ESProNet: A Model Library for the Dynamic Simulation of Industrial Symbiosis

Martin Maiwald, Linda Kosmol, Christoph Pieper, and Thorsten Schmidt

Abstract—**One approach to a more sustainable industry is the reuse of waste and by-products. In particular, the exchange of resources between companies and the reuse of energy are considered critical, as they are time-dependent and may require technical or organizational changes to the production system leading to new interdependencies between the companies. Simulation is a suitable tool for analyzing the dynamic behavior of production systems to identify and evaluate critical factors and risks with regard to compatibility or feasibility, necessary changes and their effects on the system. This paper presents a modeling and simulation approach for resource reuse and exchange in the context of industrial symbiosis. To distinguish the proposed method from related work, an overview of existing modeling and simulation approaches is presented. The suggested approach is based on the modeling language Modelica. A custom model library with reusable preconfigured model elements is developed to model and simulate different production systems and scenarios bottom-up and modularly and in order to investigate interactions between resource providers and consumers. The conceptual and mathematical development of the model components and their interaction principles are presented and demonstrated. Based on this, organizational interdependencies and their economic and ecological impacts can be analyzed.**

Index Terms—**Modelica-based modeling, dynamic simulation, sustainable manufacturing, industrial symbiosis.**

I. Introduction

Sustainable manufacturing currently seems to be one of the most challenging tasks in industry. An approach to a more sustainable industry is the reuse or exchange of waste and by-products within or between companies. The interfirm exchange of underutilized resources and sharing of utilities to create economic and environmental benefits for both parties is referred to as synergy within the concept of industrial symbiosis [1]. However, this transition entails risks from an organizational, economic and technical viewpoint. In particular, the reuse of energy (e.g. waste heat) and the exchange of resources between companies are considered critical as they may require technical or organizational changes in the production system (e.g. facility operation, new technologies) leading to interdependencies between plants or companies. Further challenges are the examination of feasibility, since the reusability of resources is determined by various factors (e.g. physical properties, temporal availability) and the evaluation of economic and ecological benefits due to different relevant aspects (e.g. disposal, transport).

Many computer-aided tools for industrial symbiosis are dedicated to input-output matching of resources [2]. However, this is limited to a rather static check of resource or company compatibility. The dynamics of supply and demand are particularly relevant for the exchange of resources, as storing and transporting them is either expensive or only possible in a limited way (e.g. waste heat). Computer-aided modeling and simulation are suitable for analyzing the dynamic behavior of production systems in order to identify and evaluate critical factors and risks with regard to compatibility or feasibility, necessary changes and effects on the system (e.g. temporary failure).

This paper presents a modeling and simulation approach for the reuse and exchange of resources in the context of industrial symbiosis that was developed within the research project ESProNet (Energy Simulation in Dynamic Production Networks). The project's objective is to provide a custom model library with reusable and preconfigured model elements for the simulation of different resource exchanges. Thus, the effect of changes and dynamics on interactions between technologies or organizations acting as resource providers or consumers or both can be investigated. ESProNet pursues a modular (object-oriented), bottom-up (technology-oriented), demand-based (pull-oriented) approach based on the modeling language Modelica. Since ecological and economic aspects of synergies depend on the organization (e.g. pricing) and technical implementation (e.g. technology), these can then be evaluated based on simulated scenarios.

The next section gives an overview of existing simulation approaches to distinguish the proposed approach from related work. Afterwards, our approach with its principles and assumptions as well as the development of the model elements with their interaction mechanisms is presented. Subsequently, the use of the developed modules for the simulation of a synergy is demonstrated. The paper finishes with a conclusion and an outlook.

II. Related Work: Simulation Review

Several modeling methods have been used for modeling and simulation of industrial symbiosis. The most common approaches are network theory, agent-based modeling, ontology-based modeling and system dynamics.

