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Mathematical Modeling of Resource Symbiosis in Industrial Technology Parks for Sustainable Development

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Abstract

This research focuses on offering an innovative approach in order to solve a problem of resource management efficiently in industrial technology parks. Increasing industrialization, along with different kinds of environmental problems, make this question topical for our time because it deals with allocation of energy, water, and material resources effectively. Hence, the current research tries to consider resource flows in industries from the perspective of the phenomenon known as industrial symbiosis. In order to improve resource flows, a new model which combines system dynamics and multi-objective linear programming approaches has been designed. Simulation of this model demonstrates its ability to reduce the amount of virgin resources used up by 15-20% and the quantity of waste produced by 18%, while comparing them to the linear production model. Information technology aspect in relation to coordination of industrial processes should be considered. It can be concluded that this research is able to unite engineering and economic aspects of the issue under discussion.

Keywords: Industrial Symbiosis, Mathematical Modeling, Industrial Parks, Resource Efficiency, Circular Economy

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1. Introduction

The uniqueness of the research presented in the paper consists of the use of multi-objective optimization in combination with system dynamics modeling in the context of modeling the process of industrial symbiosis in a dynamic environment. The growing rate of industrialization, along with a number of problems related to lack of resources and environmental problems, makes it necessary to build resource-efficient systems. Traditional economic models, which presuppose the use of the "take-make-dispose" paradigm, prevent achieving ecological balance in the future. Therefore, global goals, such as UN Sustainable Development Goals (UN SDGs), call for transforming the current state of affairs and implementing circular and resource-efficient economies, based on the principles of responsible production and consumption [1-3].

One of the main components of the modern economy is the industrial parks, which combine productive processes, innovations, and technologies [4-6]. Park complexes increase productivity and provide opportunities for the development of cooperation among industries [7]. Nevertheless, the issue of fragmented system of resource management is still relevant due to lack of proper coordination among independent companies and insufficient interaction concerning the use of materials and energy resources and wastes [8-10].

As contemporary science becomes more focused on the construction of robust mathematical frameworks that would help to overcome system uncertainties and optimize its performance, numerous studies were recently devoted to optimizing complex dynamic systems [7].

It is worth noting that the idea of industrial symbiosis is becoming widely spread now due to the potential of high resource efficiency [4, 8]. Industrial symbiosis implies the exchange of materials, energy, and waste between companies. Hence, output of one company becomes input for another [8]. Industrial symbiosis was studied in numerous sources and considered to play a key role in the creation of circular economies and eco-industrial parks. Although the implementation of industrial symbiosis can provide many advantages for businesses, several issues might arise during the process. In particular, the problem is associated with the need to have a high level of coordination, information asymmetry, heterogeneity of the flows, as well as dynamicity of the industrial system (changeable production volumes and demands) [4, 11-12].

Nowadays, mathematical modeling is considered one of the most common tools when analyzing the relations between organizations and optimizing resource flows. There exists a great variety of different methods for constructing such models based on input-output analysis, optimization techniques, and system dynamics [11, 13-14]. Furthermore, taking into account the fact that sustainability means achieving the right balance between the economy and the environment, multi-objective models should be developed [7]. Most of the models constructed for the analysis of industrial systems and flows fail to take into account both sides of the problem and do not consider dynamical character of real systems [15]. Additionally, they do not consider the dynamic nature of real systems and, thus, cannot fully simulate their functioning [16-17]. Such disadvantages make it crucial to develop more advanced mathematical models. In this regard, the main objective of the paper is to elaborate a mathematical model to optimize the symbiosis of the resource flows in the system. In particular, the application of multi-objective linear programming (MOLP) together with system dynamics can provide better results.

While there are plenty of papers discussing static input-output models of industrial parks [4, 8], they fail to address the issue of time lag and feedback loop of the dynamics of the resource availability [16, 18]. It is why the current research will attempt to solve this problem through the integration of multi-objective optimization with system dynamics.

2. Model and methods

2.1. Industrial symbiosis conceptual framework

The suggested system is viewed as a dynamic network, with the effectiveness of the resource exchange determined via feedback loops. The reinforcing loop takes place when the decline in waste disposal costs allows increasing the capital spent on symbiotic infrastructure creation due to higher revenues. In contrast, a balancing loop occurs due to the physical limits of waste processing capacity. Thus, as opposed to standard static optimization models, the proposed approach accounts for dynamic relationships and feedback effects, offering more realistic predictions.

