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From Waste to Value: A Hybrid Decision-Making Framework for Industrial Symbiosis Implementation in an Industrial Park

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ABSTRACT

The transition from a linear to a circular economy is a crucial strategy for addressing resource scarcity, waste generation, and climate change. Industrial Symbiosis (IS) plays a central role in this transition by facilitating the exchange of waste and by-products across industries, thereby improving both environmental and economic performance. This study develops and applies a hybrid methodology for IS implementation in the Manisa Industrial Park (Türkiye), one of the country's largest industrial zones. The proposed framework integrates Multi-Criteria Decision-Making methods (AHP, VIKOR, and ELECTRE), Material Flow Analysis (MFA), and Mixed-Integer Linear Programming (MILP) to identify sectoral priorities through expert consultation and survey-based criteria weighting, and to optimize inter-company waste exchange networks. The findings designate the metal, plastic, plant-based, and chemical sectors as priority domains, while the optimization results indicate a relative improvement of up to 35% under normalized assumptions through optimized waste exchange networks. The proposed framework bridges theoretical models with real-world applications, providing a replicable decision-support tool for enterprises, policymakers, and industrial park administrators in emerging economies, while aligning with key Sustainable Development Goals (SDGs) related to decent work, sustainable cities, and climate action.

1. Introduction

Increasing population and urbanization globally have led to increased industrialization, resulting in increased carbon dioxide emissions. Global warming has resulted in resource depletion, an

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increase in natural disasters, rising environmental degradation, and adverse effects on all living organisms, including humans [1, 2]. Some environmental studies predict that material consumption will double by 2050 and that waste generation will increase by 70%. This necessitates a transition from a linear to a circular paradigm, exemplified by the Circular Economy (CE) [3]. Industrialization is crucial for economic continuity, but it also requires avoiding environmental damage and mitigating global warming. Effective waste management is essential for preventive measures [4]. System designs that reuse waste as a resource will lead to a reduction in the consumption of natural resources [5]. The CE plays a crucial role in sustainability by addressing challenges posed by the growing economy, increasing resource consumption, and environmental limits in waste management [6]. It promotes systemic, restorative, or regenerative materials designed to maintain the utilization of materials and goods [7-9]. Industrial Symbiosis (IS) represents an innovative business strategy that is important for the success of the CE at the company level. IS is a creative and inclusive economic model, particularly for industrial parks that offer transportation advantages within the supply chain [10]. The term IS, which is associated with industrial ecology, refers to the exchange of materials, energy, water, and other by-products. Such partnerships among companies can enhance resource efficiency and improve the environmental performance of participating companies by minimizing waste and reducing greenhouse gas emissions [11]. Industrial parks are government-controlled areas where various industries operate together. Establishing an IS association requires identifying the waste potential and raw material requirements of companies in the area. These data are collected and modeled using various methodologies to ensure efficient material flows [12, 13]. Various techniques can be applied to assess the potential advantages of executing the IS project. The predominant methodologies used in the literature include Input-Output analysis, Life Cycle Assessment (LCA), Material Flow Analysis (MFA), Network Analysis, and Ecological Network Analysis [6]. These methods quantitatively model waste-resource flows and the allocation of each material. MFA is a quantitative evaluation method employed to investigate material flows and forecast the environmental impact within a system. By examining material inputs and outputs, it seeks to clarify the relationship between economic activity and its impact on the environment [14]. MFA facilitates the identification of input and output types and quantities, which is essential for assessing potential symbiotic relationships and economic partnerships between companies. IS faces challenges such as complex decision-making and unclear material flows. These challenges are particularly relevant in developing countries such as Türkiye, where rapid industrialization and urbanization require a more resource-efficient and sustainable industrial framework. In Türkiye, 19 of the 26 regional development plans incorporate provisions aimed at achieving IS objectives. This study aims to design a comprehensive model to tackle these difficulties and enhance the nation’s sustainable growth. The novelty of this paper can be summarized as follows. By applying the proposed model to the Manisa Industrial Park in Manisa, this research is among the first to address IS implementation in a large-scale industrial zone. The study bridges the gap between theoretical frameworks and real-world applications by validating the model with real-world data and expert consultations, offering useful insights into industrial decision-making. The findings of this study provide important practical and managerial insights for enterprises and policymakers in Türkiye on how to manage the implementation of IS within the framework of the CE concept.

2. Preliminaries of The Study

This study aims to establish a symbiosis network in the Manisa Industrial Park (MIP) using MCDM techniques. A hybrid Analytical Hierarchy Process (AHP), VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR), and ELimination Et Choix Traduisant la REalité (ELECTRE) methods were used to optimize inter-company symbiosis relationships in terms of environmental and economic impacts. VIKOR was selected to determine sectoral priorities for IS implementation. The ELECTRE model was used to evaluate waste sharing and resource use, revealing which sectors can establish more advantageous collaborations. The study combined the results from the hybrid MCDM approach with the Material Flow Analysis (MFA) and a Mixed-Integer Linear Programming (MILP) model to optimize waste and resource flows, reduce material flow costs, and achieve resource savings. Accordingly, this study develops a comprehensive model to support sustainability and circularity in the MIP. The methodological inputs are cross-referenced with the appendices to improve transparency: Appendix A presents the initial and final survey questions, Appendix B reports the indicators, respondent information, and AHP-derived weighting results, and Appendix C provides the representative numerical dataset used for MILP parameterization, including waste amount conversion, feasible flow matrices, normalized distances, and transportation costs.

2.1 Research Design

This study aims to design, implement, and validate an IS model for manufacturing companies in the Manisa Industrial Park (MIP). The methodology comprises four phases: Analysis, Data and Design, Implementation, and Conclusion. The research begins with a literature review using Google Scholar, focusing on ”Industrial Symbiosis” and ”Industrial Park” to evaluate existing IS models. Keywords like ”Circular Economy,” ”Sustainability,” and ”Waste Management” are used to identify relevant indicators. A multiple case study analysis was conducted to ensure the model is both theoretically and practically relevant. A survey was created using Google Forms, refined using the Delphi technique, and analyzed using AHP, VIKOR, and ELECTRE methods. A conceptual MFA model was developed to address key challenges and opportunities across sectors. The model was validated in real-world contexts, and further improvements are made if necessary. The final validation phase involves iterative improvements and approval for broader applications (Figure 1).