All these models represent the evolution of synergies in industrial parks, but differ in terms of level, scalability, objective and focus. Table I gives an overview of the different characteristics. The combination of the characteristics is exemplarily shown for network theory approaches in the form of a black line. The presented approach is highlighted in grey. The level describes the investigated system and implies how strongly elements are

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abstracted, e.g. at network level plants are often defined only with inputs and outputs, while at plant level existing processes or technologies are described within the plant. Scalability refers to whether only one level can be modeled and simulated or whether there is a hierarchy of model elements and model elements can be aggregated (bottom-up) or broken down (top-down). Since most simulations are research-oriented, their objective is to provide insights and explanations of how synergies arise or come to a halt, and which factors are relevant and influence each other. Some simulations have been built to support practitioners in decision-making about the implementation of a potential synergy by analyzing and evaluating potential real synergy scenarios in terms of feasibility and economics. Most models focus on economic (cost, savings, etc.) and environmental (emission, landfill etc.) aspects, while technical (quantities, operating mode, etc.) and social aspects (trust, contacts, etc.) are less important.

Simulations based on network theory operate on a high non-scalable level of abstraction modeling industrial ecosystems as directional [3] or non-directional networks [4] consisting of nodes and edges. While nodes represent plants or resources, edges represent synergies. The development of synergies is random or according to certain rules. Cause and effect relationships are investigated, following the principle that a failure of a node or edge leads to the failure of further nodes, since these are connected to each other. Hence, the relevance and (direct or indirect) dependence of nodes or edges for a system is determined. The development of synergies is simulated in one-year time steps.

TABLE I: CHARACTERISTICS OF MODELING AND SIMULATION APPROACHES FOR INDUSTRIAL SYMBIOSIS

Category	Characteristics				
Approach	Network Theory	Agent-Based	System Dynamics	Ontology-Based	Object-oriented
Level	Network / EIP	Industrial Plant	Process	Technology	
Scalability	None	Top down	Bottom up		
Objective	Research	Decision-Support			
Focus	Economic	Environmental	Technical	Social	Causation
Time	Discrete	Continuous			

The majority of simulations for industrial Symbiosis are agent-based. They represent networks, industrial plants or processes as interacting objects (agents) with individual behavior determined by objectives (high profit, low pollution, etc.) and properties (resource demand, willingness to cooperate, etc.). Though they are not scalable the approach used to model the agents respectively the systems behavior is bottom-up. These models are also primarily dedicated to research and investigate industrial symbiosis development patterns based on certain behavior. The behavior may be driven by various factors such as contract design [5], economic profit [6], social embeddedness [7], cooperation culture [8], environmental impact [9] etc. Some models additionally include environmental or market agents (e.g. resource agent, consumer agent). In this way, the influence of prices or supply and demand quantities of the market or the environment on synergies is analyzed. These models often focus on social and economic aspects considering ecological factors.

Models developed with a system dynamics approach ([10],[11]) tend to represent the park and plant level. These models are developed in a top-down manner, but they don't provide hierarchical model elements. System dynamics models tend to be more abstract than agent-based models as the objective is to analyze the system's structure. These models aim at understanding the evolutionary path of industrial symbiosis by describing logical relationships between variables (e.g. waste generation, waste stock) using causal chains and stock-flow models. These variables are usually of economic or technical nature.

Zhou et al. [12] use ontologies as the basis of their simulator. This project has resulted in a comprehensive simulation tool (J-Park Simulator). Industrial units, processes, plants and networks are modeled as surrogate models with their economic, environmental and technical properties and relationships to each other in hierarchical levels. The simulation is practice-oriented with the aim to map real systems to support the energy management of industrial parks. The advantage of the ontology is its interoperability, which allows (real or even real-time) data from different systems (data sources) to be processed. This tool is the only one that provides a dynamic simulation. All other approaches use annual data (e.g. average demand) to simulate time steps of one year.

In addition, hybrid modeling approaches have been increasingly used in recent years. These include, for example, combinations of agent-based modeling with system dynamics [13] or with ontologies [14] or the combination of ontologies and network theory [15].

In summary, it can be said that there are only a few approaches that develop practice-oriented simulation tools. However, simulations are a good tool to be more informed about a system when making decisions. Apart from the J-Park Simulator, the simulation models seem to be intended only for use by their developers. It should be noted, however, that other simulation tools have been mentioned in the literature, for which unfortunately little or no information is given and whose status is unclear. There seem to be no simulations to check how well technologies or companies fit together now and in future (e.g. temporal overlap of supply and demand, resource temperature). We consider a simulation to be necessary that models an existing system and the effects of changes to it (new synergy, changed shift system, new storage unit, etc.) in order to evaluate the performance of the system. Furthermore, most simulation models contain elements at a high level of abstraction and generally at a high level but the actual fit depends on units below those (e.g. department, facilities). Following the input-output approach, it makes sense to look at the sources and sinks at lower levels as these are specifically affected and possibly also adaptable. However, this would require more precise models. Moreover, most simulations are not dynamic simulations. When exchanging resources, time matters. Annual average data and yearly steps are too rough if resource flows do not show a continuous supply pattern or if demand and supply patterns (e.g. seasonal) differ between companies, especially in the case of energy exchanges.

