Development of an Evaluation Method for Simulation Results in the Context of Industrial Symbiosis: A Target System for Increasing Resource Efficiency and Resilience

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Abstract. The importance of energy and resource efficiency has increased significantly in recent years. Industrial symbiosis (IS) increases resource efficiency, among other things, with the help of energy and material exchange relationships between companies. In addition to efficiency, resilience is also becoming increasingly important. IS can contribute to avoiding production interruptions through a broad network of alternative relationships. The exchange relationships in an industrial cluster can be simulated. However, a standardised method for evaluating the simulation results is necessary in order to be able to compare different variants with each other. This article presents a target system that considers economic, ecological, symbiotic and resilient aspects. Different weightings of the target functions make it possible to set individual priorities. The method is demonstrated using an example with four companies and different simulation model variants.

Introduction

Recent years have impressively highlighted the importance of energy and resource efficiency. Industrial parks in particular can leverage potential through the application of industrial symbiosis (IS). IS describes a concept that increases resource efficiency through the exchange of water, energy, waste and by-products between companies, among other things [1], [2].

In addition to efficiency, resilience, i.e. the ability to respond to resource shortages, for example, is playing an increasingly important role for companies [3], [4]. In this respect, too, IS offers opportunities, on the one hand because not all material and energy requirements have to be covered externally – keyword: self-sufficiency – and on the other hand because, where applicable, the networking of companies provides alternatives to previous sources of supply or customers.

Currently, the design and operation of industrial parks are often not geared towards these internal exchange processes. The research project "Energy-efficient industrial cluster optimisation" (EnICO) aims to optimise energy and material exchange relationships in an industrial cluster using simulation. Simulation is used to determine overall optimal interaction relationships, taking into account various target functions.

This is based on a standardised method for evaluating the simulation results, which also takes into account different weighting preferences with regard to the target functions on the part of the users. To this end, a target system has been developed that combines several target functions and makes it possible to set different evaluation priorities.

1 State of Research

An industrial cluster is a collection of several neighbouring companies that engage in exchange relationships. This fulfils the basic requirement of spatial proximity, which Chertow identifies as an essential prerequisite for industrial symbiosis (IS), even though internal company and supraregional symbioses are now also the subject of research [1].

In the literature, such clusters are also referred to as Eco Industrial Parks (EIP) [1], [5]. One of the best-known examples is the EIP in Kalundborg, Denmark [6].

MAIWALD ET AL. have developed a model library in the SimulationX simulation environment (www.esi-group.com/products/simulationx) that enables the dynamic simulation of an EIP [7]. Automated evaluation or optimisation is not yet planned, but is considered by the authors to be an important further development of their simulation.

There are numerous key performance indicator systems for EIPs in the literature. These are often classified according to economic, ecological and social key performance indicator types [8].

VALENZUELA-VENEGAS ET AL. describe an important key performance indicator for the topic of resilience. This so-called resilience indicator has a value range of [0, 1], where the value 1 corresponds to the best possible resilience and the value 0 corresponds to no resilience. It is composed of the Network Connectivity Index NCI and the Flows Adaptability Index ϕ [9]:

$$\text{Resilience Indicator} = \frac{1}{2} * NCI + \frac{1}{2} * \phi \qquad (1)$$

The Network Connectivity Index NCI of the industrial cluster considers the number of connections. For example, a company may have only one connection to another company or several connections to other companies. The more connections there are within the EIP, the higher the probability that, in the event of one company failing, there will be at least one other source of supply or purchase. The Flows Adaptability Index ϕ assesses the extent to which the lost resource flows can be compensated for if a company fails. This is because such a failure means that the company is no longer available as a buyer of its input products and an emitter of its output products. The proportion of non-compensable losses is determined for each company [9].

As the research project focuses less on social aspects, economic and ecological indicators in particular are incorporated into the assessment method. Due to its importance, the resilience indicator is also explicitly included.

2 Description of the Method

A standardised evaluation is necessary for the classification of simulation results. The steps underlying this article are presented below:

1. Selection of relevant indicators and conversion of these into suitable target functions.
2. Weighting of the target functions under different objectives.
3. Consideration of decision-maker preferences with regard to the weighting of these objectives.

The key figures are selected on the basis of a literature review and a comparison with the information available in the simulation model. Key figures with only limited significance are not taken into account in order to keep complexity to a minimum and thus increase traceability.

The result is a target system with six target functions:

- Z_1: Minimise connection costs
- Z_2: Minimise external electricity procurement
- Z_3: Minimise external heat procurement
- Z_4: Minimise external resource procurement
- Z_5: Maximise the proportion of symbiotic relationships
- Z_6: Maximise resilience indicator

The objective function Z_1 takes into account both the investment and the operating costs of a symbiotic relationship (e.g., district heating pipeline, truck transport), because not every theoretically possible connection is also economically viable.

The objective functions Z_2 to Z_4 address the requirement that, as far as possible, all electricity, heat and resources generated within an EIP should be reused internally. Z_5 also takes this into account by maximising the proportion of symbiotic relationships between individual companies.

The resilience indicator in Z_6 is based on the considerations of Valenzuela-Venegas et al. and has been adapted to the SimulationX environment [9].

	economic	ecological	symbiotic	resilient
Z_1	0.091	0.042	0.043	0.039
Z_2	0.187	0.172	0.098	0.093
Z_3	0.187	0.196	0.098	0.093
Z_4	0.442	0.456	0.098	0.093
Z_5	0.058	0.076	0.374	0.230
Z_6	0.035	0.058	0.289	0.452

Table 1: Weightings of the target functions among the various objectives.