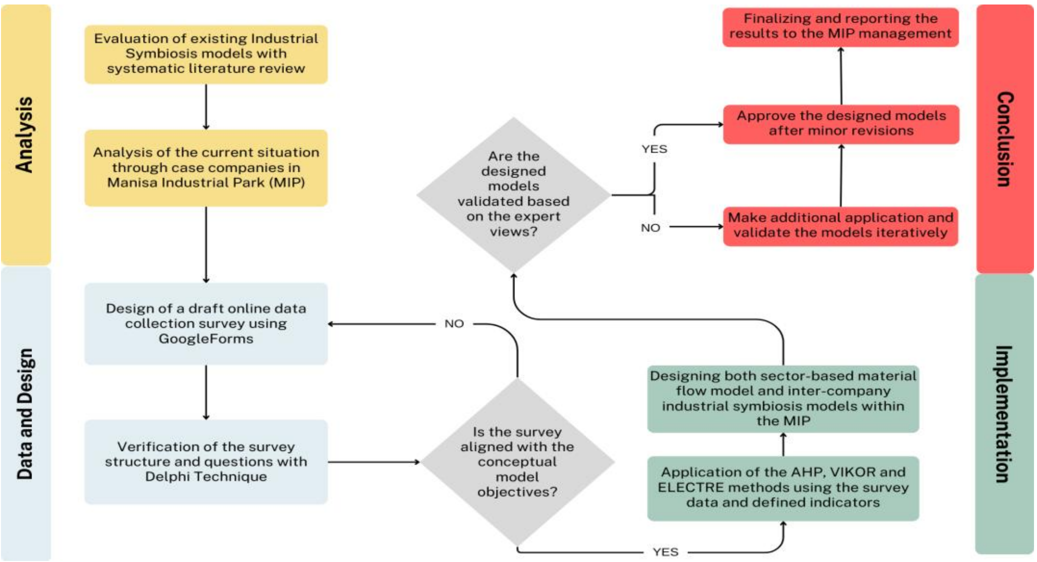

Fig. 1. The research framework of this study

2.2. Problem Description

The study focuses on the MIP in Türkiye, aiming to develop a conceptual industrial symbiosis model based on waste types and quantities generated by companies. The selected pilot companies were evaluated in relation to CE and IS objectives, and their waste transformation processes were examined using MFA. The initiative aims to enhance environmental performance, reduce waste, promote resource efficiency, and facilitate biomass recovery, based on MIP's strategic importance in Türkiye's industrial and economic growth. Established in 1964, the MIP is Türkiye's second-largest industrial park. Additionally, its proximity to Izmir Port, Türkiye's major export hub, and Adnan Menderes International Airport allows it to play a key role in the country's foreign trade, with an annual trade volume of 9.6 billion USD. Beyond its economic significance, it is the first industrial park in Türkiye to generate its own energy, ensuring a continuous, clean, and safe power supply to its companies. Furthermore, MIP has also actively implemented projects aimed at achieving a zero-carbon footprint, setting an example for other industrial regions with its commitment to environmental responsibility [15]. The location of the MIP is shown in Figure 2, which illustrates its geographical location and industrial distribution.

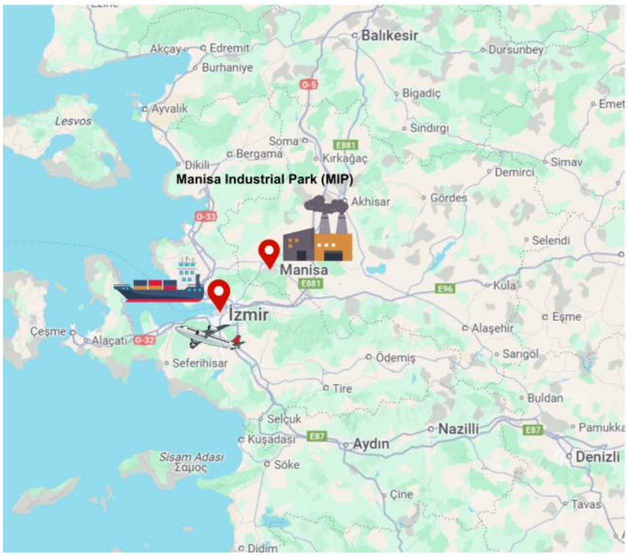

Fig. 2. Location of the MIP (Manisa, Türkiye)

2.3. Data Collection

In this phase of the study, a situation analysis was conducted for the pilot companies within the MIP using the multiple case analysis method [16]. The Delphi technique was used to enhance the validity of the data collection process by incorporating expert opinions from industry and academia, thereby improving the credibility of the data and enabling re-evaluation based on collective feedback [17]. The study involved establishing environmental criteria for IS with 15 companies from various sectors, including iron and steel, food, aluminum, textiles, and electronics. The first stage of the Delphi process involved developing a survey for these companies, which was refined with input from three experts at the MIP Innovation Center. Initially, a survey included 25 questions, excluding company profile information such as company name, sector, main products, and number of employees. These questions were developed based on the sustainability and circularity indicators identified from the literature review and from an IS perspective (Appendix A, Section A1). Following three rounds of expert feedback, the survey was reduced to 16 questions and finalized for implementation (Appendix A, Section A2). The survey development process identified relevant data types and included company-specific details such as NACE codes and fields of activity in a draft prepared using Google Forms. The survey aimed to assess companies' awareness of IS, examine their waste structures, and gain insights into their waste management strategies. The questions were categorized into range-based, numerical, and binary Yes/No formats, and the survey was available online for two weeks. Detailed information about the survey respondents is provided in Appendix B, Table B.2. Through this comprehensive data collection strategy, the study ensures that the IS model is empirically grounded and applicable to real-world industrial contexts. Survey responses were coded into the predefined categories and ranges (Appendix B, Table B.1) to ensure consistency across companies while preserving confidentiality. Range-based responses, such as waste quantity classes, were converted into ordinal values used to form the decision matrices. Yes/No items were binary coded. The resulting matrices were then used as inputs for AHP weighting in Super Decisions and VIKOR/ELECTRE computations in MATLAB.

2.4. Data Analysis Methods

AHP was used to derive criteria weights because it is widely accepted, transparent, and well-suited to communicate trade-offs to practitioners. VIKOR was selected to obtain a compromise ranking of sectors under conflicting criteria, reflecting the need to balance multiple priorities in industrial symbiosis planning. ELECTRE was chosen due to its outranking logic, which supports pairwise dominance interpretation and is useful when compensatory aggregation may be undesirable. While newer approaches, such as fuzzy, probabilistic, or robust MCDM, can provide additional insights under uncertainty, they often require more detailed data and parameterization. Therefore, this study adopts classical methods as a practical and reproducible first-step framework and suggests advanced methods as extensions. Super Decisions V3.2 was used for pairwise comparison and weighting analysis, ensuring a structured and objective approach to determining criteria importance in IS decision-making. The AHP-derived criteria weights were used as input parameters in the VIKOR and ELECTRE analyses to rank the sectors and identify priority areas for potential industrial symbiosis. The prioritized sectors then guided the MFA stage, where material, waste, and resource flows were quantified at the sectoral and company levels. These quantified flow values were subsequently used as input parameters in the MILP model to optimize inter-company waste exchange networks and evaluate the potential improvements under normalized assumptions. Appendix B, Table B.3. displays the normalized values by cluster and limiting values, which indicate the relative importance of each criterion in the decision-making model. Among the evaluated criteria, Solid Waste Recycling Policy has the highest weight (0.16301), highlighting its significance in the analysis. Other important factors include the raw material consumption amount (0.12557), production capacity (0.11551), and waste amount (0.12323), suggesting that material flow and production efficiency play crucial roles in the decision framework. The results provide a structured basis for decision-making, ensuring that the most impactful criteria receive appropriate consideration in further analysis. Subsequently, the VIKOR and ELECTRE analyses were conducted using MATLAB R2023a. The results are presented in Sections 3.4.1 and 3.4.2.

2.4.1 VIKOR Method

VIKOR is an MCDM method designed to identify a compromise solution that is closest to the ideal solution [18]. It provides a systematic evaluation of alternatives under conflicting criteria by considering both group utility and individual regret [19-21]. Previous studies, such as Huang *et al.* [14] and Maille *et al.* [22], have employed mathematical programming and multi-objective optimization to identify waste reuse synergies and optimize industrial networks. These studies address spatial constraints and economic efficiency; however, they do not incorporate MCDM techniques such as VIKOR. Therefore, the existing literature highlights a clear research opportunity to integrate VIKOR into IS decision-making.

2.4.2. ELECTRE Method

The ELECTRE method is a widely used outranking-based MCDM technique developed to handle complex decision problems involving multiple conflicting criteria [23]. It is particularly useful when decision-makers need to rank or select alternatives while considering trade-offs among economic, environmental, and regulatory factors, making it well-suited for sustainability-oriented evaluations [17]. In waste management research, for instance, Opricovic *et al.* [24] applied ELECTRE to the selection of waste treatment systems, evaluating trade-offs between cost, environmental protection, and regulatory compliance. Although this study demonstrates the applicability of ELECTRE to waste-related decision-making, there remains a notable lack of studies that directly integrate ELECTRE into IS optimization within industrial parks.

