These tools can aid in the development of effective public policies focused on efficient resource management, enabling the achievement of sustainable economic development. In reference to previous studies by other authors, it can be stated that such policies are increasingly recognized as essential for addressing global environmental challenges. The findings are consistent with earlier research on industrial symbiosis and resource efficiency but are broader than in previous works. They also include the development of tools for modeling and visualizing tools for resource decoupling at the meso- and micro-levels. Future research could consider a regional scope to explore how public policies supporting the circular economy and climate goals can be integrated.

#### 4. Conclusions

As a result of the conducted research, using the Osanna Triangle, Ward’s Method, Heat Map, and Spearman’s correlation analysis, an innovative combination of these methods was applied. The use of these statistical tools allows for the proposal of general modeling and visualization methods that enable the identification of resource consumption at both the micro- and meso-economic levels. These tools provide companies (micro-) with an average benchmark that can support CE strategies and decision-making in resource management.

Poland has been used as a case study to analyze resource allocation modeling at the meso- and micro-economic levels and the development of visualization tools, offering

both significant theoretical and practical value. By integrating statistical methods, such as the Osanna Triangle, Ward's clustering analysis, and Spearman's correlation analysis, this study achieves, for the first time, a multidimensional visualization of resource consumption structures and economic outcomes for industrial divisions. Addressing gaps in traditional macroeconomic indicators, it enables more precise formulation of industrial policy. The findings reveal resource dependency characteristics in key industrial divisions, such as the chemical and metallurgical industries.

The main conclusions are based on a comparison of industrial divisions and the application of well-known statistical methods, which were applied in an exploratory manner. The analysis focuses on visualizing patterns of resource consumption. The results indicate that divisions such as paper production, wood products, and furniture manufacturing exhibit similar characteristics in terms of raw material usage. A similar pattern was also observed in the metallurgical industry and metal products manufacturing, which share common resource consumption patterns. As a result, it can be concluded that the findings are stable and align with actual observations of resource consumption in specific industrial divisions. Through the analysis of the resource intensity indicator, the study not only quantifies the high dependency on resources in industrial divisions, such as paper production, but also confirms strong correlations between material, energy, and water resources. These findings have significant value for resource allocation optimization and promoting green industrial transformation.

It can be noted that a limitation of the study may be that the analysis is based on the classification of economic activities in Poland (PKD/NACE Rev2), so similar future studies could be conducted using other classifications, such as NAICS or ISIC. A further limitation could be the availability and granularity data. Moreover, the data collected in different industrial sectors may vary in scope and detail, which could limit the ability to draw consistent conclusions from the conducted research.

In future research, an analysis of industrial divisions in other countries could be conducted. Future research could explore the regional perspective to examine how public policies supporting the circular economy and climate goals can be further integrated. Additionally, studies could explore a regional perspective to examine how public policies supporting the circular economy and climate goals can be further integrated. Research on resource consumption patterns will allow for more effective formulation of policies supporting industrial transformation.

In line with previous studies, it can be asserted that such policies are increasingly recognized as critical for addressing global environmental challenges. However, the findings regarding industrial symbiosis and resource use efficiency go beyond the previous works analyzed, including the development of tools for modeling and visualizing resource allocation at the meso- and micro-levels. The application of the proposed methods can provide both detailed insights into the structure of the use of selected resources and a comprehensive picture of similarities between industrial divisions.

The findings of this study can be useful in supporting formulating industrial policies, such as implementation of low-emission technologies tailored to specific industrial divisions, with the goal of optimizing resource utilization, fostering sustainable development, and achieving decoupling. More statistical tools, i.e., Spearman correlation method, can be used to determine the relationship between the use of resources essential for industrial production and to examine whether resource consumption is correlated, i.e., whether the use of a particular raw material in industrial processing is dependent on the use of another.

This approach can help in developing more precise, effective, and industry-specific public policies that will promote the principles of the circular economy, including efficient resource management. As a result, it will be possible to better tailor regulations and

support mechanisms to the specific needs of industries, which can contribute to decoupling economic growth from the primary consumption of resources and reducing resource wastage. Public policy plays a key role in promoting the principles of the circular economy (CE) by implementing regulations and support mechanisms. Effective policies should include both legal and economic instruments, such as extended producer responsibility systems, tax incentives for sustainable technologies, and incentives for eco-design.

Another important aspect of public policy is the harmonization of reporting standards and data collection across different sectors of the economy, which enables precise analysis of material flows. Supporting cooperation between the government, the private sector, and research institutions allows for the development of more effective strategies that promote both economic growth and the minimization of negative environmental impacts. Furthermore, effective public policy should include mechanisms that support the optimal use of resources, such as promoting industrial symbiosis, developing secondary raw material markets, and investing in technologies that enable the efficient recovery and reuse of resources. To effectively support a circular economy, it is necessary to increase data availability at the meso- and micro-levels and develop analytical tools that enable better monitoring of resource use. Governments should introduce targeted support for low-emission technologies and integrate industrial policies with sustainable development goals. It is also crucial to raise awareness among businesses through education and information campaigns to encourage more efficient resource management.

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