Modeling Material and Energy Flow in an Eco-industrial Park using Discrete Event Simulation

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Abstract. In recent times, a specific number of eco-industrial parks have emerged as a viable solution to address the escalating environmental challenges. Within these industrial parks, factories engage in mutual interaction through the flow of materials and energy. By modeling the material and energy flow within an eco-industrial park, we gain a comprehensive understanding of how resources circulate. This understanding not only provides strategic insights but also enables the identification of optimization opportunities, fostering more efficient resource utilization, waste reduction, and significant cost savings. Therefore, this research focuses on modeling the material and energy flow in the park using the discrete event simulation technique. We will provide a detailed explanation of our modeling approach, outlining how we employ this method to optimize resource usage, reduce waste, and minimize the environmental impact of industrial activities within the park. As part of our research, we have also developed a simple virtual eco-industrial park example to validate and demonstrate the effectiveness of our modeling approach. This practical illustration will serve to showcase the real-world applicability and benefits of our research in creating more sustainable and efficient eco-industrial parks.

Introduction

In response to the increasing global environmental concerns, eco-industrial park (EIP) has emerged as a proactive and sustainable solution.

EIPs are communities of manufacturing and service businesses collaborating to enhance environmental and economic performance through effective management of resources like energy, water, and materials. This collaborative approach seeks collective benefits greater than individual optimizations [1]. The concept of EIPs has recently captured significant interest from both industry and academic research communities, much of the focus has been on the planning and design stages, with limited attention to operational parks [2-5]. Boix et al. provide a comprehensive literature review on the optimization methods applied to the design of EIP [6]. As of 2011, there were over 20,000 operational industrial parks globally [7], offering substantial opportunities for material, energy, and waste savings. However, research on operational parks has been limited, often targeting specific environmental issues rather than providing comprehensive analyses for optimization. For instance, one study utilized a Monte Carlo model to simulate wastewater treatments in an industrial park in China, focusing on reducing pollution [8].

This paper aims to bridge this gap by employing modeling and simulation techniques to thoroughly investigate an operational industrial park. By employing modeling techniques, we can comprehensively analyze the intricate interactions and processes within the park. The central activity in an EIP revolves around the physical exchange of materials, energy, and services. Efficiently managing the flow of energy and materials is a cornerstone of any industrial park's operations. Prior to efficient management, the analysis and modeling of material and energy flow are essential. Consequently, this article places its primary focus on the simulation and modeling of energy and material flow within existing industrial parks, employing discrete event simulation method (DES).

Widely utilized in modeling, DES enables the study of systems that are discrete, dynamic, and stochastic [9]. It facilitates the simulation and understanding of how materials and energy traverse the system, providing valuable insights into resource management, waste reduction, and energy efficiency. A detailed explanation of our modeling approach will be provided, and a simple hypothetical park will be used to demonstrate the effectiveness of our modeling techniques.

The paper is structured as follows: a brief conceptual model is described in Section 1 while a more detailed formal model of material and energy flow are addressed in Section 2 and 3 respectively. The implementation and application of the simulation model are introduced in Section 4. The paper is concluded in the last section.

1 Conceptual Model of Material and Energy Flow in EIP

1.1 Eco-industrial Park

In EIPs, common components typically include the factory infrastructure, material flow systems, and energy flow systems. These components are essential for the functioning of the park and its sustainable operations. Figure 1 illustrates a simplified EIP where multiple factories coexist. Suppliers from outside the EIP provide raw materials, and customers from outside the EIP consume the final products manufactured within the park. Instead of solely relying on externally purchased raw materials, the factories within the EIP promote resource synergy by using outputs from neighboring factories as valuable raw materials.

Moreover, in pursuit of sustainable waste management, the EIP adopts waste-to-energy (WTE) technology instead of depositing waste in landfills.