2.5. Material Flow Analysis

The identification and quantification of inputs and outputs within each enterprise are key components of industrial ecology and are technically critical for determining potential symbiotic relationships among enterprises [6]. MFA is crucial for monitoring inputs and outputs, identifying inefficiencies, fostering sustainable symbiotic relationships, and supporting effective facility management in industrial parks or IS networks [25, 26]. In this context, examining integrated material flows and balances can support the reduction of fossil fuel use, the increased use of renewable resources, the balancing of production and consumption quantities on a material basis, and the circular use of resources through recovery. Figure 3 presents a sample material flow diagram (MFD) at the company level. According to the diagram, inputs such as raw materials, energy, and water enter the production system, where raw materials are transformed into value-added finished or semi-finished products. Meanwhile, solid, liquid, and gaseous waste, emissions, and non-value-added outputs emerge as process outputs. The data collection phase was designed to identify waste and consumption trends by considering companies' material flow systems, reduce inconsistencies in data analysis, and minimize potential incompatibilities during the application of the model to the pilot cases.

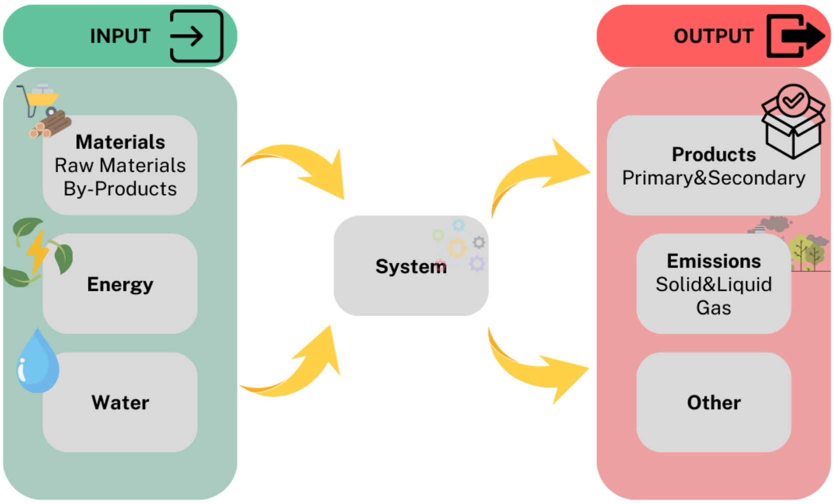

Fig. 3. A Generic Material Flow Diagram (Source: Authors)

3. Application Results

The material flow analysis in this study is based on company-level data collected through surveys and expert consultations, as summarized in Tables B.1 and B.2 in Appendix B. These tables provide structured information on raw material types, waste categories, production capacities, and waste quantities reported by companies operating in the Manisa Industrial Park. Based on this dataset, material flows were classified into four main waste streams: metal and derivatives, plastic and derivatives, plant-based waste, and chemical waste. For each company, input and output flows were identified by using the data from reported raw material types with corresponding waste categories and quantity ranges. The categorization of waste quantities into defined ranges, e.g., 0-1,000, 1,000-5,000, 5,000-10,000, 10,000+ units) enabled a consistent comparison across companies and sectors while preserving the confidentiality of sensitive industrial data. This approach allowed the identification of dominant waste-generating sectors and the assessment of their potential roles as suppliers or receivers within industrial symbiosis networks. The MFA results indicate that companies operating in metal processing, plastics manufacturing, food production, and chemical-related industries generate waste streams with sufficient volume and compatibility to support symbiotic exchanges. For example, metal and plastic wastes were identified as high-frequency and high-volume outputs across multiple companies, suggesting strong potential for cross-sectoral reuse. Similarly, plant-based waste generated by food-related companies was identified as a feasible input for other industrial processes, supporting circular material use within the industrial park. The material flow diagrams (MFDs) presented in Figures 4–7 are based on these findings and illustrate the direction and type of waste-resource exchanges among companies. Due to confidentiality constraints imposed by the participating companies, actual company-level material flows could not be explicitly modelled. Therefore, the analysis relies on categorized and range-based data to represent material flows within the industrial park. Overall, the MFA serves as an analytical bridge between data collection and decision-support modelling, providing a practical basis for prioritizing symbiotic relationships and informing subsequent optimization and cost assessment stages.

3.1 Sector-Based Material Flow Analysis

When an IS project is implemented within an industrial park and aligned with the corporate strategy of enterprises, it presents viable and innovative business opportunities, benefiting both the companies and the sustainability objectives of the entire industrial zone [27]. The VIKOR and ELECTRE methods were used to analyze potential sectors in MIP. The VIKOR method identifies industries that prioritize industrial symbiosis, while the ELECTRE method evaluates interactions among these sectors. The VIKOR and ELECTRE methods were used to analyze potential sectors in the MIP. VIKOR was used to prioritize and cluster companies based on waste types, while ELECTRE was applied to evaluate interactions among the prioritized sectors. The results reveal the metal, plastic, plant-based, and chemical sectors as potential sectors for IS integration. A conceptual IS model considering material flows was created for 15 pilot companies in the MIP.

Figure 4 presents a model following the principles of IS among companies operating in the metal sector in the MIP. The model suggests that reusing scrap and its derivatives in heating boilers and household appliance sectors, such as aluminum casting, electrical parts, and cable grouping, enhances resource efficiency and contributes to sustainable production practices. Directing metal waste to other sub-sectors like wheel and cooler production also reduces waste management costs.

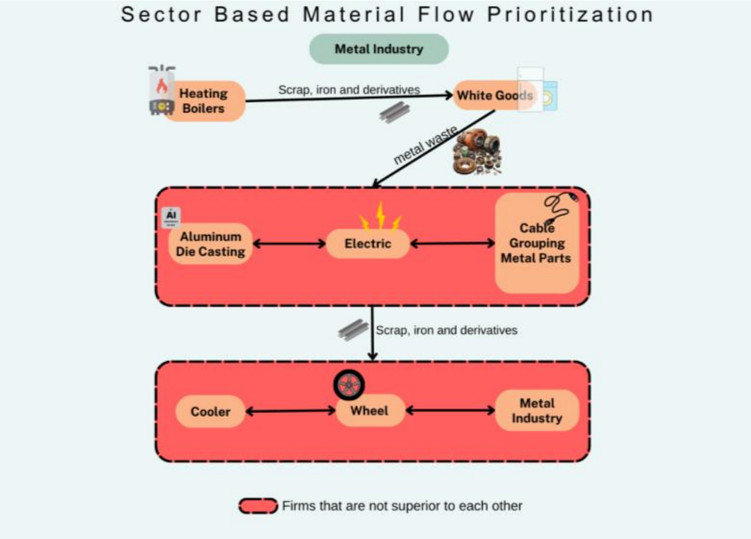

Fig. 4. Industrial symbiosis model for metal waste: cross-sectoral reuse of scrap and derivatives to enhance resource efficiency and cost minimization

The symbiotic relationships highlighted by the red frame in the figure, which indicate that companies are not hierarchically superior to one another, demonstrate resource sharing and a win-win principle. A symbiotic relationships network explaining how IS can be achieved in the plastics and derivatives sector is shown in Figure 5. It creates a structure that supports the reuse of plastic waste among sectors such as electricity, heating boilers, cable assembly, and the automotive supply industry. The flow of plastic waste between the electrical sector and plastic manufacturers ensures that waste is converted into high-value products. In addition, the recovery of plastic waste in the heating boiler and cable grouping sectors reduces production costs and minimizes environmental impacts. This figure demonstrates the link between the automotive supply industry and the textile sector, highlighting the potential use of plastic derivatives and chemical waste in various sectors, particularly in the textile sector, while minimizing environmental harm.