Optimization of thermal and energy flows plays a crucial role within industrial clusters, as proven by earlier studies on the topic related to performance improvement in industrial systems and sustainable engineering solutions [7, 19].

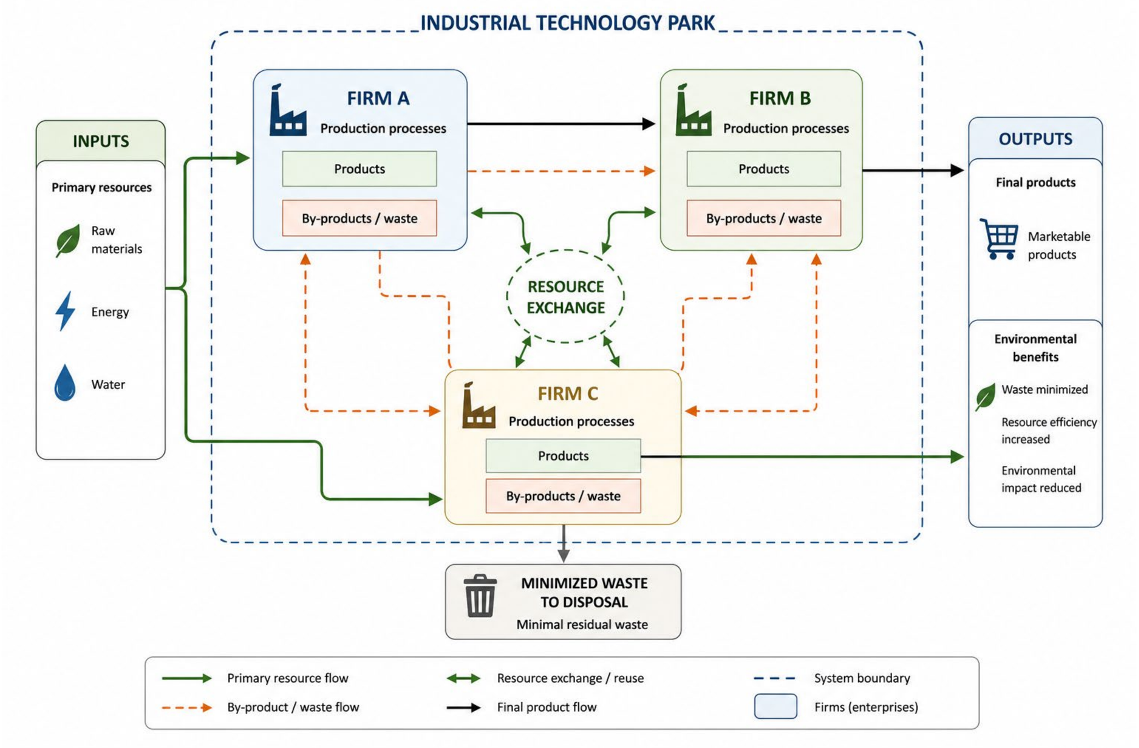

Figure 1. Conceptual model of industrial symbiosis in a technology park

Figure 1 depicts the concept of industrial symbiosis in terms of the industrial technology park. The model suggests the presence of a network of interconnected enterprises that interact via exchanges of material, energy, and by-product flows. Resources are initially introduced to the system and distributed among firms, which produce both products and waste. Waste can be used further as an input flow for another enterprise through a well-coordinated exchange system.

2.2. Mathematical modeling of the system

In order to represent mathematically the process of resource exchange, a multi-objective linear programming model will be built in order to optimize resource flows between firms. The optimization goal involves cost and environmental impact minimization at the same time. The multi-objective model will be transformed into a single objective one using the weighted sum approach via software [7].

Decision variables

Let: x_{ij} — quantity of resources exchanged from enterprise *i* to enterprise *j*; R_i — amount of resources consumed by enterprise *i*; W_i — waste produced by enterprise *i*.

