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RESEARCH PAPER

Exchange-Based Industry Selection for Eco-Industrial Parks: A Mixed-Integer Programming Mathematical Model

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Abstract

The optimal use of natural resources and energy has become an important issue and has been given attention worldwide due to the increase in population and environmental pollution. In recent years, Eco-industrial parks (EIPs) have gained popularity as a way to make better use of natural resources. In these parks, companies try to cooperate with each other by exchanging materials and energy and pay more attention to environmental issues. Unlike previous models proposed in this field, which were based on existing EIPs and were presented for improvement, we present a new model for creating these parks. In this study, we propose a mixed integer programming (MIP) model, considering real and feasible exchanges, which, taking into account sustainability conditions (economic, social, and environmental), selects industries to establish the park so that the value of exchanges is maximized and the costs of infrastructure construction are minimized. The results show that the selected set of industries leads to economic benefits, where the total value of exchanges exceeds the costs of infrastructure, thus supporting profitability and sustainability.

Keywords:
Eco-Industrial Park, Industrial Symbiosis, Sustainability, Mixed integer programming, Circular economy.

1. Introduction

The accelerating consumption of natural resources and global warming call for improved policies to support cleaner production and the sustainable use of resources. In response, many developed nations have adopted the concept of Circular Economy (CE), which emphasizes the importance of reusing, recycling, and recovering materials throughout production, distribution, and consumption processes to promote sustainable development (Kirchherr, Reike, & Hekkert, 2017) .The goal is to shift away from the traditional "produce-consume-dispose" model and establish a circular system where waste is reintegrated into the production process. This method reduces reliance on raw materials and resources, minimizes environmental harm, and allows manufacturing facilities to operate as integrated, self-reliant "industrial ecosystems". Fig1. illustrates the fundamental difference between the functioning of a linear flow and a circular

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economy. While industrial parks follow a linear flow, EIPs operate based on the principles of the circular economy. This distinction is presented in the figure in a simplified and conceptual manner.

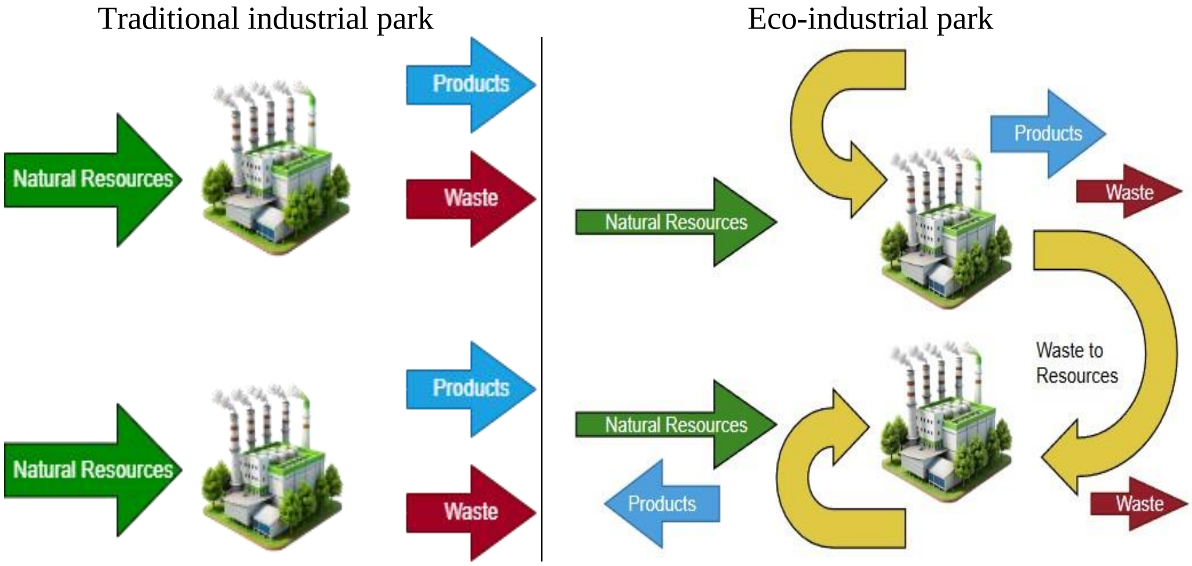

Figure 1. The difference between traditional industrial park and Eco-industrial park

A key strategy involves drawing inspiration from natural processes and applying these principles to industrial systems. This approach underpins the field of industrial ecology, which gained widespread recognition through the pioneering work of (Frosch & Gallopoulos, 1989). They advocated for reducing resource consumption and waste generation by reusing the by-products of one industry as inputs for the other one. This approach, termed industrial symbiosis (IS), facilitates the exchange of materials, energy, waste, and water among interconnected businesses, leveraging geographical proximity to enhance efficiency and collaboration(Ehrenfeld & Chertow, 2002). Creating this framework will set up an organized system for resource exchange among companies, leading to economic benefits by improving resource efficiency and reducing environmental impacts through lower waste and resource use(Lowe, 1997) .One of the most prominent examples of this concept is EIPs. Although the term "Eco-industrial park" has been the subject of extensive debate due to difficulties in establishing a precise definition, a widely accepted interpretation describes it as "an industrial system designed for planned exchanges of materials and energy, with the goals of reducing energy and raw material consumption, minimizing waste, and fostering sustainable economic, ecological, and social relationships" (Alexander et al., 2000; Force, 1997). A highly effective way to foster industrial symbiosis is by creating an EIP. In this setup, nearby businesses exchange products, byproducts, waste, and energy, working together to improve the environmental, economic, and social outcomes of the entire system. It's all about collaboration for a more sustainable and efficient future. Creating an EIP involves looking at ways to improve processes, identifying possible network connections, setting up a unified control system, and carefully considering the environmental, economic, and technological impacts along the way(Lowe, 2001) .While the concept of an EIP appears promising, its implementation and development encounter several obstacles. According to, these challenges can be divided into two main categories: technical/economic challenges and organizational/commercial/political challenges, which include the following:

Technical/Economic Challenges: For an EIP to succeed, the exchanges between participating companies must be viable. This requires establishing connections among the companies where resources such as energy, byproducts, and water can be effectively shared as inputs and outputs. Another difficulty lies in achieving the optimal and cost-effective integration of material and energy flows, whether within individual processing units, across different areas, or between distinct companies. Additionally, the lack of existing infrastructure between companies can hinder integration, necessitating systems to efficiently allocate material and energy flows among participants.