In the second step, the weightings of the objective functions for different objectives (economic, ecological, symbiotic, resilient) are determined using the Analytic Hierarchy Process (AHP) [10]. The objective functions are compared in pairs in terms of their importance for the individual objectives. In total, the weightings (value range [0, 1]) for each objective add up to 1. This step was carried out as part of the project using findings from the literature review (see Table 1). In future, it is planned to involve companies in the evaluation in order to validate the results and adjust them if necessary.

Finally, the point allocation method is used to take the decision-maker's preference into account, i.e. in the final application, a decision can be made as to which weighting should be given to the individual objectives [11]. To do this, 100 points are distributed among the four objectives and a total weighting is calculated according to the objective preference.

3 Application of the Method

The procedure for applying the method is illustrated below using a simple and fictitious example. An industrial cluster with four companies is considered: a steel producer (I1_STEE), a combined heat and power plant (I2_CHP), a paper manufacturer (I3_PAMI) and a plastics manufacturer (I4_CHEM). Each company manufactures a main product, the production of which generates by-products.

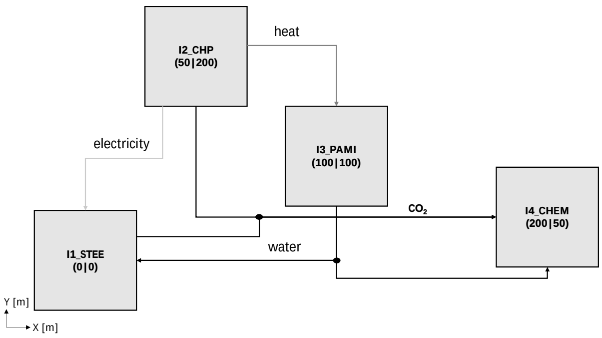

Figure 1: Schematic representation of the symbiotic exchange relationships between the companies (variants 1 and 2).

Figure **1** shows a schematic representation of the exchange relationships between the companies. The black connections represent material connections, red connections represent heat connections and yellow connections represent electricity connections.

Four simulation model variants (SV) of the simulation model are created, which differ in the type of their exchange relationships and are evaluated using the method presented:

- SV 1: Multiple symbiotic relationships for material, heat and electricity flows.
- SV 2: The symbiotic connections are analogous to variant 1, but supplemented by the consideration of losses.
- SV 3: All required energy and material quantities are sourced externally; there is no symbiotic exchange.
- SV 4: Basic structure analogous to variant 2, but water and electricity are sourced externally.

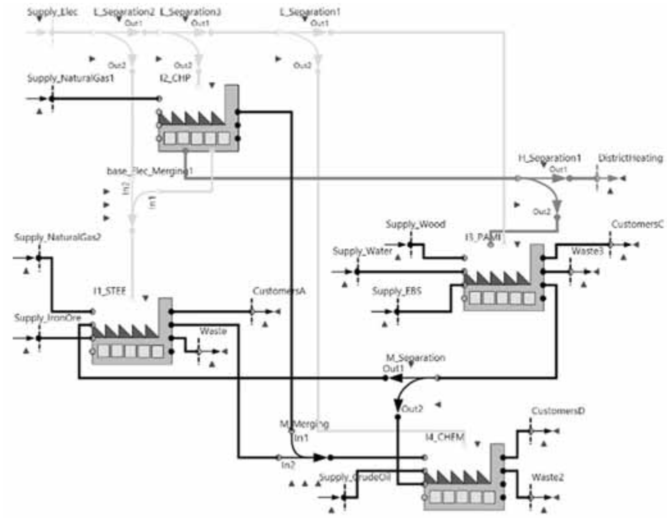

Figure 2: Complete simulation model SV 1.

Figure 2 shows the complete simulation model SV 1 with all exchange relationships taken into account. The simulation library by MAIWALD ET AL. is used, which has been expanded to include a loss component that enables, among other things, the consideration of transmission losses in district heating pipes [7].

Each variant of the simulation model is evaluated using this method. The weighting of the target functions according to Table 1 and the following decision-maker preferences are used: economic: 30; ecological: 30; symbiotic: 25; resilient: 15. These fictitious decision-maker preferences represent a balanced distribution with a slight focus on economic and ecological objectives.

The total utility values shown in Table 2 result in the following ranking of the simulation variants: $SV\,1 \succ SV\,2 \succ SV4 \succ SV\,3$.

This means that the total utility value of variant SV 1 exceeds the total utility value of all other variants and, with the selected weighting and decision-maker preference, represents the overall optimal solution. It should be noted that the slight differences between SV 1 and SV 2 are solely due to the consideration of transmission losses. These are very small in the example model and can therefore only be shown in the sixth decimal place. This is more of a theoretical distinction with little practical relevance, as losses are to be expected in any case in reality.

Overall, it is clear that simulation variants SV 3 and SV 4 are rated significantly lower. This is because the symbiosis potential is not fully exploited here.

SV 1	SV 2	SV 3	SV 4
0.211665	0.211662	-0.522877	-0.019082

Table 2: Total utility values of the simulation model variants (SV) of the scenarios.

4 Summary

The method presented here for evaluating simulation results in the context of industrial symbiosis makes it possible to systematically evaluate and compare simulation results. Users can weight different objectives according to their preferences. This enables the evaluation of selected manually created simulation model variants, as in section 3. However, a particular strength of the method is that it can also be used to evaluate numerous automatically created simulation model variants and can be used in the context of automated optimisation.

The next step is to check the weightings of the AHP (see section 2). Here, it is advisable to have the pair comparisons carried out by company representatives, for example, in order to obtain valid weightings for possible practical use. The method can then be used in the context of practice-oriented simulative optimisation.

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