Objective functions

Two objectives are optimized by the mathematical model over the time period *T*:

1. Total operational cost minimization:

$$\min Z_1 = \sum_{t=1}^{T}\left(\sum_{i=1}^{n}\sum_{j=1}^{n} c_{ij}x_{ij}\,(t) + \sum_{i=1}^{n} c_i R_i(t)\right) \tag{1}$$

2. Environmental impact minimization:

$$\min Z_2 = \sum_{t=1}^{T}\sum_{i=1}^{n} e_i\, W_i\,(t) \tag{2}$$

where: c_{ij}— resource exchange cost; c_i— primary resource cost; e_i— environmental impact coefficient; $U_i(t)$ denotes internal consumption of recycled resources by the company.

In order to convert multi-objective optimization into single objective optimization, the method of weighted sum is applied and formulate the single scalar objective function:

$$min\ Z = \sum_{k=1}^{n} \omega_k \cdot \frac{f_k(x) - f_k^{opt}}{f_k^{max} - f_k^{min}} \tag{3}$$

where: $f_k(x)$ – value of the k-th objective function;
f_k^{opt} – ideal value of the k-th objective (an anchor point);
ω_k – weights of the relative importance of the objectives, with $\sum_{k=1}^{n} \omega_k = 1$.
The weights ω_k are selected with the help of the Analytical Hierarchy Process (AHP) based on expert's evaluations of economic, environmental and social aspects of the industrial park.
The multi-objective model is constrained as follows:
1. Total output cannot be greater than the total waste flow produced by the source enterprises.
2. Maximum throughput constraints of recycling infrastructure: $x_{ji}(t) \leq C_{ji}$, where C_{ji} – maximum capacity of recycling infrastructure between j-th and i-th firm.
3. Satisfaction of demands: the total resource inputs should cover the minimum needs of the enterprises.
Dynamic resource balance:

$$R_i(t) + \sum_{j=1}^{n} x_{ji}(t) = P_i(t) + \sum_{j=1}^{n} x_{ij}(t) + W_i(t) \tag{4}$$

where $P_i(t)$ is the required production to satisfy demand at time?
Capacity and state constraints:

$$0 \leq x_{ij} \leq X_{ij}^{max} \tag{5}$$

Non-negativity condition:
$x_{ij}(t), R_i(t), W_i(t) \geq 0 \qquad \forall i, j, t$

State equations (system dynamics consideration):

The dynamics of resource stock are taken into account in the park, the stock of the recycled resource S_i, produced in the system for i-th enterprise is calculated using the formula below:

$$S_i(t + \Delta t) = S_i(t) + \left[\sum_{j \in J}^{n} x_{ji}(t) - U_i(t)\right] \cdot \Delta t \tag{6}$$

With the restriction: $S_i(t) \geq 0$ for all t.
Where:
$S_i(t)$ denotes the stock of resource i at time t;
$x_{ji}(t)$ – the resource influx rate from firm j to firm i;
$U_i(t)$ – the rate of resource consumption by firm i;
Δt – simulation time step ($\Delta t = 1$ month in this case).

This equation is needed to reflect the temporally dynamic nature of the model, thus enabling system stability analysis. The model is coherent with those previously discussed in the literature.

2.3. Modeling approaches and simulation scenarios

The suggested mathematical model is estimated numerically via simulation for various scenarios of the resource exchange between enterprises in the technology park. The variations are taken into account according to the number of enterprises, resource demand, cost coefficient, and environmental impact factors.

Table 1. *Model parameters and variables*

Parameter	Description	Unit
x_{ij}	Resource flow between firms	tons
R_i	Primary resource input	tons
W_i	Waste generation	tons
c_{ij}	Transportation cost	\$/ton
e_i	Environmental impact coefficient	index

To address the objective (Z_1 – cost minimization) conflict regarding cost and environmental impact (Z_2 – emission minimization), the weighted Tchebycheff scalarization approach is used within MOLP. Since the first objective is cost minimization (Z_1) and the second one is emission reduction mass (Z_2), it is necessary to transform two objectives into one by applying the normalization procedure.

The resulting problem looks as follows:

$$\min\left[\omega\cdot\frac{Z_1-Z_1^{min}}{Z_1^{max}-Z_1^{min}}+(1-\omega)\cdot\frac{Z_2-Z_2^{min}}{Z_2^{max}-Z_2^{min}}\right] \quad (7)$$

where $\omega \in [0,1]$ is the preference weight of the decision maker. The preference of weight is assumed to be $\omega = 0.5$. To determine the Pareto-optimal point, the analysis of the sensitivity of the industrial symbiosis network to changes in environmental and economic preferences will be conducted.