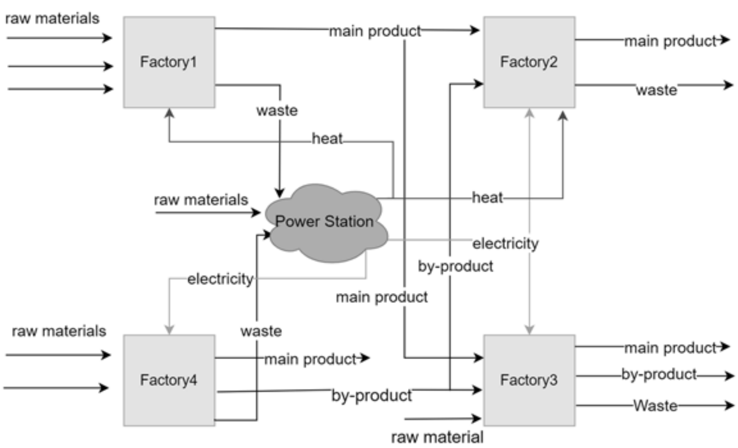

Figure 1: An EIP example.

Moreover, in pursuit of sustainable waste management, the EIP adopts waste-to-energy (WTE) technology instead of depositing waste in landfills.

This process recovers energy from waste sources in the form of heat, electricity, or transport fuels [10], complemented by a dedicated power plant within the park. This integrated approach minimizes environmental impact and provides a valuable energy source for the park's factories, promoting eco-friendly solutions and reducing reliance on external energy sources. Notably, in many cases, WTE plants are combined heat and power (CHP) producers [11]. In addition to WTE initiatives, the EIP enhances energy efficiency by incorporating CHP plants, known for simultaneously producing electricity and useful heat from a single fuel source. Unlike traditional power plants, CHP plants capture and utilize waste heat for heating and cooling applications, optimizing energy utilization.

1.2 Material and Energy flow in an EIP

From the perspective of each factory, materials can be categorized into two aspects: input materials and output materials. Input materials encompass not only the raw materials acquired from external suppliers but also the innovative utilization of by-products and waste generated within one factory, fostering a symbiotic relationship with another.

On the output side, factories yield main products that form the core of their operations, accompanied by valuable by-products and, inevitably, waste materials. In an industrial park, energy operates in two essential forms: electricity and heat. These dual components play a crucial role in powering various processes and activities within the industrial complex.

Material and energy flow refers to the movement, transfer, or transition of materials and energy within a system or process. In the context of Industrial Park, the material flow contains the exchange of materials between factories and within a single factory. Between factories, material flow could be materials transition from the output storage of one factory to the input storage of another. Within a factory, materials move from the input storage to the machines for processing. Once processed, the resulting output materials are routed to the output storage area, awaiting delivery to their respective customers.

When considering energy flow within the context of an industrial park, two distinct types can be identified. The first type involves energy carried along with material flow. For instance, when an output material possesses a higher temperature and another factory within the park requires specific temperature conditions for its inputs. The second type of energy flow pertains to the energy generated by the power plant within the park. The energy produced by CHP is consumed by the various factories and members operating within the industrial park. It plays a crucial role in supporting the energy needs of the park's internal processes and activities.

Material and energy flow control refers to the management, regulation, and optimization of the movement of materials and energy within EIP. Material and energy flow control encompasses decision-making at various stages of material and energy flow, addressing questions of what, where, when, and how materials and energy move within a system.

Typical decision-making aspects in material and energy flow control include:

- material and energy dispatching
- supplier selection
- alternative material choice
- inventory management.

These decisions are critical in optimizing the efficiency, sustainability, and cost-effectiveness of material and energy utilization within industrial processes.

2 Formal Model of Material Flows

2.1 Factory

Factories or industrial facilities are common elements within EIPs, and they can be integrated into an input-output model. Input-output modelling, having the advantage of tracing all primary inputs, wastes, by-products, and main product flows of a production unit, is an appropriate tool for designing industrial symbiosis networks [12].

Input and Output. To ensure the production of high-quality products that meet user requirements, factories often rely on specific production recipes [12]. These recipes are represented by input ratios, which indicate the quantity of raw materials needed to produce one unit of the main product. However, due to uncertainties in the production process or variations in raw material quality, these input ratios can exhibit stochastic behavior.