Organizational/Commercial/Political Challenges: Contrary to what might be expected, these challenges often surpass technical/economic obstacles in terms of complexity. Each business involved in an EIP operates under its own set of rules and regulations, which can influence how information is shared within the park. Effective communication, mutual trust, and collaboration among all participants are essential for ensuring the EIP's success. Due to the aforementioned reasons, collaboration among companies within an EIP is both critical and essential. Therefore, the selection of industries to participate in the EIP becomes a matter of great importance. Selecting industries that are capable of creating feasible interconnections where the outputs of one serve as inputs for another can effectively address one of the key challenges in this domain. However, to the best of our knowledge, few studies have addressed this issue, as most research has focused on the exchanges within existing EIPs. As mentioned, industrial units within EIPs can collaborate and exchange resources in various ways, including:

- Sharing water, materials, and energy
- Transforming waste into useful by-products
- Exchanging expertise, workforce, and technical resources
- Facilitating the transportation of goods and personnel
- Utilizing shared facilities, such as heating systems or water infrastructure

These exchanges in industrial symbiosis can be classified into the following categories:

- Material exchange among industrial units (e.g., raw materials, by-products, and waste)
- Reusing industrial water and wastewater through treatment and redistribution
- Sharing energy across different units and reusing it effectively(Boix et al., 2015).

Based on the above analysis reveals that effective resource exchange among industries is fundamental to successful EIPs. This research will attempt to further address the importance of this issue to the extent that, to ensure the feasibility of cooperation between industries, the feasibility of exchanges between them will be prioritized in order to create an EIP with the presence of active industries capable of sharing resources. To advance this concept, this paper develops a mathematical model to optimize industries selection, providing a systematic approach for establishing eco-industrial parks with mutually beneficial synergies. The literature motivates us to explore why the exchanges are important by addressing the following research questions.

(1) What combination of industries can be selected in an EIP with the aim of maximizing the value of exchanges and minimizing environmental impacts?

(2) How can environmental and social considerations be incorporated into the EIP network design model in the form of mathematical constraints?

This paper makes the following key contributions:

- Propose an innovative MIP model tailored for selecting industries for an EIP.
- Inclusion of considerations of air pollution, Hazardous waste and industries priority.
- Proposing a model by considering sustainability.

The remainder sections in this paper are organized as follows: Section 2, the related literature review, Section 3, the problem description, Section 4, computational results and analysis, and finally Section 5, conclusion.

2. Literature Review

The goal of building EIPs is to identify industries that are able to exchange waste, by-products, and energy with each other and bring them together in a single area (Chertow & Ehrenfeld, 2012) .This approach provides an organized framework for inter-industry resource sharing, thereby increasing economic benefits by enhancing resource efficiency and minimizing environmental impacts through reduced waste and raw material usage (Lowe, 1997). In recent years, there has been a significant increase in research on industrial symbiosis and eco-industrial parks, driven mainly by population growth and the growing focus on sustainability. In this section, we'll take a closer look at studies on eco-industrial parks that are closely related to the focus of our own research. This section aims to review pertinent literature focusing on incorporate optimization of exchanges and the importance of it.

Various optimization approaches have been studied for water, energy, and material exchange networks in EIPs (Boix et al., 2015; Duhbacı, Özel, & Bulkan, 2021; Kastner, Lau, & Kraft, 2015). These techniques include material flow analysis (Sun et al., 2017), life cycle assessment(Ismail, 2020),mathematical programming (MP) (Afshari et al., 2020), input-output approach (Yazan et al., 2016), Single Leader Multi Follower (Salas et al., 2020), Energy-Water-Food (Fouladi, AlNouss, & Al-Ansari, 2021), Two-stage stochastic programming (Daş, Yeşilkaya, & Birgören, 2024), Mixed Integer Nonlinear Programming (Pang et al., 2023). An important point in the research conducted by scholars in this field is that most studies focused on improving the connections between industries within an existing EIP, and to the best of our knowledge, fewer studies have explored the selection and optimization of industries for the formation of an EIP. A notable study in this field investigated the design of EIPs by mimicking natural ecosystems, with a specific emphasis on the construction sector (Genc & Kurt, 2024). Their study examined how the role of connectance influences the optimization of industrial networks within EIPs. Using a dataset of potential symbiotic relationships, they developed seven theoretical EIP scenarios with varying constraints, such as flexibility in waste distribution and requirements for firms to both send and receive waste. The scenarios were analyzed using food web metrics to compare their performance against each other and natural ecosystems. The study found that maximizing connectance alone was ineffective for network optimization, as it often led to unstable configurations with few firms. Instead, scenarios that closely resembled natural food web metrics, particularly those balancing complexity and interdependence, showed better potential for sustainability and efficiency. Belaud et al,2017 explored a decision-making approach for designing and commercializing the "Les Portes du Tarn" EIP near Toulouse, France. It aimed to create a practical, collaborative method to develop the park, focusing on eco-industrial synergies and ensuring social and environmental acceptability. Based on life cycle thinking, the approach divided the process into five phases and used a multi-criteria decision-making model involving key stakeholders. The method emphasized collaboration, resource flow quality, and economic viability. It was successfully tested, uncovering synergies like water recycling and guiding companies into the park. In another research, focused on the forest industry and the formation of industrial symbiosis by considering active industries in this sector within an EIP, the locations of the factories in the EIP were determined using the ALDEP technique based on available information and life cycle assessment (LCA). Finally, a mathematical model was presented to align with the economic and environmental benefits. An integrated multi-objective optimization and decision-making framework for sustainable planning and designing of eco-industrial parks developed by (Ransikarbum, Wattanasaeng, & Madathil, 2023). They created a mixed-integer linear programming model that simultaneously considers three key sustainability objectives: economic efficiency, social responsibility, and environmental protection. A data-driven approach to designing eco-industrial parks introduced by (Hein et al., 2017) , focusing on industrial symbiosis and improving both economic and environmental outcomes. It used models of industrial plants to estimate resource inputs and waste outputs, identifying collaboration opportunities through public data and rule-based systems. A multi-objective optimization framework was applied to balance economic gains and environmental benefits. The approach was tested using the Kalundborg EIP, identifying synergies and suggesting new ones, while highlighting the need for more detailed plant models for better accuracy. (Wang et al., 2022) examined the spatial planning of the Yueyang Green Chemical Industry Park in China, focusing on industrial symbiosis to promote sustainable development by integrating industrial, urban, and ecological systems. The authors proposed a methodology combining ecological footprint analysis, capacity estimation, and GIS-based spatial evaluation to design a symbiotic industrial network and optimize land use. It emphasized mimicking natural ecosystems, where waste becomes a resource, and integrating industrial with spatial planning for sustainability. The study identified three symbiotic exchange types: closed-loop, waste exchange, and network, and applied this approach to reduce waste, optimize resources, and enhance regional development at the park. However, the investigation into how exchanges contribute to the design of industrial networks within an EIP, particularly in optimizing theoretical EIPs, remains limited. The majority of studies on mathematical models for planning and optimizing EIPs mainly focus on improving their efficiency and performance. However, they often miss the strategic perspective needed for establishing a truly effective EIP. This study attempts to comprehensively address the issue of selecting industries for the construction of an eco-industrial park, considering sustainability conditions. In this framework, a mathematical model is proposed, considering three dimensions of sustainability, namely economic, environmental, and social, with the aim of selecting industries under conditions where there are possible exchanges between them.