2.4. Evaluation metrics

The following measures will be employed to measure the success of the proposed system:

Efficiency of resource utilization ratio

$$RE = \frac{Reused\ resources}{Total\ resources} \quad (8)$$

Reduction in waste ratio

$$WR = \frac{W_{baseline}-W_{model}}{W_{baseline}} \quad (9)$$

Measure of cost reduction

These criteria help compare the efficiency of traditional linear systems and the proposed symbiotic system.

3. Results and discussion

3.1. Simulation results

In order to evaluate the proposed mathematical model, a series of simulation experiments have been carried out. The purpose of these experiments was to compare the performance of the proposed symbiotic model with a traditional production process model in terms of resource utilization. It was assumed that companies operated independently in the baseline scenario and exchanged no resources. On the other hand, the symbiotic approach allows for recycling resources and redistributing them within a company.

As seen in the results provided below, the proposed model provides considerable advantages in terms of performance when compared to a traditional production process. The performance of both models was tested with the example of a system comprising three firms with varying capacity and resource requirements. The data in Table 2 shows the performance of the baseline and proposed models, respectively.

Table 2. *Comparative performance of baseline and proposed models*

Indicator	Baseline model	Proposed model	Change (%)
Total resource consumption (tons)	100	82	-18%
Waste generation (tons)	40	34	-15%
Reused resources (tons)	5	28	+460%
Operational cost ($)	1000	870	-13%

The numbers given in Table 2 clearly show that the proposed model offers greater efficiency. The greatest improvement is seen in resource reuse rates, which are considerably higher due to the adoption of the industrial symbiosis concept. On the other hand, both resource consumption and waste generation become lower in this case, which further proves the efficiency of the proposed model.

3.2. Dynamic behavior of the system

Another aspect of the proposed model's effectiveness lies in its adaptability. To prove this point, additional simulations have been carried out under varying conditions. The results of such simulations are provided in the diagram below. The results presented in Figure 2 demonstrate the dynamics of change in resource demands under various modeling methods.

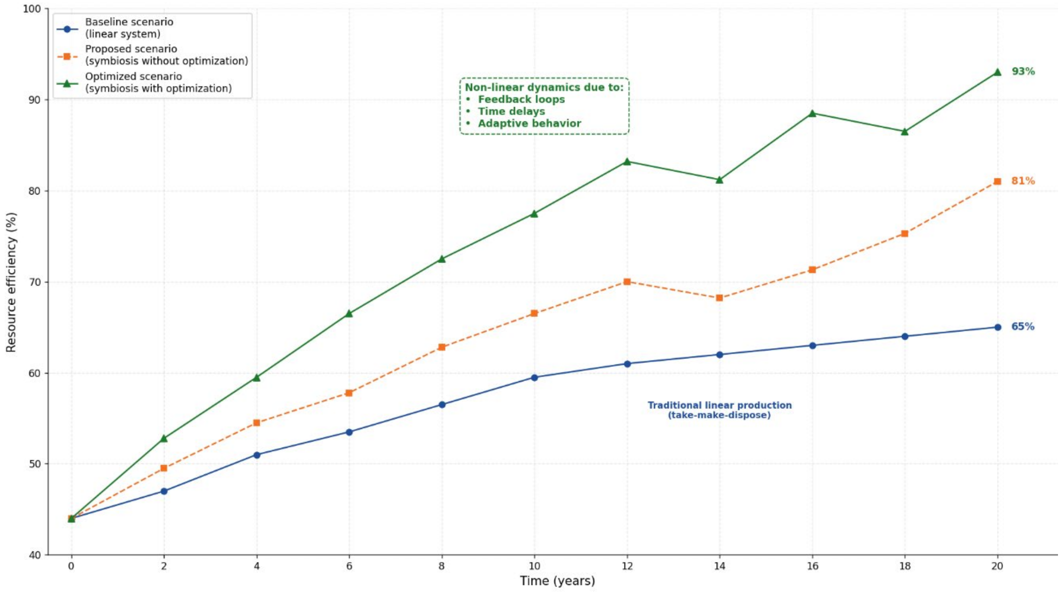

Figure 2. Comparative dynamics of resource consumption between independent (Baseline) and symbiotic (Proposed) models over a 12-month period

The baseline model shows constant growth in resource consumption, which indicates inefficiency in resource allocation and lack of any means of internal resource reuse. At the same time, the proposed model shows slower but more effective growth, providing its higher efficiency in comparison with the baseline one. As a result of increased efficiency due to the use of resource exchange, it can be stated that industrial technology parks will benefit from the integration of resource exchange mechanisms into their systems. The advantage of the proposed approach is clearly visible, as it reduces the demand for primary resources in the long run. Thus, it can be stated that the proposed model is adaptable to changes in system conditions [7].