III. Library Development

The development environment used is SimulationX. It supports Modelica to simulate individually created models with preconfigured or user-defined model elements. These elements are organized in domain-specific or custom model libraries. Since there are currently no suitable model elements for our purpose, a custom model library is developed (Fig. 1). These elements can then be parameterized and connected to represent the system under observation.

In the following, the guiding principles and underlying assumptions of our modeling method are presented and explained to clarify the scope of the simulation. We also describe how these were implemented. Subsequently, the conceptual and mathematical development of the model elements and their interaction is explained.

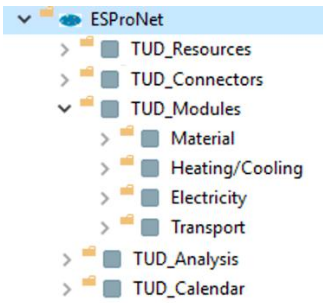

Fig. 1. ESProNet library in SimulationX.

A. Guiding Principles and Underlying Assumptions

1) Modularity

Modularity refers to both functional and hierarchical modularity. All elements in synergies can be subdivided into functions. Basic reusable and configurable functional modules are provided within the model library. These modules can be combined into compounds, changed or replaced to model simple abstract (e.g. generic source-sink-relations) as well as complex systems (e.g. production system of interlinked technical equipment).

Implementation: As Modelica is an object-oriented modeling language it adopts the object-oriented paradigm with concepts such as inheritance and polymorphism. Furthermore, SimulationX provides a simple way to assemble model elements into compounds and to define the displayed properties

Industrial symbiosis encompasses the basic concept of sources (outputs) and sinks (inputs) and their interaction, be it a company or a technology. However, a company has many attributes at a high level, while departments or units have many properties that are critical to adaptation, especially in terms of energy and transportation. Therefore, a bottom-up development of the model elements is fundamentally pursued. Thus, specific levers of a company and possible necessary adjustments for synergies (e.g. operation of a plant) can be identified. Although the development of bottom-up models is suggested, it is sometimes not necessary to build all elements of a system from the unit level, since perhaps not all participants in a synergy or a production system need to be presented in detail. Hence, elements of different hierarchical levels should be able to be placed in a model.

Implementation: The model elements within a model have a name affix indicating the hierarchical level they represent. The structuring is as follows: workstation, department, factory, enterprise.

2) Multi-domain

Different domains (material, heat, power) should not be considered independently from each other because resources may be utilized in different ways. The function (e.g. material input, heating, cooling) that a resource can fulfil depends on its properties (temperature, calorific value, etc.). For example, wood can not only be reused as material, but can also be used for thermal energy through combustion.

Implementation: Interfaces (‘connectors’) for the different domains are provided to determine relevant properties and define compatibility. In addition, these connectors visualize the necessary functions of an element. Furthermore, there are modules that provide the transformation of material to heat and vice versa.

3) Graph theory

The models created must follow the rules of graph theory, in particular, they must represent a directed graph (digraph) where the elements are the nodes and the flow of information or resources are edges. This is to ensure that the model is complete, directed and weighted and does not contain isolated elements or loops (cycles are allowed).

Implementation: This is supported by SimulationX and Modelica, since the network approach is followed, in which model elements are linked by connections.

4) Pull-orientation

According to the Kanban principle, there are two flows, an information flow (‘request’) and a physical resource flow. Information is passed from each level or component to the beginning of the system or process and, if necessary, converted and calculated. The physical resource flow is directed from predecessor to successor. A return at the same edge is not permitted. This principle assumes that a synergy only arises when a specified need has to be met and not just because there is an offer.

Implementation: The request is a vector with information about the resource type and the required properties that is transferred via the connectors (see Section ‘Interaction’).

5) Supply limit

The supply quantity is limited by the demand. Thus, it is not possible to deliver more than was requested. However, a storage component may be used to decouple supply and demand. A company would not simply buy more just because an offer exists. The difference between offer and demand is categorized as waste.