3. Problem Description

Globally, natural resources are finite. To meet the growing demands of an expanding population, reusing materials and cutting back on newly extracted raw resources is key. Beyond that, the rising frequency and intensity of natural disasters are causing severe environmental damage (Perrucci, Vazquez, & Aktas, 2016) .By reusing materials instead of constantly relying on fresh extraction, we can ease the pressure from increasing production needs whether driven by population growth or supply chain disruptions like those seen during the pandemic.

One solution gaining traction since the 1992 Earth Summit is eco-industrial parks. Researchers and policymakers worldwide have explored this model to cut costs and reduce environmental harm while manufacturing new products (Gibbs & Deutz, 2005). Today, these parks blend industrial ecology principles, cleaner production methods, and smarter waste management—not just to make industries greener, but also more efficient and profitable. At their core, they facilitate material exchanges between businesses in traditional industrial parks, creating both economic and environmental wins for everyone involved (Huang, Zhen, & Yin, 2020). In the design and planning of eco-industrial parks, mathematical optimization model, particularly linear and mixed-integer programming (MIP) have been widely used due to their tractability, interpretability, and computational efficiency. Several review studies highlight MIP as one of the most common modeling approaches in industrial symbiosis and EIP design because many cost, flow, and allocation relationships can be reasonably linearized without significant loss of realism(Demartini, Tonelli, & Govindan, 2022; Lawal et al., 2021).

In this study, we propose a solution for identifying suitable industries to participate in an EIP. This paper demonstrates how industries can be selected for establishing an EIP in a way that maximizes potential exchanges between them. In this article, we have considered the connections and exchanges between industries within the park and have ignored exchanges with industries outside the park. In this regard, a MIP model is designed and proposed in this research. The following conditions are assumed:

- The size of industries and infrastructure has been estimated as medium based on European Union standards.

- Feasibility of material exchanges has been determined based on real-world data.
- The value of exchanges is calculated and considered based on euros.
- The designated area for establishing the EIP has basic infrastructure and facilities in place.
- The model considers job creation for local residents by the industries, though it doesn't include specialized workforce requirements.
- The priority of each industry and infrastructure has been defined and calculated based on two key indicators: overall profitability and noise pollution levels. These two indicators are considered simultaneously, such that higher profitability results in a higher score, while lower noise pollution also contributes to a higher score.

To introduce the model, the indexes, parameters and decision variables of the mathematical model are defined as follows:

Sets

i, j	industries
k, l	infrastructures
m	materials

Parameters

e_{ijm}	If exchange of material m between I and j is possible =1; otherwise =0
o_{klm}	If exchange of material m between k and l is possible =1; otherwise =0
a_{kjm}	If exchange of material m between k and j is possible =1; otherwise =0
d_{jm}	Demand of j for material m
d'_{lm}	Demand of l for material m
v'_{klm}	The value of exchanging material m between k and l
v''_{klm}	The value of exchanging material m between k and l
v'''_{kjm}	The value of exchanging material m between k and j
cap_{im}	The capacity of I from material m
cap'_{km}	The capacity of k from material m
fc_i	The fixed of constructing industry i
tb	The total budget for building infrastructures
p_e	Penalty for hazardous waste generation
$pmax_i$	Maximum permitted hazardous waste for industry i
sa_k	Required infrastructure area for infrastructure k
s_i	Required industry area for industry i
emp_i	The number of jobs created by industry i
$Minjobs$	Minimum number of jobs created
M	Big M
lb_i	The amount of pollution produces by i
ln_i	The amount of pollution produces by industry i after increasing the technology
N	The amount of pollution to decide about the industry
$priority_i$	The priority of industry i
$priority'_k$	The priority of infrastructure k

Variables

x_i	If industry i selected to construct =1; otherwise = 0
y_k	If infrastructure k selected to construct =1; otherwise = 0
t_i	If the pollution is above the N, the industry will select with higher price
p_i	If industry i selected to construct with penalty =1; otherwise = 0
w_{ijm}	The amount of material m that exchange between I and j
v_{ijm}	The amount of material m that exchange between i and j
g_{kjm}	The amount of material m that exchange between k and j
$Totalexchange_m$	The total exchange of material m

3.1. Deterministic Mathematical Model

The optimization model operates under the assumption of a centralized planner (the park authority), which determines the set of industries that may enter the park. Industries are not autonomous decision makers in this formulation; instead, they must comply with predefined environmental and technical regulations set by the park. Therefore, binary selection variables represent the park's admission decisions. In the mathematical model of this study, the objective function involves maximizing the value of exchanges and priorities and minimizing costs. The objective function specifically considers that industry exchanges are of high importance and an industry is selected if it contributes positively to the total value of trade, which means that industries are not independent of each other. This study aims to provide a comprehensive modeling approach for maximum adaptability in different contexts.