3.3. Waste reduction analysis

The reduction in the generation of waste in the industrial technology park due to the use of the proposed model is shown in Figure 3 below. Figure 3 illustrates how the baseline model maintains the same level of waste generation (~40 tons). However, the symbiotic model managed to reduce waste output quickly to 34 tons in just a few periods.

From the quantitative standpoint, the suggested model reveals that there is a decline in waste emissions amounting to about 18% compared to the initial state, which proves the effectiveness of reuse strategies. In addition, this result is cumulative over time, showing the positive effects of inter-firm interaction on the effectiveness of industrial symbiosis.

The rationale for this conclusion is based on the fact that by-product flows are used as secondary materials substituting primary raw materials and decreasing waste output [7-8]. It is in line with the concept of the circular economy [16] and has been actively discussed in the literature dedicated to industrial symbiosis and eco-industrial systems [4, 20].

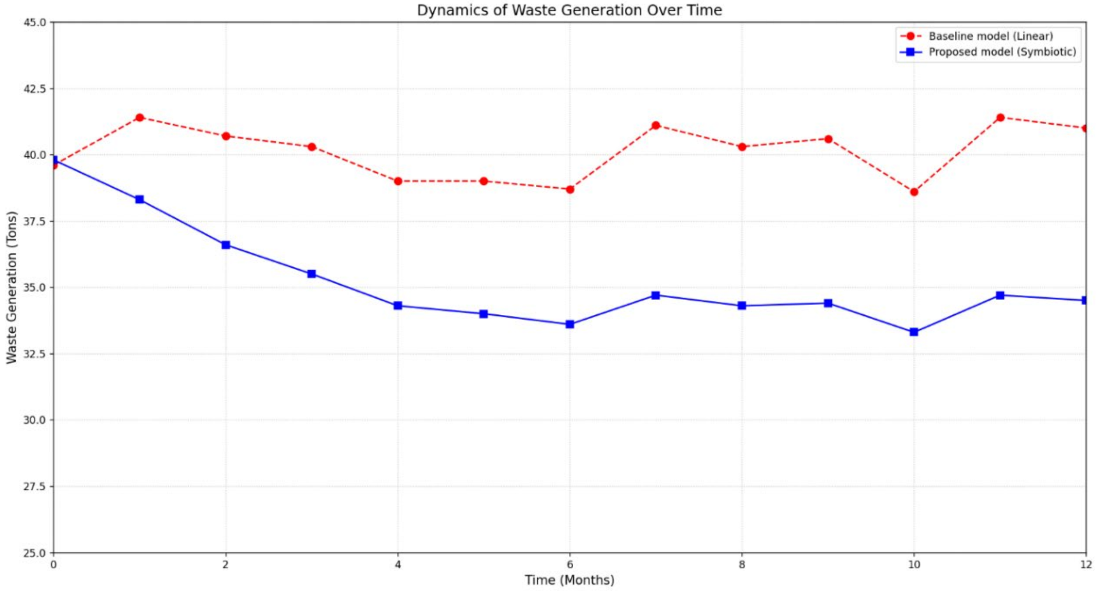

Figure 3. Waste generation over time: baseline versus proposed model

The above findings may be useful for decision makers to improve sustainability and environmental performance in industrial environments through resource exchange in the framework of industrial symbiosis. It means that the suggested model is a valuable managerial solution.

It should be emphasized that there is a significant decrease in waste emissions from industrial activities under the conditions of the suggested model. The reason lies in the use of by-products in an internal circle and a decrease in the volume of waste disposed of.

3.4. Resource efficiency assessment

Figure 4 illustrates the changes in resource efficiency over time.