Additionally, factories may have multiple options for each input. Equation (1) illustrates a scenario where a factory has three inputs, and for the first input, there are two alternative materials to choose from. The input ratio is denoted as '*r*'.

$$InputAmount = productAmount \times [[r_{1a}, r_{1b}][r_{2a}][r_{3a}, r_{3b}, r_{3c}]] \quad (1)$$

Throughout the production process, input materials undergo a transformation, resulting in the generation of the main product, by-products, and waste materials. The output from each factory can be mathematically represented using the formula (2):

$$outputAmount = productAmount \times [1\ w_1\ w_2\ w_3]^T \quad (2)$$

where the vector '*w*' represents the output ratios. These ratios specify the quantities of by-products or waste materials produced in conjunction with one unit of the primary product. Given the intricate nature of the production process, it is important to recognize that numerous uncertain factors come into play. Furthermore, occasional, random changes in output ratios may occur because of advancements in production technology.

Inventory and production process. Input and output materials are typically stored within the factory's warehouse, with each type of material having its dedicated inventory. Inventory management involves defining safety levels (L_s) and target levels (L_t) for each type of material. The purpose of these levels is twofold:

1) To prevent production disruptions caused by a shortage of raw materials, the factory initiates the purchase of raw materials when the current inventory level (l) reaches the safety level (L_s), with the aim of restoring it to the target level (L_t).
2) To prevent overproduction, if the inventory of the primary product reaches the target level (L_t), production within the factory is halted. Additionally, if the quantity of waste exceeds the available inventory capacity, any excess material is disposed of in a landfill.

In our production setup, each factory has a maximum production capacity denoted as C_m, representing the highest achievable monthly or yearly production volume. Factories typically operate at a target capacity level, denoted as C_t, where C_t is less than or equal to C_m. The actual capacity, denoted as C, may vary due to factors such as machine breakdowns, worker absences, and other operational fluctuations.

Specifically, the actual capacity can change as follows: $C = C + \Delta$, where Δ represents either a capacity loss or gain. Production planning follows a level strategy, assuming customer demands (d) equal to the target capacity ($d = C_t$). A production plan specifies the quantity of products to be completed on a weekly or monthly basis, which then generates a material requirement plan divided into daily or shift-based schedules. These schedules are transmitted to the shop floor as manufacturing orders. The shop floor accepts and schedules items within the manufacturing orders for processing. Individual machines are consolidated into a single machine, and the processing time (p) for one item is calculated as $p = 1/C$. If raw materials for a particular item are insufficient, the item enters a queue following the "first in, first out" (FIFO) rule, ensuring items are processed in the order they arrived.

2.2 Material Flow

Material flows are governed by specific protocols that dictate when and how materials are moved within the system. Each type of material adheres to its own set of rules and procedures. This section outlines three types of material flow protocols: pushing, purchasing, and ordering. Purchasing and ordering fall under pulling protocols, involving requesting materials as needed, while pushing protocols supply materials without direct requests.

Before detailing material flow protocols, let's introduce the batch concept, which is widely employed by manufacturers to optimize production. In our model, batches take various forms. Production batches, defined in the production planning system, are subdivided into smaller process batches (manufacturing orders) on shop floors, each containing multiple jobs. Suppliers deliver products in delivery batches, while customers order in order/purchase batches, typically multiples of the delivery batch.

Pushing. In this protocol, the produced material is directly delivered to customers as soon as a delivery batch is assembled, as depicted in Figure 2. When one process batch is produced in one factory, the output inventories of this factory will be updated. Push events happen regularly in the factory to check if the amount of output inventories is enough to form a delivery batch. If sufficient material is available, it's transported to the chosen customer. However, if no customers can accept the delivery batch due to capacity constraints, and the supplier's output inventory reaches its limit, excess material may be discarded if it's considered waste.

Purchasing and Ordering.