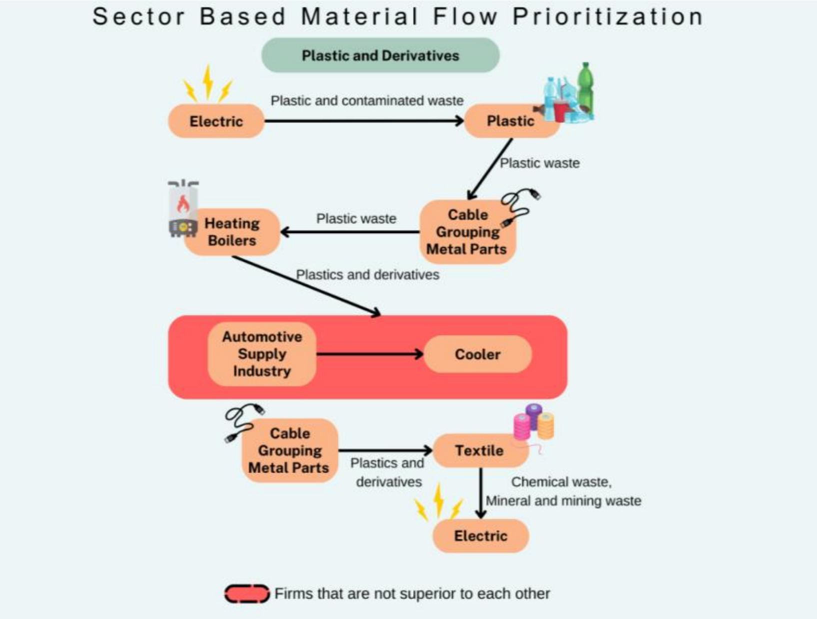

Fig. 5. Industrial symbiosis model for plastic waste: cyclic reutilization across key sectors to reduce production costs and mitigate environmental impacts

Figure 6 shows the evaluation of plant-based waste within the circular economy through industrial symbiosis from a technical point of view. The model indicates that plant-based waste generated by the food industry is evaluated in a symbiotic relationship with the primary home appliances sector. This agreement guarantees the repurpose of waste as raw material, thereby contributing to the reduction of environmental constraints associated with waste disposal. Paper waste, particularly from the food and large appliance sectors, can be utilized in the textile sector for textile composites, reducing natural resource usage and promoting energy-efficient manufacturing methods. This integration of waste management and materials engineering highlights the potential of paper waste in various industries.

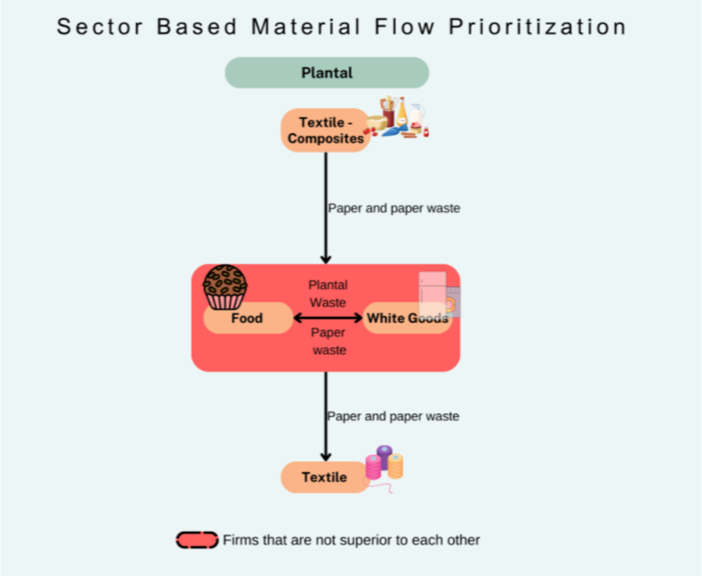

Fig. 6. Industrial symbiosis concept for plant-based waste: reusing food industry by-products as raw materials to mitigate environmental limitations and enhance energy-efficient manufacturing

Figure 7 shows the symbiotic relationships that can be created with chemical waste. This graphic indicates that chemical waste from the tire and automotive industries can serve as a raw material for the textile industry, while the by-products of the textile industry can be utilized in the construction sector. The cable and refrigeration sectors represent further areas for the utilization of chemical waste.

3.2 Industrial Symbiotic Relationships Between Case Companies

The study developed an industrial symbiosis model using a two-stage approach. The VIKOR method was used to prioritize sectors for symbiotic relationships, followed by the identification of companies producing relevant waste streams and the analysis of their potential. The ELECTRE method was used to define waste flows and their directions among identified companies. The analysis tested the feasibility of these relationships and identified which companies should prioritize waste exchange (Figures 8 and 9). In the metal and derivatives pool, Company A provides scrap and iron-derived waste to Company B, establishing a unidirectional flow between them. Company B, in turn, supplies metal waste to Companies C, D, and E, which have equal symbiotic importance. Among these three companies, there exists a bidirectional flow, meaning they both supply and receive metal waste from each other. At the next level of importance, there are Companies F, G, and H, which also share an equal level of importance and maintain bidirectional waste exchanges among themselves. These companies receive scrap iron and derivatives from Companies C, D, and E, and no superiority was identified among them in terms of waste exchange priority. In the plastic waste and derivatives pool, Company D holds the highest symbiotic importance. This company supplies plastic and contaminated waste to Company I, which subsequently provides plastic and paper waste to Company E. The plastic waste output from Company E serves as an input for Company A. The plastic waste output from Company A then becomes an input for Companies F and J, which share the same symbiotic importance level. However, there is a unidirectional flow between these two companies, as only Company J supplies waste to Company F. Additionally, Company E independently supplies plastic waste to K. The waste output from Company K contributes to Company D in the metal and derivatives pool by providing chemical, metal, mineral, mining, plastic, and textile waste.

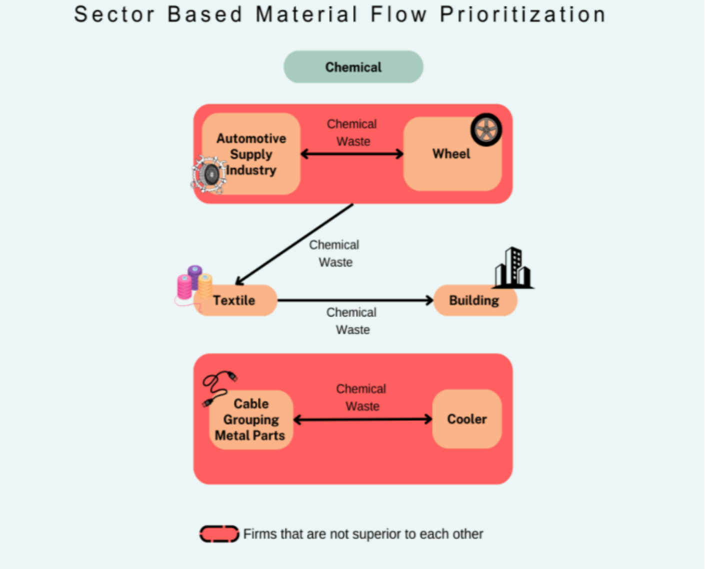

Fig. 7. Industrial symbiosis model for chemical waste: intersectoral usage of chemical by-products among the textile, building, and refrigeration industries