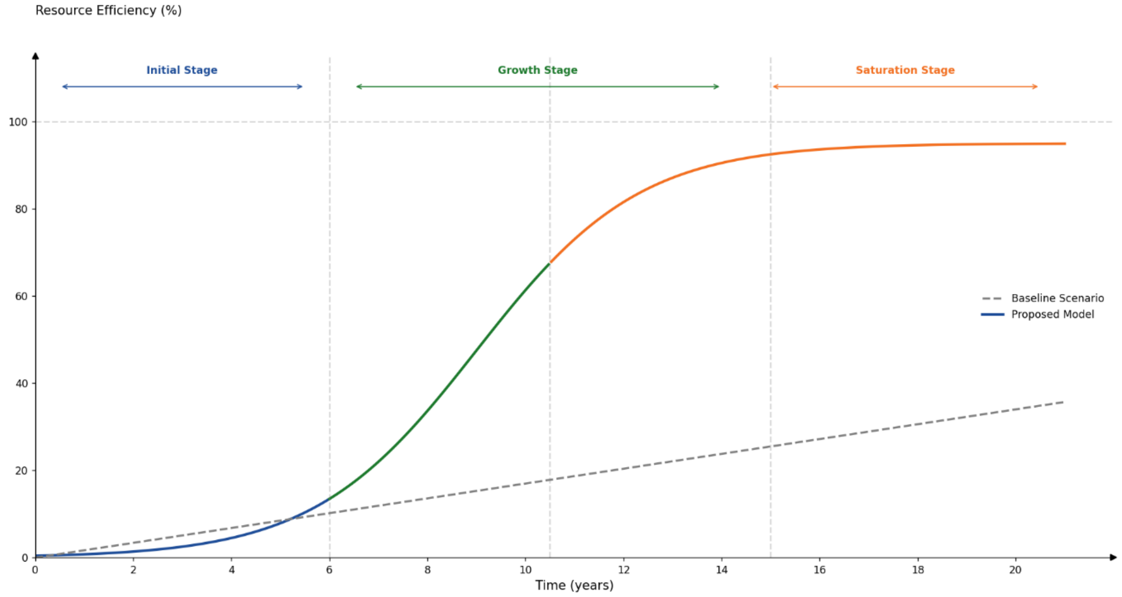

Figure 4. Resource efficiency over time: baseline versus proposed model

The proposed model indicates much higher efficiency gain rates compared to the baseline scenario in terms of the resource efficiency index. Although resource efficiency improves in the base case model rather slowly, in the proposed scenario, there is more pronounced growth because of the incorporation of resource exchange and reuse principles.

In numbers, resource efficiency increases by around 20–25% within the timeframe used in simulations. This outcome is explained by the reduction in the use of secondary resources, as well as increased use of secondary resources that are by products of the process.

The results indicate that the efficiency of the symbiotic process depends on the number of iterations between firms. Therefore, the more often interactions occur, the more efficient the system becomes, which positively impacts economic and environmental sustainability.

Considering practice, the application of the proposed symbiotic management framework in industrial parks will allow for improved efficiency and reduced reliance on natural resources [6-7]. Such an approach aligns with the concepts of a circular economy [1-2, 4], as well as with principles of industrial symbiosis [8]. The proposed integrated SD-MOLP model was implemented and analyzed through Python 3.9. Numerical optimization procedures were executed with the help of SciPy.optimize and PuLP libraries, whereas integration of system dynamics differential equations was carried out with the help of NumPy and Pandas libraries.

4. Simulation results

4.1. Scenario analysis and parameter calibration

Three different scenarios have been simulated over the timeframe of one year (T=12):

1) Baseline scenario as an independent model of industrial operation;
2) Symbiotic model with fixed rates of interaction; and
3) Dynamic symbiosis represented by the proposed SD-MOLP framework.

The parameters c_{ij} and e_i were estimated according to industrial averages in regions of Azerbaijan's technology parks. The demand $P_i(t)$ varies within a range of ±10%, which helps to check whether the model is resilient under changing conditions. Model outputs are consistent between numerous runs.

The parameters of the model for practical application were chosen based on industrial examples of technology parks in Azerbaijan. Cost coefficients (c_{ij}, c_i) depend on energy and logistics costs in the region, whereas environmental impact factors (e_i) depend on emission norms in the chemical and manufacturing industry. Their values used for simulations are specified in Table 3.