$$
\begin{aligned}
Max \; & \sum_i \sum_j \sum_m e_{ijm} \times w_{ijm} \times v'_{ijm} + \sum_k \sum_l \sum_m o_{klm} \times v_{klm} \times v''_{klm} \\
& + \sum_k \sum_j \sum_m a_{kjm} \times g_{kjm} \times v'''_{kjm} \\
& + \sum_i priority_i \times x_i + \sum_i priority_i \times t_i + \sum_k priority'_k \times y_k \\
& - \sum_i fc_i \times x_i - \sum_i fc_i \times t_i - \sum_i pe_i \times p_i
\end{aligned} \tag{1}
$$

Subject to:

$$\sum_j w_{ijm} \le cap_{im} \times x_i + cap_{im} \times t_i \quad \forall i, m \tag{2}$$

$$\sum_l v_{klm} + \sum_j g_{kjm} \le cap'_{km} \times y_k \quad \forall k, m \tag{3}$$

$$\sum_k g_{kjm} + \sum_i w_{ijm} \ge d_{jm} \times x_j + d_{jm} \times t_j \quad \forall j, m \tag{4}$$

$$\sum_k v_{klm} \ge d'_{lm} \times y_l \quad \forall l, m \tag{5}$$

$$Totalexchange_m = \sum_i \sum_j w_{ijm} + \sum_{kl} \sum_l v_{klm} + \sum_k \sum_j g_{kjm} \quad \forall m \tag{6}$$

$$\sum_i emp_i \times x_i + \sum_{ie} emp_i \times t_i \ge minjobs \tag{7}$$

$$x_i \le t_i \quad if \quad lb_i \ge N \quad \forall i \tag{8}$$

$$\sum_i lb_i \times x_i + \sum_i ln_i \times t_i \le lmax \tag{9}$$

$$x_i + t_i \le 1 \quad \forall i \tag{10}$$

$$\sum_i s_i \times x_i + \sum_i s_i \times t_i + \sum_k s'_k \times y_k \le area \tag{11}$$

$$\sum_k fc'_k \times y_k \le tb \tag{12}$$

$$hw_i \times x_i + hw_i \times t_i \le hwmax_i + M \times p_i \tag{13}$$

$$
\begin{aligned}
& x_i, y_k, t_i, p_i \in \{0,1\} \\
& w_{ijm}, v_{klm}, g_{kjm}, Totalexchange_m \ge 0
\end{aligned} \tag{14}
$$

The objective function presented in Eq.1 consist of three parts in order to maximize the total. First part considering the value of exchanges, second part for priorities and the last part for fixed costs. Constraints (2) and (3) ensure that there is no transfer, there is no connection from i to j and i to k by considering the capacity. Material exchange variables are constrained by the selection of corresponding industries or infrastructures, ensuring zero exchanges if an industry or infrastructure is not selected. Constraints (4) and (5) ensure that the transferred material satisfies the demand. Constraint (6) measures the amount of exchange for each material.

Constraint (7) guarantees that the selected industries satisfy the number of number of jobs to be created. Constraints (8), (9) and (10) state that if an industry produces more pollution than the permitted limit, the cost of building it increases compared to the normal state, which is calculated in the objective function, and an industry is either built at the normal price or higher. Constraint (11) guarantees that the industries and infrastructure selected are appropriate to the area of the desired space and that their area does not exceed the area available for construction. constraint (12) calculates the cost of building infrastructures don't exceed the budget. Constraint (13) ensures that if an industry's hazardous waste exceeds the permitted limit, it must pay a fine. Constraint (14) delineates the type of decision variables.

3.2. Big-M

The hazardous waste constraint is enforced using a Big-M formulation. To ensure rigor, the Big-M value is set to a tight upper bound equal to the sum of hazardous waste from all industries. This prevents violations of the pollution limit and ensures compliance with environmental regulations.

3.3. Social Indicator

In this study, social index is captured through job creation, which is one of the most widely used and measurable social indicators in eco-industrial park studies. Employment data are available at the industry level, and job creation directly affects the socioeconomic development of the hosting region. Although additional social indicators such as workplace safety, occupational health risks, community disturbance, and social acceptance are conceptually important, reliable and consistent quantitative data for these indicators were not available for the industries considered in our case study.

3.4. Model Validation

To validate the proposed MIP model, the following have been done:

1) logic validation: The structure of the model, particularly the exchange logic and infrastructure cost relationships, was reviewed with two domain experts familiar with EIP planning to ensure logical correctness and realistic representation of industrial interactions.
2) Numerical validation: The model was solved under multiple scenarios, and the resulting industry combinations and exchange networks were compared with patterns commonly reported in the literature.

4. Computational Experiments

The proposed mathematical model in section 3 is in order to selecting industries for an EIP. According to the results of (Genc & Kurt, 2024), which concluded that connectivity alone is not a suitable criterion for selecting industries and has no economic justification, because selecting an industry solely for the sake of establishing connectivity without considering economic dimensions can be impractical. In this article, we have tried to address the important issue of selecting industries by considering the economic value of exchanges for selecting industries, as well as environmental and social issues, by presenting a sustainable approach. In this section, the proposed mathematical model has been applied to 6 sample problems on different scales. The number of local jobs, total budget and area are changed proportionately with the model size. The MIP model is coded in GAMS 24.1.2. The solver (CPLEX) successfully reached the optimal solution with a 0% optimality gap, and the final runtime was well within acceptable limits for strategic-level planning problems. Table 1 shows the datasets used in this problem. Link density is obtained by dividing the number of links by the number of selected industries. As is clear, the number of links also increases as the number of industries increases, indicating the average number of links in which each industry is present. The types of possible and considered exchanges in this model are illustrated in Fig 2. Also, the possibility of exchanges material between industries and infrastructures are valid in real. The industries and infrastructures that we used as model inputs based on the dataset and some possible and real exchanges are explained in Tables 2 and 3.