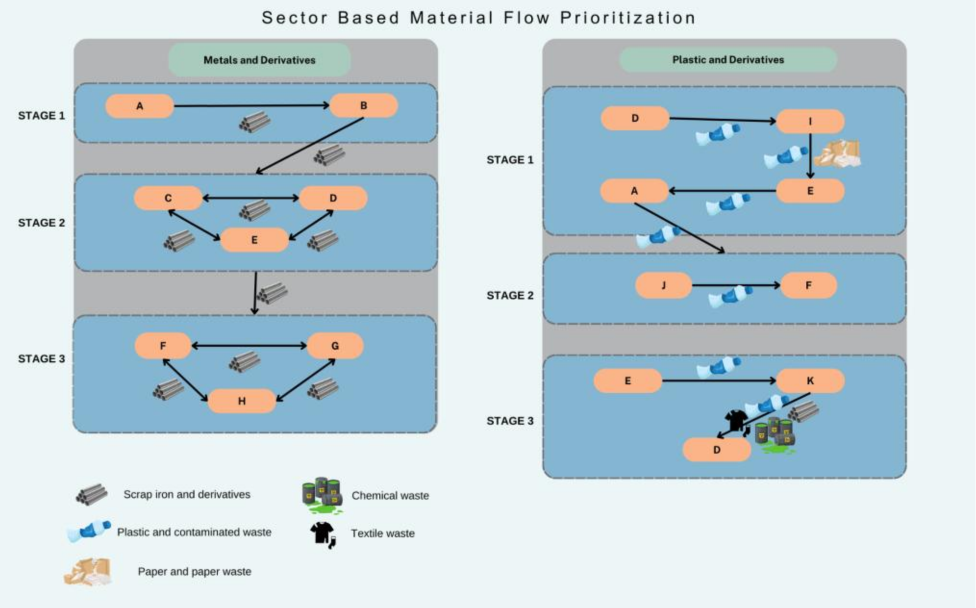

Fig. 8. Symbiotic relationships among enterprises in the metal and plastic derivatives sectors: emphasized waste exchange dynamics and feasibility evaluation

In the plant-based waste pool, Company M supplies paper waste to Companies N and B, both of which are of equal symbiotic importance. Companies N and B maintain a bidirectional exchange of plant-based and paper waste between them, ensuring mutual resource utilization. Additionally, these companies also supply paper waste to Company K, further extending the network of resource circulation within the symbiosis model. In the chemical waste pool, a bidirectional flow of chemical waste exchange occurs between Companies J and G, with no superiority identified between them. At a lower level of importance, Company K supplies chemical waste to Company L in a unidirectional flow. Additionally, Companies E and F form an independent pair, exclusively engaging in bidirectional chemical waste exchange with each other.

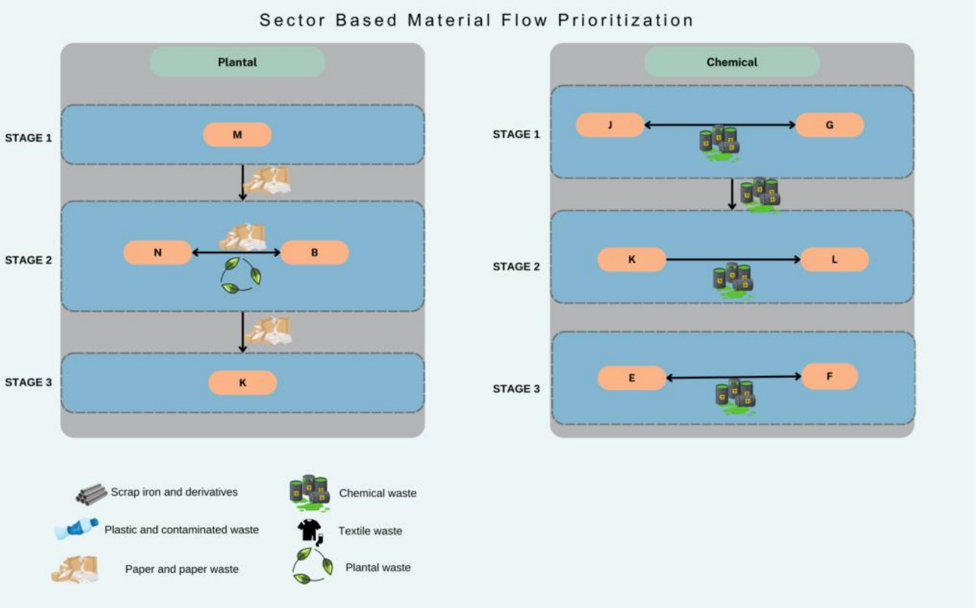

Fig. 9. Symbiotic relationships across enterprises in the plant-based and chemical sectors: directed waste exchange networks

Both structured flow systems demonstrate the interdependencies among companies, emphasizing the role of prioritized companies in facilitating waste circularity within an industrial symbiosis framework. The analysis conducted using the ELECTRE method highlights priority relationships among companies in terms of waste supply and receipt, supporting the strategic design of sustainable waste management practices.

3.3 Material Flow Cost Analysis

This section presents a MILP model for manufacturing industries, aiming to minimize transportation costs and facilitate efficient waste material exchange networks, while assessing the economic impact of industrial symbiosis through optimized waste flow between companies. The optimization problem is formulated and solved using GAMS 23.5 optimization software. The material flow between companies follows the structure depicted in Figure 9.

To address data confidentiality while ensuring transparency and reproducibility, some model parameters were instantiated using a categorized and normalized dataset derived from the indicators provided in Appendix B, Table B.1. Specifically, company-level inputs such as production capacity were converted into numerical interval midpoints, e.g., 0-1,000 → 500 and 1,000-5,000 → 3000, enabling the construction of a consistent and comparable dataset across firms without disclosing sensitive industrial data (Appendix C, Tables C.1 – C.7). This data is utilized as the demand amount of waste receiving facility and assigned to the demand parameter in the MILP model. For the same reason, supply levels were generated based on the demands of the firms, and the amount of the waste-receiving facility was determined accordingly through the outputs of the MILP model. Transportation costs were calculated based on normalized distances and average unit transport costs per waste pool. The normalized values represent relative proximity scores derived from the observed direct and indirect inter-firm link structure, where lower values indicate closer firms and higher values indicate more distant firms. Each of the distances approximated using relative vertical classes (short, medium, long) was mapped to representative numerical values to preserve confidentiality while maintaining a proportional cost structure.

The nomenclature of the developed MILP model is presented in Table 1. The MILP model was instantiated and executed separately for each industrial sector. For example, in the metals and derivatives waste pool, a fully populated parameter matrix (c_{ij}, s_i, d_j, k_{ij}) was constructed using the categorized inputs described above. The same methodological framework was applied to other sectors, including plastics, plant-based materials, and chemicals. The mathematical notation for the waste flow quantity, denoted as X_{ij}, is structured such that rows represent waste-sending companies and columns represent waste-receiving companies. Binary waste flow matrices f_{ij} were constructed to represent feasible inter-firm exchanges, as presented in Appendix C. A value of 1 indicates that a waste flow between firms i and j is permitted, while 0 indicates that such an exchange is not feasible.

Table 1
The nomenclature of the MILP model

Category	Symbol	Description
Sets	i	Set of waste-sending companies' nodes (i = 1, 2…, *n*)
Sets	j	Set of waste-receiving companies (j = 1, 2…, *n*)
Parameters	c_{ij}	Unit cost of waste transportation from company *I (€/ton)*
Parameters	s_i	Supply amount of waste-generating facility *j (tons)*
Parameters	d_j	Demand amount of waste-sending facility *j (tons)*
Parameters	k_{ij}	Normalized distances from facility *i* to *j (unit)*
Parameters	f_{ij}	Waste flow matrix representing allowed flows from *i* to *j {0,1}*
Decision variable	X_{ij}	Waste flow quantity between facility *i* and company *j (tons)*

Eq. 1 minimizes the total transportation cost associated with inter-firm waste exchanges. Eq. 2 ensures that the total quantity of waste sent by each firm does not exceed its available supply capacity, while Eq. 3 guarantees that the receiving firms meet their minimum waste demand requirements. Eq. 4 incorporates the waste flow feasibility structure by prohibiting exchanges that are not permitted according to the predefined inter-firm flow matrix. Eq. 5 imposes non-negativity constraints on transported waste quantities, and Eq. 6 excludes self-transfers to ensure that only inter-firm exchanges are considered.