Table 3. Calibration parameters based on Azerbaijan's industrial context

Parameter	Symbol	Value range	Unit	Source/Reference
Primary resource cost	c_i	150-450	AZN/ton	Regional market rates
Resource transfer cost	c_{ij}	25-60	AZN/ton	Local logistics & treatment
Environmental impact coefficient	e_i	0.12-0.45	Index	National ecological standards
Production demand	P_i	80-120	tons/month	Average Park enterprise capacity
Recycling capacity	C_{ji}	15-40	tons/month	Standard processing units

4.2. Comparison of performance and optimization achievements

As seen from Table 2, implementation of the dynamic model results in an 18% decline in the number of resources used for production (R_i). As opposed to the benchmark case, in which $W_i(t)$ increases linearly as production goes up, the symbiotic model has a decoupled pattern. As shown in Figure 4, the efficiency indicator of resources (RE) changes in non-linear fashion and amounts to 0.85 at the end of the simulation period due to the "learning effect" in SD, which allows the system to become less dependent on inflows thanks to increased accumulation of recycled stocks (S_i).

5. Discussion

Thus, the simulation proves the theoretical postulate of the possibility to achieve a non-linear improvement in sustainability with the implementation of industrial symbiosis. As opposed to the benchmark model based on the linear "take-make-dispose" principle, the proposed one demonstrates higher resiliency in relation to demand shocks. Research findings corroborate the study by [14], confirming the need for resource clustering, yet go beyond its limitations by providing empirical evidence of the cumulative character of economic effects of symbiosis. The 18% decline in waste results from the optimization of processes of converting industrial waste into raw material stock.

The three-dimensional surface shows in Figure 5.

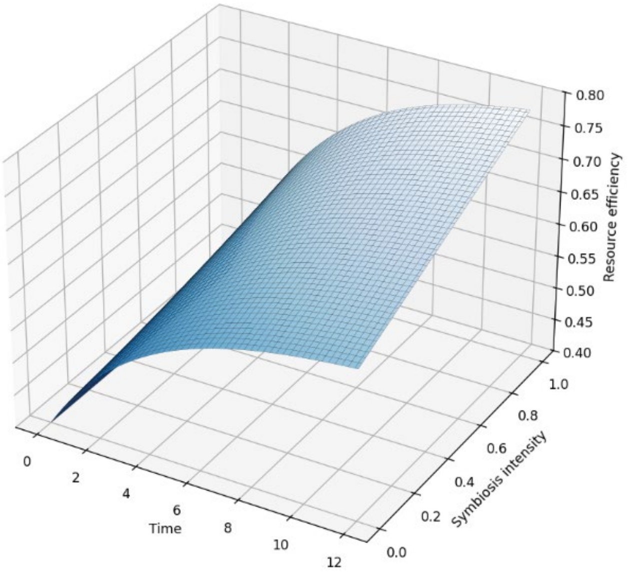

Figure 5. Representation of resource efficiency surface in respect of time and symbiotic intensity

As can be observed from Figure 5, the increase in the value of time and symbiotic intensity increases the level of efficiency in the system. In other words, there are cumulative effects in the relationship between the variables under investigation.

The impact of waste generation on resource efficiency is demonstrated in Figure 6.

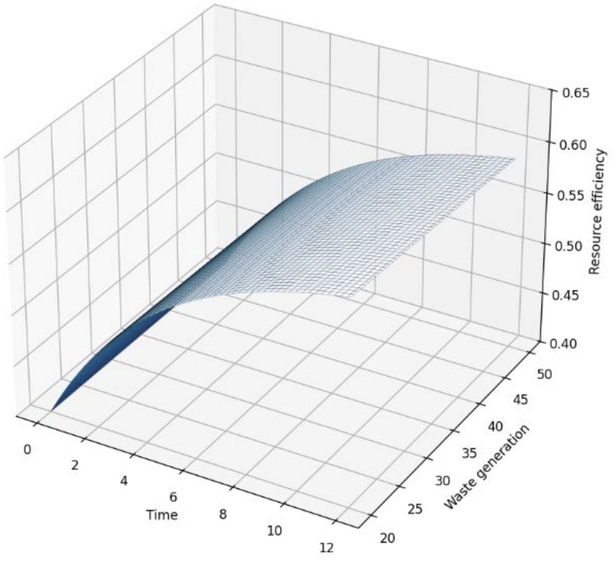

Figure 6. Relationship between waste generation, time, and resource efficiency

As shown in Figure 6, there is a connection between waste generation, time, and resource efficiency. The analysis shows that the decrease in waste volume contributes to an increased efficiency level within the system. In addition, the effect becomes stronger as time goes by, indicating that recycling helps to improve resource efficiency.