Implementation: A comparison (minimum) function is implemented in components with resource output.

6) Energy and mass balances

The input-output approach must be consistent with energy and mass balances. In order to guarantee that no energy or mass is created or missing in a system, the components and thus the entire model are based on energy and mass balances.

Implementation: Following the approach of [16] the calculation of equilibrium states for different time slices is solved with a differential equation system.

7) Physical approximation

Physical processes (esp. thermodynamics, logistics, power grid) are described approximately. It can be assumed that a synergy is only implemented if a significant improvement, i.e. the advantages exceed the disadvantages or effort, can be expected. Therefore, and due to the complexity of physical processes, we accept model errors (e.g. simplified thermodynamic state transition, omission of power voltage). Nevertheless, physical properties of resources are calculated, since they represent the basis of resource reusability and technology compatibility. Semantic matching, which is often used, is omitted.

Implementation: Modelica works with state and flow variables to solve systems of equations. The specific enthalpy is used in conjunction with pressure as state variable to determine resource properties regarding energy level and state (e.g. temperature, heat capacity, density) as accurately as possible. These are stored in a database.

B. Modules: Basic Components and Compounds

1) Resources

Resource exchange and reuse relies on the resources and their properties. Since, with the exception of electricity, energy (chemical, electrical, thermal, etc.) is usually bound to material energy carriers, we only distinguish between material and power. In order to create new resources and ensure a complete description of them, a Base Resource was defined from which specific resources (e.g. Steel, Water, Natural Gas) are derived. These are then stored in the resource library within SimulationX. Each resource is assigned an ID to guarantee supply and demand of the same resource. The various physical properties are defined, calculated or entered in the form of curves or curve sets. The data for fluids is generally based on the National Institute of Standards and Technology (NIST) chemistry webbook [17]. The physical properties for fuels are based on own databases. The data for solids is derived from approximations for practitioners. For electrical power a Base Power is set up, as this resource type does not require the aforementioned properties and we do not consider different voltage levels. For environmental analyses, however, we have considered different power mixes (e.g. power mix Germany 2017, Forecast Germany 2040, Renewable Energies).

2) Components

The conceptual modeling describing necessary concepts and their properties was carried out by means of an ontology ([18], [19]). These concepts were refined and mathematically described. All technologies contained therein (energy, production, transport, storage) are based on basic components. These basic components (functions) are the following: source (supplier), sink (consumer), storage, merging, separation. For every resource domain there is a respective basic component (Fig. 2).

Within the components mass, material and energy balances are maintained. In each component, the type of resource consumed or requested and the technical parameters that determine the capacity and processing of the resource (e.g. maximum mass flow) are specified (replaceable). Physical flows resulting from the simulation runs are stored in corresponding variables. In addition, each component contains the option to select power consumption for its operation (power mix and consumption pattern). For some properties that offer a range of choices (enumeration), additional properties are either displayed or hidden depending on the selection, so that the user is not overloaded with irrelevant information. Furthermore, a shift system is introduced to take operating modes and times into account. Thus, a load is given at any time. Although this function is already included in many production simulations, it is not included in Modelica due to the different focus and was manually implemented.

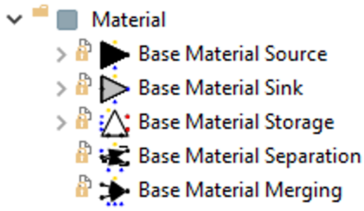

Fig. 2. Basic components of material domain.

Although the descriptive attributes are stored in the elements, some information is given externally to the element (e.g. request, shift). For this purpose, functions and signal inputs and outputs are used that are provided by Modelica by default. For sources and sinks the mathematical modeling is quite simple. Storage, merging and splitting components are more complex.

3) Compounds

Basic components are assembled to form specific technologies: transport, production, energy, storage. Data for the modeling of these comes from calculation, literature references and industrial partner measurements. To clarify how a compound works and why it is necessary, see the following example of the ESProNet heat conduction compound (Fig. 3).

The superior element has 3 connectors for heat input and output (red circles) as well as for the shift model (blue triangle). These connectors can also be found in the inner structure and show the connection of the inner with the outer structure. The compound comprises two parts: The control level (green) and the physical objects (red-blue). On the control level, information on the shift model is transferred to all components that require the information. Furthermore, this level contains two state machines that define the state of the heat conduction (Off / On) on the one hand and record delay times during start-up on the other hand. Both information is required for the start-up process.