Both purchasing and ordering are fundamental pulling protocols utilized in different manufacturing contexts. Purchasing is typically employed in make-to-stock factories, where materials are stored in warehouses until customers make purchases.

On the other hand, ordering is prevalent in make-to-order factories, where customers initiate orders that suppliers then produce and deliver.

In both protocols, regular events are triggered based on inventory levels. When the inventory reaches a safety level, actions are taken to restore it to the target level. Supplier selection policies are often employed to optimize decision-making when multiple suppliers are available.

The order details are then transmitted to the selected supplier's planning system, and the production process begins. Ultimately, orders may be split into process batches, and delivery occurs once the required quantity is fully produced.

The choice of protocol depends on the type of materials involved. For instance, waste materials are typically not subject to purchase, and by-products cannot be ordered.

The applicable protocols between external suppliers, customers, and factories are outlined in Table 1 below.

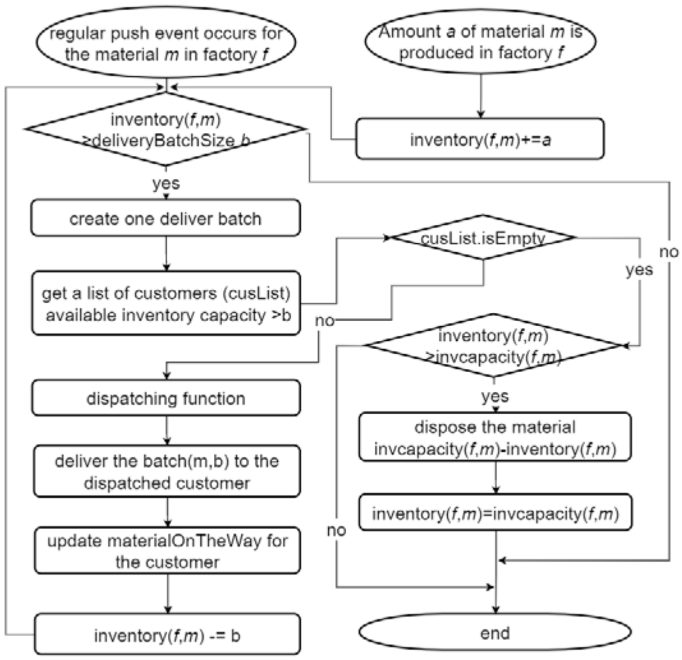

Figure 2: Pushing protocol of material flows.

Material	From	To	Protocols
Products	Supplier	Factory	Purchasing
Products	Factory	Customer	Purchasing /Ordering
By-products	Factory	Customer	Purchasing
Waste	Factory	Disposal	pushing
Products	Factory	Factory	Purchasing /Ordering /Pushing
By-products	Factory	Factory	Purchasing /Pushing
Waste	Factory	Factory	Pushing

Table 1: Possible protocols between suppliers, factories, and customers.

3 Formal Model of Energy Flow in an EIP

In our study, we focus on energy flow which concerns the consumption of energy generated by the CHP system by the factories located within the park. It illustrates how the energy produced by the CHP system is efficiently utilized by the diverse factories operating within the park. This energy flow serves as the central and indispensable component of the park's overall energy dynamics. In the following section, we will provide an in-depth explanation of our approach to modeling this specific energy flow which can be broken down into three fundamental components: power station, power consumption, and power scheduling. We will elaborate on our approach from the perspective of each of these components.

3.1 Power Station

The CHP power station element is modeled within a formal factory framework, distinguished primarily by its output type. Unlike traditional factories producing physical materials, the power station generates both heat and electricity. Its main input material comprises waste materials generated by other factories within the park. In instances where these waste materials are insufficient, the model seamlessly integrates external raw materials like coal to maintain uninterrupted operations. Additionally, our model includes parameters to configure the total number of available power generators, and the capacity allocated to each individual generator within the power station.