Table 1. Dataset used for computational analysis

Number of industries	32
Number of infrastructures	7
Number of materials	48
local jobs	100-500

Table 2. list of industries and infrastructures

Num	Industry	Num	Industry
1	steel works	17	chlorine dioxide plant
2	cement production	18	gasifier
3	glass and glass-ceramic production	19	food and fish processing
4	pulp and paper plant	20	interior decoration production
5	pharmaceutical	21	protein extraction
6	fish farming	22	chemical industry
7	bricks manufacture	23	plaster board manufacture
8	construction material production	24	iron and steel production
9	liquid fertilizer production	25	smelting
10	production of refractories	26	alumina refinery
11	production of concrete	27	nickel and cobalt refinery
12	rockwool production	28	wood factory
13	calcium carbonate plant	29	oil and fat production
14	fertilizer company	30	sugar production
15	citrate acid factory	31	car glass production
16	charcoal production	32	glass fiber production

Num	Infrastructure
1	Powerplant
2	Gas Refinery
3	Electricity production
4	Hydro powerplant
5	Wastewater treatment
6	Water purification
7	CHP plant

Dataset: The exchange data used in this study (steam, sludge, fly ash, heat, and other by-products) were obtained from the MAESTRI–SPIRE Industrial Symbiosis database. This database is part of an EU-funded Horizon 2020 project and contains validated real industrial data collected from manufacturing companies in Europe. All exchange values in Table 3 are directly extracted from these real case studies, ensuring that the model is based on realistic and operationally feasible material and energy flows.

Table 3. Feasible exchanges among industries and infrastructures

From	To	Material
powerplant	steelworks	electricity
powerplant	Fish farming	steam
Power plant	Glass and glass-ceramic production	Fly ash
Power plant	Wall-board plant	Scrubber sludge
steelworks	Cement production	Mill scales
Steelworks	Cement production	BF slag
Cement production	Construction material production	Coal fly ash
Hydropower plant	Pulp and paper plant	Electricity

Chlorine dioxide plant	Pulp and paper plant	Chlorine dioxide
Chlorine dioxide plant	Pulp and paper plant	Sodium hydroxide
Iron and steel production	Cement manufacturing	Steel slag
Pulp and paper plant	Cement production	White sludge
Pulp and paper plant	Cement production	Fly ash
Pulp and paper plant	Citrate acid factory	White sludge
Pulp and paper plant	Fertiliser company	Sludge
Pulp and paper plant	Charcoal production	Wood chips
CHP plant	Gas refinery	Steam
CHP plant	Chemical industry	Steam
Chemical industry	Plaster board manufacturer	Gypsum
Car glass production	Glass fiber production	Glass waste

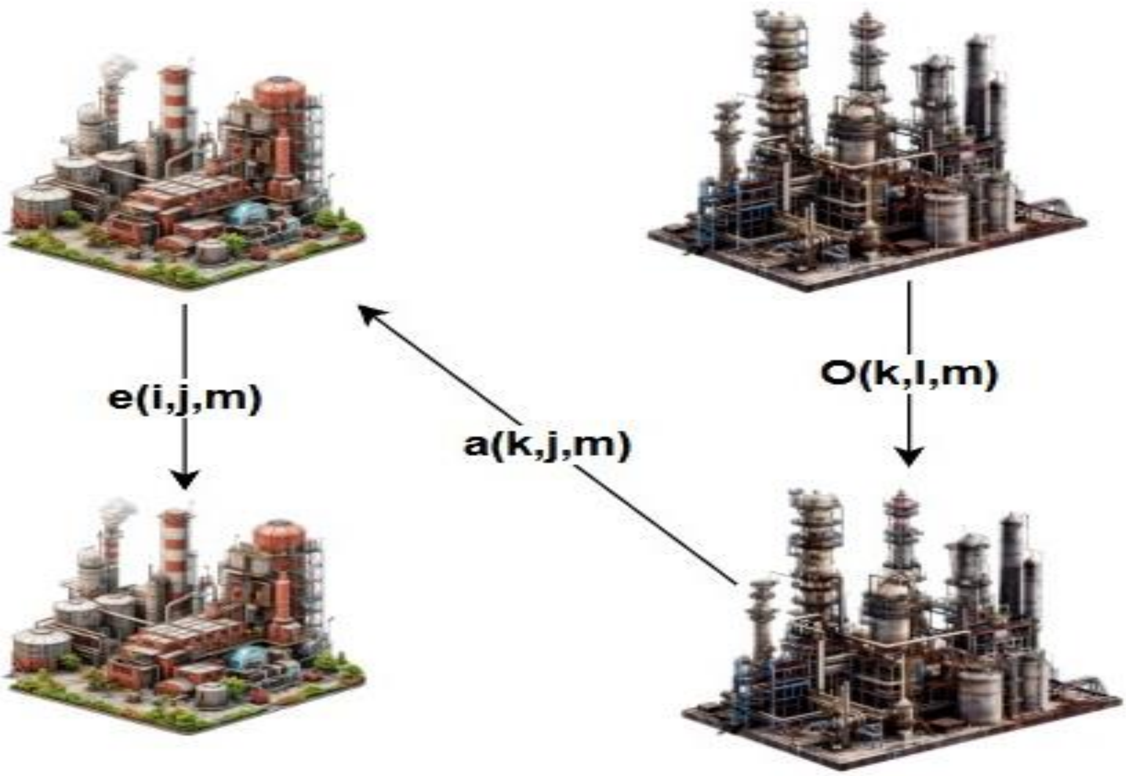

Figure 2. possible and considered exchanges

To examine the model, we solved it in different sizes until it created 400 jobs for local people. We examined the number of industries and the connections. The results are shown in Table 4. As it is clear that initially the model was solved to create 50 jobs, considering the constraints and the objective function, 5 industries were selected and the number of connections was low, and this led to the value of the objective function being negative, which is logical because the connections are limited and this has caused the fixed cost of construction to be greater than the value of exchanges. This trend continues in examples 2 and 3. In the fourth example, where we are trying to create 200 jobs for local people, the objective function becomes positive and in fact, in this example, the value of exchanges between industries exceeds the fixed cost of construction, leading to the fact that in addition to covering the construction cost, the value of exchanges ultimately leads to this construction being profitable. And finally, when the model was run for 400 jobs, we see that this value increases significantly. it selects industries by considering the value of exchanges, minimizing costs, and accounting for industry prioritization. In this case, the model identifies a set of industries, and feasible exchanges between them are established based on capacity and demand constraints. Along with the objective function, we also examined the connection density to examine, on average, how many connections each industry has. We see that the model has attempted to increase industries in a way that is also effective in terms of connections, in order to satisfy the constraints. Table 5 and 6 show the results with increasing and decreasing demand.