Objective Function

$$\text{Minimize } Z = \sum_i \sum_j c_{ij} k_{ij} X_{ij} \tag{1}$$

Subject to:

$$\sum_j^n X_{ij} \le s_i \qquad \forall i \tag{2}$$
$$\sum_i^n X_{ij} \ge d_j \qquad \forall j \tag{3}$$
$$X_{ij} = 0 \ \forall (i,j) \ such\ that\ f_{ij} = 0 \tag{4}$$

$$X_{ij} \geq 0 \qquad \forall i,j \tag{5}$$
$$X_{ii} = 0 \qquad \forall i \tag{6}$$

Due to confidentiality issues regarding firm-level cost data, the model was implemented using normalized and representative cost parameters derived from categorized inputs. Under these assumptions, the developed industrial symbiosis (IS)-based MILP model indicates a relative improvement of approximately 30-35% compared to the current waste management practices in the Manisa Industrial Park. This improvement was obtained by comparing two scenarios within the same consistent data framework: (i) the baseline scenario, reflecting the existing waste management cycle, and (ii) the optimized scenario generated by the proposed model. It should be noted that this percentage does not represent absolute monetary savings but rather a proportional efficiency gain under the given assumptions.

4. Discussion

Within the framework of the circular economy, industrial symbiosis projects represent one of the most effective strategies for waste management. The relevant literature includes studies on strategies that countries prioritize, models that promote waste exchange between industries, and material flow systems that support waste exchange. Several studies on CE and IS business models exist in the literature. Some studies focus on the notion of eco-industrial parks, while others apply single material flow models. Table 2 presents selected examples of research conducted in recent years.

Borello *et al.* [28] conducted a study on the recycling of solid food waste in Italy, focusing on consumers' willingness to participate in recycling and reuse practices within industrial symbiosis in the context of circular business models. Fraccascia *et al.* [29] proposed a taxonomy to classify IS business models, examining the governance of systems of companies practicing IS. Walmsley *et al.* [30] proposed a new framework, based on CE, industrial ecology, and process integration, to develop a comprehensive approach to sustainable industrial and energy systems. Kurdve *et al.* [31] examined the development of an urban and IS network in the West Mälardalen region of Sweden, while Mochalova *et al.* [32] focused on the management of waste generated in the underground resources sector under CE conditions. Alvarado *et al.* [33] examined a case study of CE in Trøndelag, Norway, identifying three main discourses within the CE: technical solutions, a sharing economy, and the reduction of individual consumption and lifestyle changes through local services. Haezendonck *et al.* [34] assessed the CE approach of five major ports in Belgium, focusing on energy recovery, recycling, and the organization of new cargo flows. Yesilkaya *et al.* [35] implemented a symbiotic network between pulp and paper producers based on the forest industry, using a mathematical model to minimize CO_2 emissions and production costs for business partners in the IS network. Siskos *et al.* [36] proposed a new business model called Synergy Management Services Company (SMSCO) to overcome financial and economic barriers to IS in industrial parks. The study highlights the potential of the SMSCO model to facilitate waste-to-resource shifts in sectors such as chemicals, power generation, and manufacturing, where by-products can be reused. Few studies have combined MCDM methodologies with IS implementation. For example, Yazici *et al.* [37] developed an MCDM-based approach for operational, tactical, and strategic decision-making levels. The dynamic characteristics of symbiosis applications need additional decision-making tools. The main benefit of MCDM approaches is their ability to simultaneously assess various competing factors in decision-making scenarios. In MCDM assessment criteria, scenarios where precise values are unavailable are often encountered, necessitating the use of linguistic expressions [38]. In MCDM applications, factors influencing symbiotic partnerships can be assigned weights, and their significance levels and priorities can be determined using the Analytic Network Process (ANP) [39]. Following criteria weighting, the fuzzy TOPSIS [15, 37, 40], DEMATEL [41, 42], or VIKOR [43], may be employed for ranking and modeling symbiotic connections. In IS, the resource reduction business model serves as a significant cost reduction strategy. The advantageous impacts of cost reduction can once more be illustrated through MCDM methodologies, facilitating the identification of essential and prioritized variables in projects.

Table 2
Literature review on Industrial Symbiosis

Authors	Date	Method	Country	Waste Type	Industry
Siskos & Van Wassenhove [36]	2017	Survey & Simulation	Different Countries	Miscellaneous Wastes	Different industries
Kurdve *et al.* [31]	2018	Material Flow	Sweden	Miscellaneous Wastes	Different industries
Fraccascia L. *et al.* [29]	2019	Simulation and Theoretical Model	Different Countries	Miscellaneous Wastes	Different industries
Walmsley *et al.* [30]	2019	Material Flow	New Zealand	Kraft Mill	Biorefinery
Haezendonck & Van den Berghe [34]	2020	Case Study	Belgium	Miscellaneous Wastes	Ports
Mochalova *et al.* [32]	2020	Material Flow (5R)	Russia	Subsurface Waste	Mineral Resource
Borrello *et al.* [28]	2020	Case study	Italy	Food waste	Food industry
Yeşilkaya *et al.*	2020	Case Study	Italy	Pulp and Paper	Forest industry
Alvarado et al. [33]	2021	Survey	Norway	Miscellaneous Wastes	Different industries
Yazıcı *et al.* [12]	2022	Literature Review	Different Countries	Miscellaneous Wastes	Different industries
Huang *et al.* [14]	2025	Case Study	Australia	Alum Sludge	Concrete and Cement
This study	2025	Case study	Türkiye	Miscellaneous Wastes	Industrial Park

While prior IS studies have predominantly relied on qualitative assessments, single-method optimizations, or region-specific material flow models [14, 16, 31], this study distinguishes itself along three key dimensions. First, in terms of data structure, the framework operationalizes range-based and categorized survey data that is collected under real industrial data — into a consistent decision matrix, thereby bridging the gap between practitioner-accessible data formats and quantitative modelling requirements; an aspect largely unaddressed in previous optimization-oriented IS studies [14, 37]. Second, regarding methodological integration, the literature includes successful applications of MCDM, MFA, and optimization methods, each contributing valuable insights to IS decision-making [18-21]. However, these approaches have largely been applied independently. In this study, the methods are integrated sequentially to establish a decision-support oriented analytical structure for IS implementation. Third, with respect to practical scope, while existing IS studies in emerging economy contexts have largely provided general overviews of organized industrial zones without site-specific implementation [44], this study delivers a concrete application within one of Türkiye's largest organized industrial zones, grounding the proposed framework in real expert consultation, multi-sector company data, and verifiable waste flow networks — thereby advancing from descriptive accounts to an actionable, replicable decision-support tool. As a summary, this study differs from previous studies by combining MCDM methods and cost analysis to enhance waste management within the CE framework for an industrial park.

5. Conclusion

This study proposed an integrated framework to support the implementation of industrial symbiosis in industrial parks within the context of the circular economy. The framework combines multi-criteria decision-making methods, material flow analysis, and an optimization-based cost assessment to identify priority sectors and potential waste exchange relationships among companies.

The application of the framework to the Manisa Industrial Park shows that industrial symbiosis can be operationalized as a practical management approach rather than remaining a conceptual idea. The results indicate that coordinated waste exchanges among companies in the metal, plastic, plant-based, and chemical sectors have the potential to improve resource efficiency and reduce waste-management-related costs. By adopting a system-level perspective, the proposed approach reflects the complex structure of real industrial environments.

From a methodological point of view, this study contributes to the industrial symbiosis literature by integrating decision-support tools with material flow analysis in a single framework. The use of multi-criteria decision-making methods supports the prioritization of sectors and companies based on multiple criteria, while material flow analysis helps to evaluate the feasibility of waste exchanges. The optimization component illustrates the potential economic benefits of coordinated symbiotic relationships.