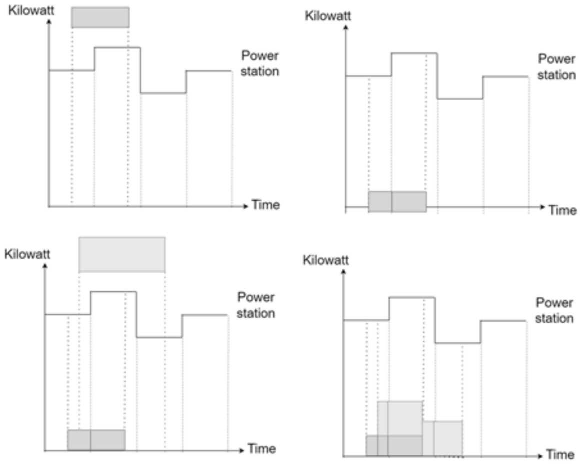

Figure 3: Area cutting algorithm.

3.2 Power Consumption

Each factory's power requirement is closely tied to its production needs and is represented as a tuple (factory, start time, end time, requested power). This structured format signifies that within the specified time frame, the factory requires a specific supply of power, as quantified by the requested power value. In our study, power consumption is managed through the application of an area cutting algorithm, as depicted in Figure 3.

This algorithm operates by representing each power request as a rectangular area on a graph. The length of the rectangle corresponds to the duration of the power request, which is calculated based on its start and end times. Meanwhile, the width of the rectangle represents the amount of power requested. Concurrently, the power production of the station is graphically depicted as an upper black line over discrete time periods.

Upon initiation of a power request, the algorithm compares its time frame with the periods of power production at the station. This comparison determines whether the request falls within a single period or spans across multiple periods. To enhance accuracy, the periods of power production are further divided into smaller segments based on the start and end times of the request. For each power request, the algorithm updates the remaining power for the relevant segments from the start time to the end time of the request. This ensures precise tracking of power utilization during specific time intervals.

Subsequent power requests undergo a similar process, where their time frames are compared with refined station periods from previous requests, and remaining power is updated accordingly.

3.3 Power Scheduling

To optimize energy utilization, the implementation of power scheduling is a key strategy. This strategic approach encompasses determining the quantity of power to be generated and strategically coordinating how individuals or organizations utilize this power.

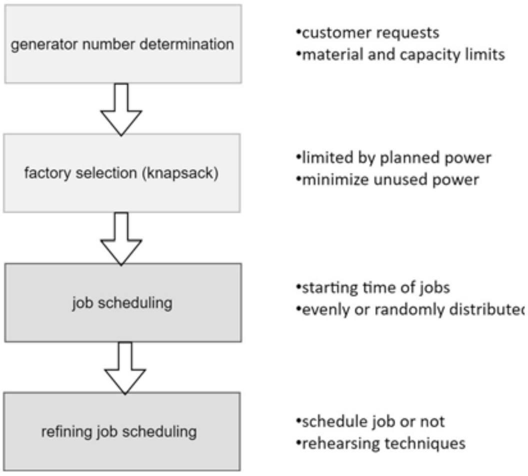

Figure 4: Energy scheduling strategy.

Our initial energy management strategy, as depicted in Figure 4, comprises several steps. Firstly, the number of generators to be activated is determined. Factories develop production plans over a specified time frame, typically a week or a month, while simultaneously creating power usage plans. These plans are transmitted to the center controller, which then calculates energy requests based on them, aggregating all requirements. The center controller formulates a power production plan, considering energy requests and the power station's capacity, including input material constraints and generator availability. This plan specifies how many generators should be activated for the upcoming period.

Next, we select users in a way that minimizes unused power, similar to solving a knapsack problem with a limit on planned power. Following factory selection, we proceed to schedule jobs, determining the start time for each. This decision can be made by either evenly distributing the starting times or assigning them randomly throughout the planned period. The final step in this energy scheduling plan focuses on improving the schedule derived from earlier steps, a rehearsing technique is used here.

A virtual power station is set up to check and improve the existing schedule. In this phase, jobs that are already scheduled request power according to the initial schedule. If there isn't enough power available to meet a job's power requirements, that specific job is excluded from the pre-determined scheduling.