Examining the model results based on the number of jobs:

Table 4. The outputs of model

Problem	Number of jobs	Number of selected industries	Number of links	Objective function	Link density
1	50	5	3	-24879980	0.6
2	100	6	8	-31870984	1.33
3	150	7	9	-23405981	1.28
4	200	10	20	9050035	2
5	300	12	24	38294037	2
6	400	14	29	129494043	2.07

Table 5. The output of the model by increasing the demand

Problem	Number of jobs	Objective function
1	50	-24879980
2	100	-31851052
3	150	-20174081
4	200	9049115
5	300	36244129
6	400	130296001

Table 6. The output of the model by decreasing the demand

problem	Number of jobs	Objective function
1	50	-24879980
2	100	-30112355
3	150	-33154870
4	200	7101223
5	300	25460521
6	400	100425123

To better illustrate the process of changes in the objective function, Figure 3 shows these changes. It starts with a negative value and then becomes positive as the problem gets bigger. In fact, establishing an EIP with about 5 industries cannot be logically efficient, and this is also clear in the model. It should be noted that EIPs have an important difference from industrial parks, and that is that in industrial parks we also have small industries. For this reason, the number of industries located in these parks are usually much higher than in an EIP. However, EIPs usually operate with a smaller number of industries but larger ones. We also tested the model for possible changes in demand. We considered how demand would affect the outcome if it increased or decreased by 30%, and the results are shown in Figure 4. As it’s clear, with the change in demand, the objective function undergoes some changes, but these changes have a natural and reasonable trend and the objective function does not undergo unacceptable and severe changes. This indicates that the model reacts to changes in demand, but these changes are not irrational.

The connections of the problem in the case of 400 jobs created are shown in Figure 5. As it is clear, the possible connections between the selected industries, considering the conditions of the constraints, are from materials that are referred to as waste (except for resources such as electricity). This is while under these conditions these materials are consumed as a consumable for another factory and benefit from this proximity and exchange of materials. Items such as electricity are also considered in this model because first it was in the dataset, second the exchange of this energy is also one of the unavoidable issues for the life of industries and finally since power plants are considered among the infrastructures, this exchange is also considered.

In this model 14 plants and 29 exchanges are selected based on the capacity, demand, minimum jobs creation and also the limitation of air pollution.

Given that the main focus in the presented mathematical model is on material exchanges, we examined the contribution of each material to the exchanges, and in Figure 6, we compared the contribution of each material to the exchanges after normalizing the values. Well, as expected, electricity accounts for the main share of these exchanges, but given that the exchanges of other materials are of greater importance to us, we examined these exchanges in Figure 7 by excluding electricity.