This study also has some limitations. The analysis focuses on a single industrial park and is based on available company-level data, which limits the generalizability of the results. In addition, the optimization model mainly addresses economic performance and does not explicitly include environmental impact indicators or uncertainty in waste quantities and market conditions. Future research can extend this framework by including environmental indicators, such as greenhouse gas emissions, and by applying multi-objective optimization approaches. Scenario analysis and uncertainty modelling may also improve the robustness of the results.

5.1. Practical and Managerial Implications

The methodology offers a structured approach to reducing waste management costs and maximizing resource efficiency in industrial parks. Implementing the IS model across various industrial sectors demonstrates its adaptability and effectiveness in optimizing waste flow networks. Strategic collaboration among companies is essential for generating economic and environmental benefits and contributes particularly to SDG 8 (Decent Work and Economic Growth), SDG 13 (Climate Action), and SDG 17 (Partnerships for the Goals). Adopting IS models aligns businesses with corporate social responsibility strategies, enabling them to gain competitive advantages in sustainable operations.

At a broader implementation level, policymakers play a crucial role in supporting IS practices through regulatory frameworks, financial incentives, and digital infrastructure. Expanding this model to additional sectors and industrial clusters can enhance circular economy efforts, reduce landfill dependency, and decrease greenhouse gas emissions, contributing to SDG 11 (Sustainable Cities and Communities). Integrating industrial symbiosis with sector-wide material flow analysis provides a scalable, efficient, and environmentally responsible solution for industrial waste management, ensuring economic profitability and sustainability.

Accordingly, the practical implications of this study can be summarized at three levels:

Firm-level actions:

1. Companies can use the proposed framework to identify potential waste-to-resource opportunities and assess whether their waste streams can serve as inputs for other firms within the industrial park.
2. Companies can use the identified intercompany symbiotic relationships to participate in targeted matchmaking activities and preliminary feasibility assessments.

Industrial park-level actions:

1. Industrial park administration can use the indicator set presented in Appendix B as a standardized template for the regular collection of waste and resource data, enabling a more structured and comparable information base.
2. Industrial park administrators can establish a shared database for waste, resource, and by-product information to facilitate continuous monitoring and future symbiosis matching.
3. The sector prioritization results could support the selection of a limited number of sectors for initiating pilot industrial symbiosis actions, reducing complexity and implementation risks.
4. The identified intercompany symbiotic relationships can further be used to organize targeted matchmaking activities and preliminary feasibility assessments among companies.

Policymaker-level recommendations:

1. Policymakers can use the insights generated by the framework to prioritize incentives and digital infrastructure investments that support the wider adoption of industrial symbiosis in organized industrial zones.
2. Policymakers can design targeted incentive schemes for companies participating in verified waste exchange or resource recovery initiatives.
3. Policy support can also focus on standardizing industrial waste data reporting to improve transparency and comparability across organized industrial zones.

Abbreviations

CE: Circular Economy
IS: Industrial Symbiosis
MIP: Manisa Industrial Park
MCDM: Multi-Criteria Decision Making
MFA: Material Flow Analysis
MFD: Material Flow Diagram
SDG: Sustainable Development Goal
LCA: Life Cycle Assessment
AHP: Analytical Hierarchy Process
ANP: Analytical Network Process
VIKOR: VIseKriterijumska Optimizacija I Kompromisno Resenje
ELECTRE: ELimination Et Choix Traduisant la REalité
MILP: Mixed-Integer Linear Programming

Appendix A

A.1. Initial Survey Questions

Open-ended Questions

1. It is estimated that the circular economy will generate savings worth at least USD 700 billion annually. Is this a convincing factor for your company? Why?
2. According to reports by the Ellen MacArthur Foundation, companies that engage in the circular economy will systematically achieve benefits. Would you like to update your products, services, and production systems in light of the circular economy?
3. Which current circular economy examples do you take as role models or follow?
4. Would you like to become part of an industrial symbiosis project, generate revenue from your waste, and purchase your raw materials at a more profitable price?

Descriptive/Range-based Questions

1. What is your annual production capacity? Please indicate in tonnes.
2. What is your annual capacity utilization rate, or OEE level? You may provide an approximate percentage.
3. What are the primary, virgin, and secondary, recycled, raw materials required for production?
4. What are the quantities of your raw materials? Please indicate in tonnes.
5. Where do you procure your raw materials from?
6. What are your final products?
7. What are your waste types and quantities? Please indicate in tonnes.
8. What are the percentages of waste generated according to the waste types you specified?
9. What is the amount of process-based wastewater generated as a result of production? Please indicate in cubic metres.
10. What is your electricity consumption? Please indicate in kWh.
11. What is your natural gas consumption? Please indicate in kWh.
12. What is your renewable energy consumption? Please indicate in kWh.

Yes/No Questions

1. Do you have a wastewater recycling policy?
2. Do you have a waste disposal policy?
3. Do you have a solid waste recycling policy?
4. Do you have an energy recovery/recycling policy?
5. The 9R strategies are a set of strategies designed to reduce resource and material consumption in product chains and to make the economy more circular. In this context, have you conducted a 9R assessment for your processes and products?
6. Do you have any R&D project supported by a public institution or legal entity?

A.2. Final Survey Questions (After Delphi Rounds and Expert Evaluations)

Range-based Questions

1. What is the unit of your annual production capacity?
2. What was your production capacity in the last operating year?
3. What types of raw materials do you use?
4. What is the unit of your raw materials?
5. What was the quantity of raw materials used in the last operating year?

6. What types of waste do you generate? (Please specify sub-types.)
7. What was the amount of waste generated in the last operating year?
8. What was your average electricity consumption over the last three years?
9. What was your average water consumption over the last three years?
10. What was your average natural gas consumption over the last three years?

Yes/No Questions

1. Do you have a wastewater recycling policy?
2. Do you have a waste disposal policy?
3. Do you have a solid waste recycling policy?
4. Do you have an energy recovery policy?
5. The 9R strategies aim to reduce resource and material consumption and promote circularity in product value chains. In this context, have you identified and implemented 9R strategies for your processes and products?
6. Do you have any R&D projects in the field of sustainability supported by public or governmental organizations?

Appendix B

Table B.1
Defined indicators considered for the data collection phase

Indicators	Entered Data Type	Metric Value
Production unit	pcs, tons, m3, kWh, kg, m, lt	pcs (1), kg/tons (2), m^3/lt (3), kWh (4), m (5)
Production capacity	0-1000, 1000-5000, 5000-10.000, 10.000+	0-1000 (1), 1000-5000 (2), 5000-10.000 (3), 10.000+ (4)
Raw material unit	pcs, tons, m3, kg, m, lt	pcs (1), kg/tons (2), m^3/lt (3), m (4)
Raw material type	Herbal, Animal, Paper and Derivatives, Chemical, Metal and Derivatives, Forest Products and Derivatives, Textile	Herbal (1), Animal (2), Paper and Derivatives (3), Chemical (4), Metal and Derivatives (5), Forest Products and Derivatives (6), Textile (7)
Raw material quantity	0-1000, 1000-5000, 5000-10.000, 10.000+	0-1000 (1), 1000-5000 (2), 5000-10.000 (3), 10.000+ (4)
Waste amount	0-1000, 1000-5000, 5000-10.000, 10.000+	0-1000 (1), 1000-5000 (2), 5000-10.000 (3), 10.000+ (4)
Waste type	Herbal, Animal, Paper and Derivatives, Chemical, Metal, Mineral and Mining, Forest and Agricultural, Plastic, Textile	Herbal (1), Animal (2), Paper and Paper Waste (3), Chemical (4), Steel (5), Mineral and Mining (6), Forest and Agricultural (7), Plastic (8), Textile (9)
Average electric consumption over three years (kWh)	100.000-500.000, 500.000-1.000.000, 1.000.000-3.000.000, 3.000.000+	100.000-500.000 (1), 500.000-1.000.000 (2), 1.000.000-3.000.000 (3), 3.000.000+ (4)
Average water consumption over three years (m3)	1000-10.000, 10.000-20.000, 20.000-50.000, 50.000-100.000, 100.000+	1000-10.000 (1), 10.000-20.000 (2), 20.000-50.000 (3), 50.000-100.000 (4), 100.000+ (5)
Average natural gas consumption over three years (m3)	0-25.000, 25.000-250.000, 250.000-2.500.000, 2.500.000-25.000.000, 25.000.000+	0-25.000 (1), 25.000-250.000 (2), 250.000-2.500.000 (3), 2.500.000-25.000.000 (4), 25.000.000+ (5)
Waste disposal policy	Yes, No	Yes (1); No (2)
Solid waste recycling policy	Yes, No	Yes (1); No (2)