4 Implementation and Application

In this section, we have used a virtual and simplified industrial park as an illustrative example to demonstrate our modeling approach. We made this choice due to our constraints in obtaining data from a specific real-world industrial park. We utilized simulation software, specifically AnyLogic, to create this example, which is depicted in Figure 5.

In this example, Factories 1 and 5 serve as primary manufacturing facilities within the EIP, while the upstream two factories act as suppliers of raw materials to support the main factories. Factories 3 and 4 are responsible for managing the waste generated by the main factories. All waste from these factories is directed to a central power station within the park, which generates energy to support the park's members.

To provide context for this example, several assumptions were made: Material flows between factories follow a 'push' protocol. When multiple input sources are available, materials from upstream factories take precedence over those from external suppliers. Factories acquire materials from external suppliers through a purchasing process rather than traditional ordering. The target inventory level equals the inventory capacity. The safety inventory level is maintained at a quantity equivalent to a 30-day supply of throughputs.

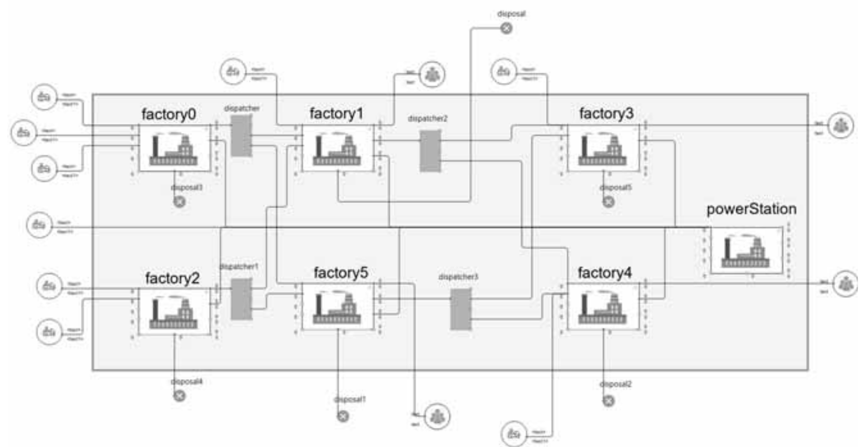

Figure 5: Instance of an EIP Created Using AnyLogic.

It's worth noting that while the power station utilizes recycled waste to generate energy, its output may not always meet the energy needs of all park members.

4.1 Experiment of Material Flow

The experiment on material flow aimed to establish an efficient dispatching policy for scenarios where a single material is shared among multiple customer factories, common in industrial symbiosis networks.

The application employed various dispatching policies:

(1) Random dispatching.

(2) Directing materials to factories with the highest available inventory.

(3) Allocating materials based on the ratio of available inventory to capacity.

(4) Assigning materials to factories maximizing main product output.

(5) Allocating materials to minimize main product output.

(6-9) Allocation based on maximum requirements lookahead up to three planning periods.

The KPIs used to evaluate the different policies are divided into three categories: total waste disposal, total sales, and external requirements, which denote economic and environmental objectives. "Total waste disposal" refers to waste disposal across all factories within the park. Specifically, "Total Sale 1" represents the main product amounts that can be sold by factories 1 and 5, while "Total Sale 2" represents the main product outputs of factories 3 and 4. "External requirements" refer to the number of raw materials purchased by factories 1, 3, and 4 from external suppliers. The simulation results of these evaluations are presented in Figure 6.

The simulation results emphasize the effectiveness of scenario 6, "maximal requirement lookahead 0," in minimizing waste disposal. Prioritizing factories with high demand for waste material reduces excess disposal. Conversely, scenario 2, the "available inventory-based rule," leads to higher waste disposal due to surplus allocation to plants with substantial available inventory. Regarding "total sales 1" and "total sales 2," scenario 3, the "available inventory ratio-based rule," proves most effective. This suggests that downstream factories can meet input material requirements, reducing production stoppages, enhancing throughput, and increasing sales. Scenario 4 performs worst for the total external requirement KPI.