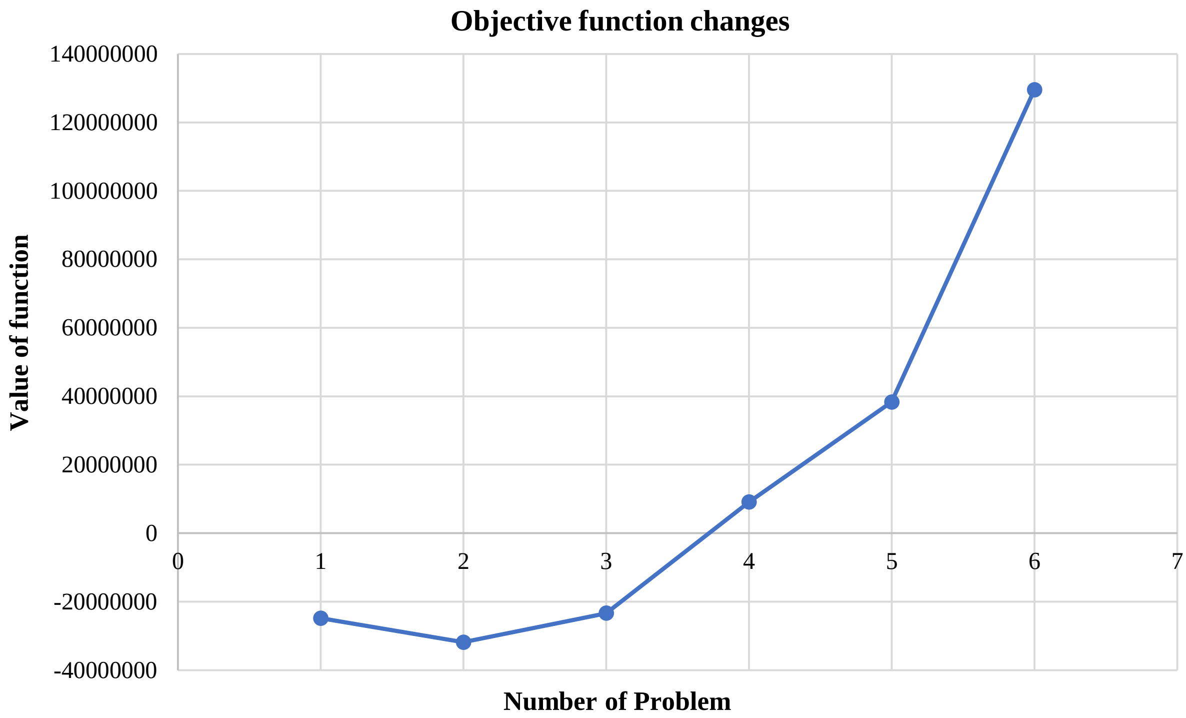

Figure 3. The changes of function

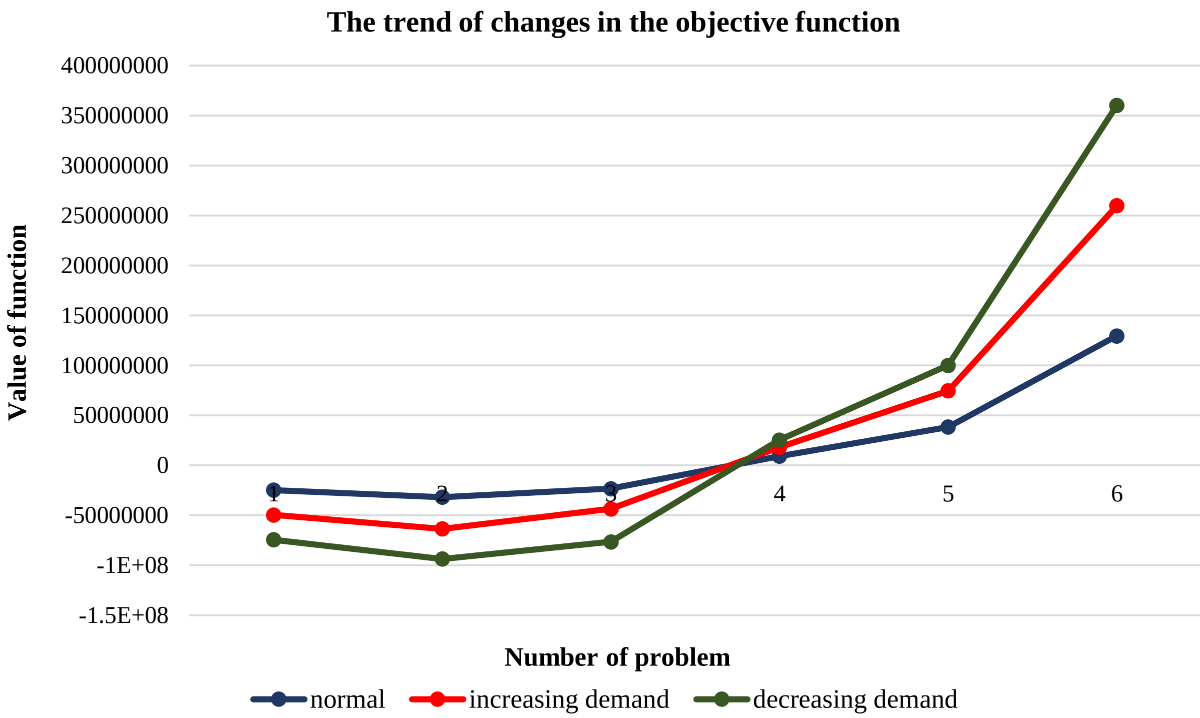

Figure 4. The changes of objective functions with different demands

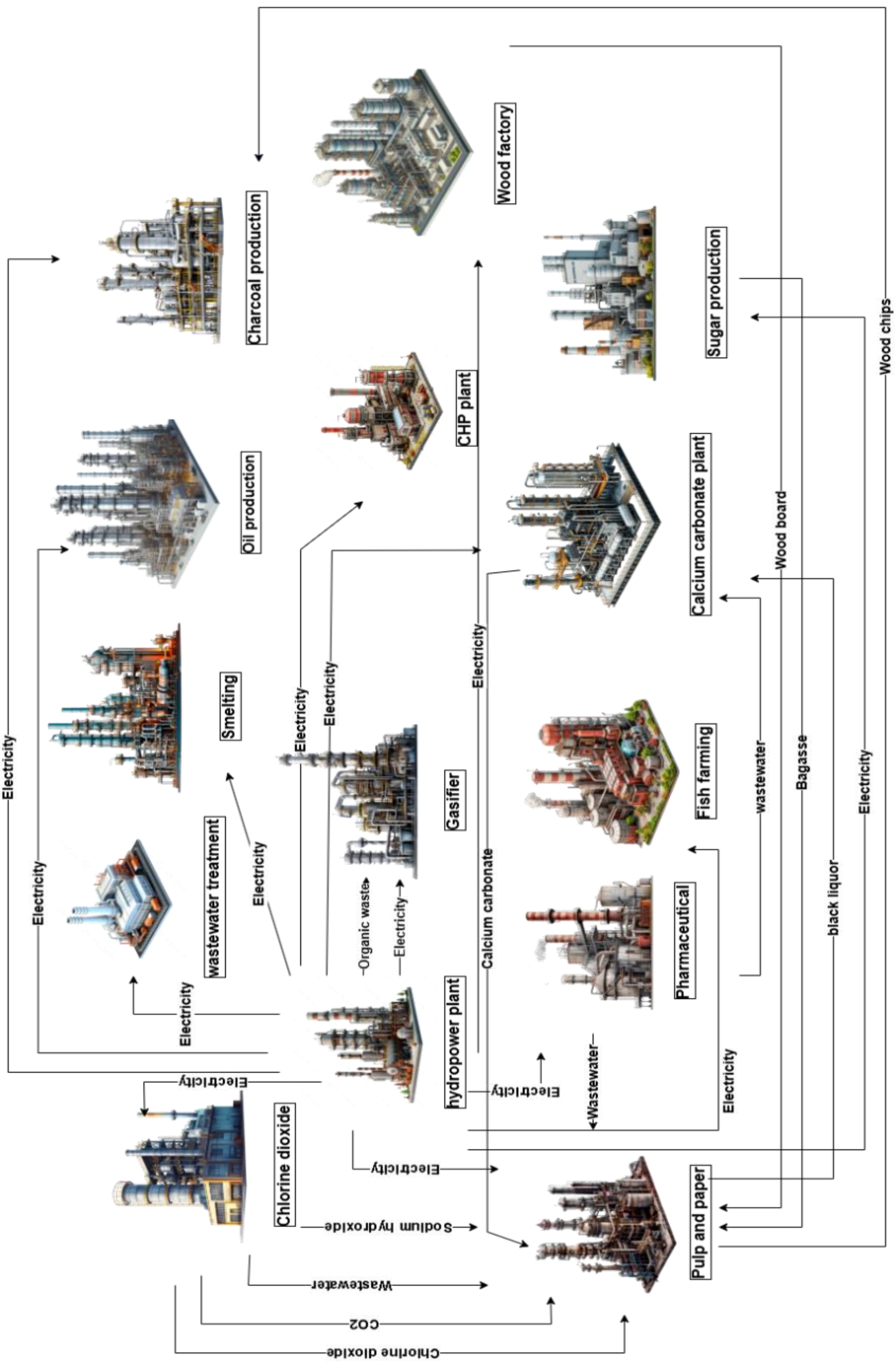

Figure 5. The exchanges among selected industries.