Table B.1
Continued

Wastewater recycling policy	Yes, No	Yes (1); No (2)
Energy recovery policy	Yes, No	Yes (1); No (2)
9R analysis	Yes, No	Yes (1); No (2)
Sustainability and R&D project initiative	Yes, No	Yes (1); No (2)

Table B.2
Information about the Online Survey Respondents

Expert ID	Title	Sector	Working experience (years)
E1	Production Engineer	Iron and steel products	10-May
E2	Supply Chain Manager	Cooling systems	10+
E3	Sustainability Manager	Food products	10+
E4	Plant Manager	Textile composites	10+
E5	Environmental Management Systems and EHS Engineer	Consumer electronics and metal products	5
E6	Integrated Management Systems Engineer	Aluminum casting and wheel products	10+
E7	Safety and Sustainability Manager	Steel wheel products	10+
E8	Technical Functions Director	Heating, and air conditioning products	10+
E9	General Vice-Manager	Quartz surface products	10+
E10	Safety Manager	Whitegoods products	10-May
E11	Supply Chain Manager	Electrical and rubber products	10
E12	Corporate Risk and Sustainability Specialist	Automotive batteries and energy storage products	10-May
E13	Project Leader	Sheet metal parts	10-May
E14	Environmental Specialist	Medium-voltage electrical equipment	10-May
E15	R&D Engineer	Textile products	10-May

Table B.3
Normalized priorities and inconsistency values of the significant criteria over the acceptable threshold

Criterion	Normalized by Cluster Limiting	Inconsistency
9R Analysis	0.10635	0.04713
Sustainability and R&D Project Initiative	0.07461	0.04713
Waste Disposal Policy	0.08637	0.04713
Waste Amount	0.12323	0.04713
Wastewater Recycling Policy	0.05094	0.04713
Energy Recovery Policy	0.06089	0.04713
Raw Material Consumption Amount	0.12557	0.04713
Solid Waste Recycling Policy	0.16301	0.04713
Average Consumption Amount (Electric+Water+Natural gas)	0.02960	0.04713
Production Capacity	0.11551	0.04713

Appendix C
A Representative Numerical Dataset Used in the MILP Model

Table C.1
Conversion of Categorized Waste Amount Inputs into Numerical Values

Indicator	Category Code	Range	Numerical Value (Midpoint)
Production Capacity	1	0-1000	500
	2	1000-5000	3000
	3	5000-10,000	7500
	4	10,000+	12,500
Waste Amount	1	0-1000	500
	2	1000-5000	3000
	3	5000-10,000	7500
	4	10,000+	12,500

Table C.2
0-1 Waste flow matrix for the metal and
0-2 derivatives waste pool, f_{ij}

From / To	A	B	C	D	E	F	G	H
A	0	1	0	0	0	0	0	0
B	0	0	1	1	1	0	0	0
C	0	0	0	1	1	1	1	1
D	0	0	1	0	1	1	1	1
E	0	0	1	1	0	1	1	1
F	0	0	0	0	0	0	1	1
G	0	0	0	0	0	1	0	1
H	0	0	0	0	0	1	1	0

Table C.3
0-1 Waste flow matrix for the plastic
0-2 and derivatives waste pool, f_{ij}

From / To	D	I	E	A	J	F	K
D	0	1	0	0	0	0	0
I	0	0	1	0	0	0	0
E	0	0	0	1	0	0	1
A	0	0	0	0	1	1	0
J	0	0	0	0	0	1	0
F	0	0	0	0	0	0	0
K	1	0	0	0	0	0	0

Table C.4
0-1 Waste flow matrix for the
0-2 plant-based waste pool, f_{ij}

From / To	M	N	B	K
M	0	1	1	0
N	0	0	1	1
B	0	1	0	1
K	0	0	0	0

Table C.5
0-1 Waste flow matrix for the
0-2 chemical waste pool, f_{ij}

From / To	E	F	G	J	K	L
E	0	1	0	0	0	0
F	1	0	0	0	0	0
G	0	0	0	1	0	0
J	0	0	1	0	0	0
K	0	0	0	0	0	1
L	0	0	0	0	0	0

Table C.6
Sector-Independent Normalized Distance Matrix, k_{ij}

From / To	A	B	C	D	E	F	G	H	I	J	K	L	M	N
A	0	1	2	2	1	2	2	3	2	1	2	3	2	2
B	1	0	2	1	2	3	3	4	2	2	1	2	1	1
C	2	2	0	1	1	2	3	3	2	3	2	3	3	3
D	2	1	1	0	1	2	3	3	1	3	1	2	2	2
E	1	2	1	1	0	1	2	2	1	2	1	2	3	2
F	2	3	2	2	1	0	1	1	2	1	2	3	4	3
G	2	3	3	3	2	1	0	1	3	1	3	4	4	4
H	3	4	3	3	2	1	1	0	3	2	3	4	5	4
I	2	2	2	1	1	2	3	3	0	3	2	3	3	3
J	1	2	3	3	2	1	1	2	3	0	3	4	3	3
K	2	1	2	1	1	2	3	3	2	3	0	1	2	1
L	3	2	3	2	2	3	4	4	3	4	1	0	3	2
M	2	1	3	2	3	4	4	5	3	3	2	3	0	1
N	2	1	3	2	2	3	4	4	3	3	1	2	1	0

Table C.7
Sector-Independent Transportation Cost Matrix, c_{ij} (€/ton)
(Short distance (k=1): 6€/ton, Medium distance (k=2/3): 10€/ton,
Long distance (k=4/5): 15€/ton)

From / To	A	B	C	D	E	F	G	H	I	J	K	L	M	N
A	0	6	10	10	6	10	10	10	10	6	10	10	10	10
B	6	0	10	6	10	10	10	15	10	10	6	10	6	6
C	10	10	0	6	6	10	10	10	10	10	10	10	10	10
D	10	6	6	0	6	10	10	10	6	10	6	10	10	10
E	6	10	6	6	0	6	10	10	6	10	6	10	10	10
F	10	10	10	10	6	0	6	6	10	6	10	10	15	10
G	10	10	10	10	10	6	0	6	10	6	10	15	15	15
H	10	15	10	10	10	6	6	0	10	10	10	15	15	15
I	10	10	10	6	6	10	10	10	0	10	10	10	10	10
J	6	10	10	10	10	6	6	10	10	0	10	15	10	10
K	10	6	10	6	6	10	10	10	10	10	0	6	10	6
L	10	10	10	10	10	10	15	15	10	15	6	0	10	10
M	10	6	10	10	10	15	15	15	10	10	10	10	0	6
N	10	6	10	10	10	10	15	15	10	10	6	10	6	0

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Conflict of Interest

The authors declare no conflicts of interest.

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