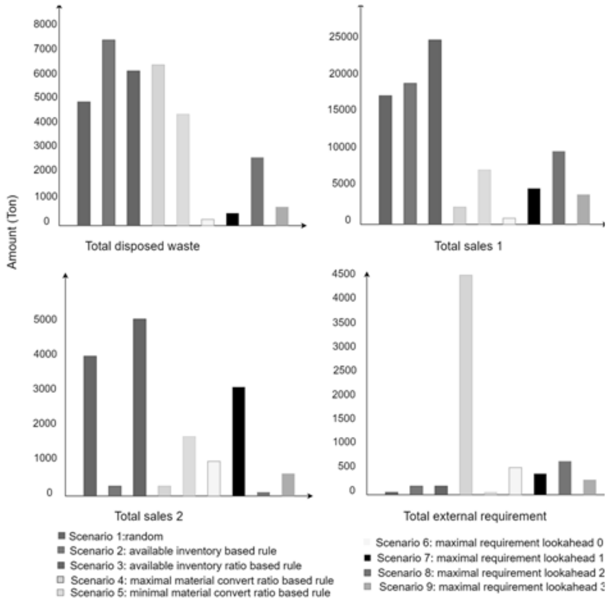

Figure 6: Experiment results of the material flow control.

This is likely due to consistently directing waste materials to the factory with the highest material transformation ratio, forcing other factories to purchase external materials for production. Overall, the simulation provides valuable insights into how different policies impact waste disposal and sales performance.

4.2 Experiment of Energy Flow

In this experiment, the simulation duration spans 10 weeks, with each planning period structured as a one-week timeframe, totaling 10 planning periods. The objective was to optimize energy utilization in each planning period. Table 2 presents the outcomes of the experiment for each planning period. It includes details such as the selected factories, indicating which factories were chosen to utilize the energy produced by the internal power station during the respective period.

Plan period	Selected factories	Scheduled jobs ratio	Energy utilization
1	0,1,4,5	0.81	0.66
2	1,3,5	0.72	0.62
3	0,1,2,5	0.77	0.69
4	2,5	0.69	0.68
5	0,1,2,4,5,	0.78	0.75
6	2,4,5	0.59	0.65
7	2,4	0.80	0.67
8	1,2,5	0.66	0.63
9	0,1,2,3,4,5,	0.82	0.79
10	3,5	0.77	0.79

Table 2: Experiment results in each period.

The scheduled jobs ratio represents the proportion of scheduled jobs compared to the total planned jobs across all factories. Additionally, the energy utilization ratio denotes the percentage of energy consumed by the scheduled jobs relative to the total energy generated by the power station.

5 Conclusion

In response to escalating environmental concerns, EIPs have emerged as innovative and sustainable solutions for industrial development. Given this context, effective management becomes imperative for these industrial parks. To pave the way for such management, a comprehensive understanding of the dynamic interactions and processes within EIPs is crucial. Material and energy flows are the primary representations of interactions among factories. Consequently, this paper employs discrete event simulation techniques to model the intricate material and energy flows within the park, providing a detailed account of our model's construction.

Through our modeling efforts, we aim to optimize the allocation and distribution of resources within these parks, with a specific emphasis on waste reduction and the maximization of energy utilization. The outcomes of our study can provide practical guidance for eco-industrial park management and policy development, ultimately contributing to a more sustainable and environmentally responsible industrial landscape.

While our primary emphasis remains on existing operational parks, it is worth noting that our modeling approach can also be adapted to the planning phase of industrial parks, providing a means to evaluate the advantages of establishing industrial symbiosis.

Despite our comprehensive approach, it's important to note that, in this study, our management efforts are limited to a simple energy schedule. A more refined strategy is required. Therefore, our future research will specifically concentrate on energy scheduling, aiming to develop strategies that optimize energy utilization through production scheduling.

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