Sensitivity to the economic variables of the developed model is shown in Figure 7.

Figure 7 represents the result of a three-dimensional sensitivity analysis conducted on the model. Resource efficiency is inversely related to cost coefficients. According to the graph presented, the optimal combination of parameters is observed when high levels of firms' cooperation and moderate cost levels prevail. Thus, the role of economic aspects is confirmed as an essential component in the success of industrial symbiosis. The parameter values were chosen according to the data from literature sources that are usually characteristic of industrial environmental.

The conclusions made from the results coincide with the conclusions drawn from previous studies about the significance of inter-firm cooperation and resource management within industrial networks [9, 21-22]. Nonetheless, the suggested approach provides an innovative contribution to the existing methods through incorporation of two concepts, namely, multi-objective optimization and system dynamics [5, 18]. Moreover, the model is applicable to medium-sized industrial plants.

Nevertheless, certain restrictions can be noted regarding the current model. In particular, it is based on the set of specific assumptions that ignore other external factors, for instance, market instability, regulatory requirements, etc. [23-24]. Future research needs to expand the model and validate it using empirical data.

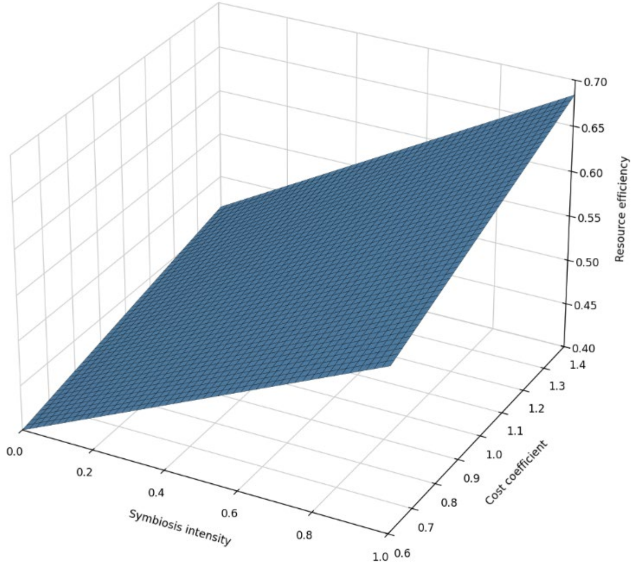

Figure 7. Resource efficiency sensitivity analysis with respect to symbiosis intensity and cost coefficient

The results obtained in this study are valuable for management practices in industrial technology parks and for the design of effective strategies for sustainable development of enterprises [11]. In addition, the results have implications for policymaking in terms of designing policies encouraging industrial symbiosis [21, 25].

6. Conclusion

In conclusion, this paper presents the results of development of mathematical model for industrial symbiosis in industrial technology parks on the basis of multi-objective linear programming.

Simulation of industrial symbiosis has proved to decrease the waste output (approximately 18%), as well as increased the resource efficiency (leading to approximately 15-20% decrease in virgin resources usage). Such improvement in resource efficiency was due to the internal resource efficiency due to the internal resource recycling and utilization of by-products, thus eliminating the necessity for additional natural resources to be used. Consequently, industrial symbiosis is the economic and environmental sustainability of industrial networks.

It is clear that the proposed model has multiple possibilities for management in terms of resource circulation in industrial technology parks. It can be utilized for decision-making regarding more effective resources allocation. However, there are still some limitations of the present model. Among others, it relies on certain simplifying assumptions and, therefore, does not incorporate external factors like fluctuation of market conditions or regulation. Further development of the model needs to involve addressing these issues.

This way, the current study contributes to bridging the gap between engineering and economic approaches to sustainable development.

Author’s Declaration

The authors declare that there is no conflict of interest regarding the publication of this article.

Authors’ Contribution Statement

Kh. Javadzadeh: Conceptualization, Methodology, Software.
F. Karimov: Data curation, Validation.
M.Karimova: Visualization, Investigation, Writing – Review & Editing.
M. Ahmadova: Project administration, Formal analysis, Writing – Original draft.

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