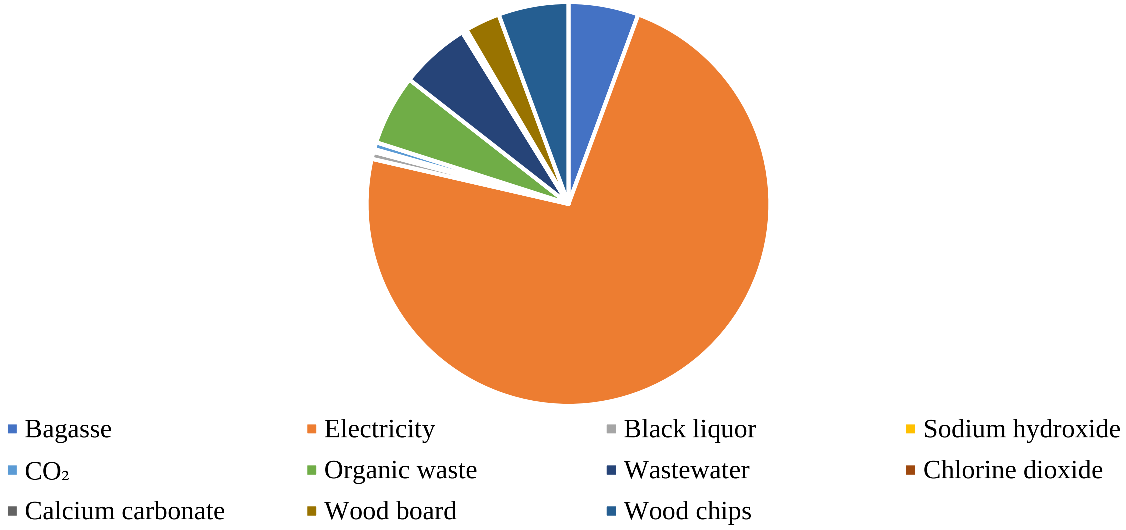

Figure 6. Share of each material in the exchanges

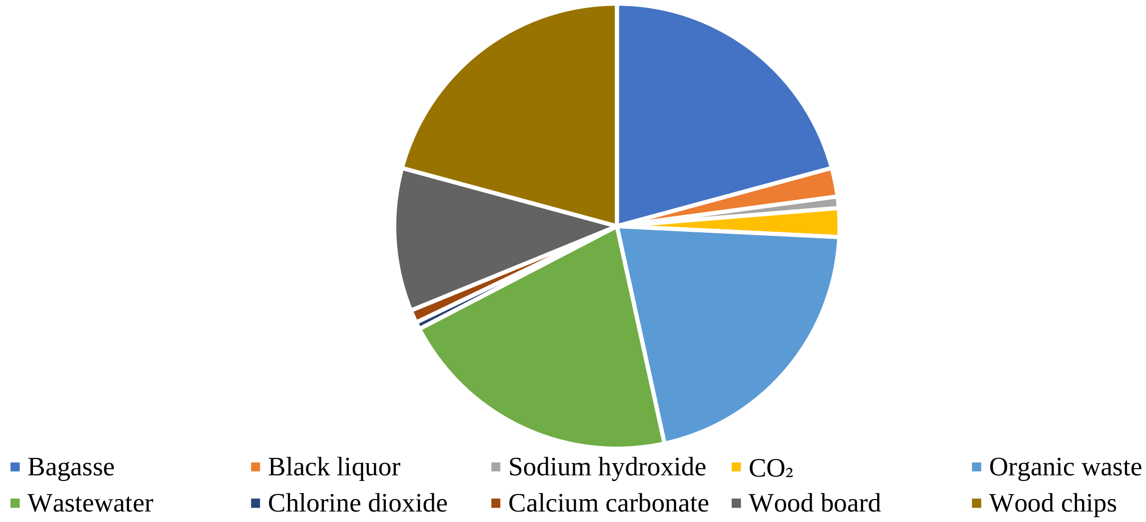

Figure 7. Share of each material in the exchanges without electricity

4.1. Managerial and Policy Insights

To better understand the results and findings of this model, some managerial insights were mentioned. Insights obtained based on the analysis of the results can help managers to make decisions and avoid mistakes. The results show that the pulp and paper plant, as one of the industries with the highest exchanges (10 types), plays the role of the engine of the synergistic network; therefore, in the mentioned conditions, the park manager can focus on attracting this industry in the first stage, because its presence facilitates the entry of other complementary industries. The results show that the high cost of infrastructure construction for the steel works makes it a non-optimal choice. This is despite the fact that it can have good connections with other industries. Therefore, park managers can make the presence of this industry affordable again by providing infrastructure subsidies or private sector participation so that its presence brings added value.

5. Conclusion

Eco-industrial parks (EIPs) and the optimal use of resources are one of the most important topics in sustainable development. Several researchers have investigated this area and proposed solutions to improve current practices. Unlike most previous studies that focused on optimizing existing EIPs, this study presents a mathematical model for selecting industries to establish a new EIP. The model aims to maximize the value of material and energy exchanges while minimizing the costs of infrastructure construction, taking into account three dimensions of sustainability: economic, social, and environmental. To evaluate the model, the model was solved under different job creation requirements. In small scenarios, the limited number of exchanges made the park economically unviable. However, as the model size increased and more industries were selected, the number of practical exchanges increased, ultimately leading to a suitable economic configuration. Therefore, the model provides a decision support tool for locating industries that can exchange resources efficiently. Future research could explore dynamic scenarios or integrate geographical and spatial constraints.

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