The physical part of the heat transfer cycle is represented by a total of four technology type representatives: (continuous) heating, storage, heat sink and (continuous) cooling. The composition within the compound aims at an exact mapping of the behavior of a heat pipe. Starting on the left, heat is transferred from a heat source to a medium (water, thermal oil etc.) in a cycle (Heat_Input). The medium then passes through two storages (Flow and Flow2), which abstractly represent the heat pipe. Two storages are required due to the start-up characteristics, whereby the cold medium must first be pressed out of the pipeline. If one storage would be used, the temperature would rise slowly and would thus neglect the temperature jump after the cold medium has been pressed out of the line. At the discharge point (Heat_Output), heat is removed from the cycle if it is requested from a downstream point. The return flow (RFlow) is represented by one storage component. All storages are subject to a heat loss which depends on the specific of the heat conduction and the ambient temperature.

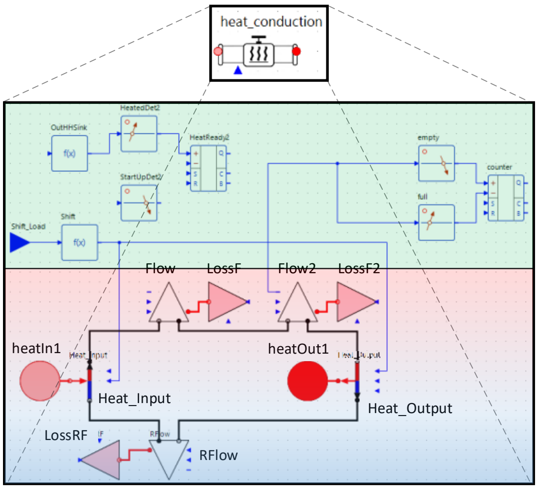

Fig. 3. Heat conduction compound.

The compounding is necessary for the higher-level control as well as for the calculation of physical flow quantities in the cyclic process. The mass flow is determined within Heat_Input, but depends on the temperature of the return flow, which is calculated in Heat_Output or RFlow. Furthermore, the setting of parameters that are valid for several components of the inner structure (maximum heat flow, operating pressure etc.) only need to be done once.

C. Interaction

For the individual model elements or components to exchange resources with each other, the connections between them must be specified. Components can be connected by edges in SimulationX and other Modelica development environments. These edges can be physical resource flows, information flows or both. However, components cannot be connected by edges at one's discretion, but require specific interfaces/connectors. Mathematical modeling with Modelica requires that these connectors define state and flow variables, which are then transferred from one element to the other.

1) Connector

Depending on the domain, the connectors contain different flow parameters, i.e. a material connector has a mass flow with a temperature, a heat connector has a heat flow with thermal power with medium temperature in addition and the power connector has power as a flow variable. In addition, a parameter vector is defined in the connectors that determines which properties of resources are passed on to the component (ID, phase, temperature, density, etc.).

2) Request

The pull-orientation is implemented via a request vector. This vector contains the resource ID, the requested quantity (material flow, heat flow, etc.), the type of request (forced or conditioned), temperature requirements (ideal, maximum, minimum) and pressure (maximum, minimum). A forced request means, the request has to be followed while a conditioned request means, the request can be followed. This is due to the fact that production technologies, especially those of other companies, operate independently and do not necessarily provide the required amount of resources (conditioned) while storage and energy technologies primarily serve the sufficient supply of production (forced). This interaction is shown in Fig. 4.

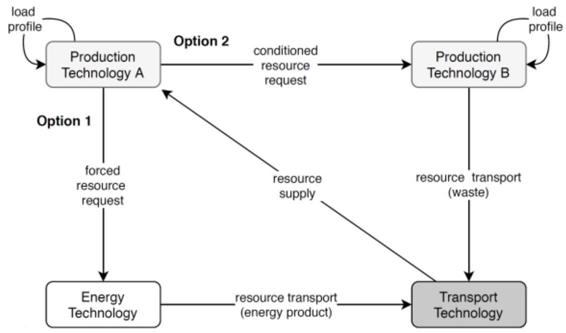

Fig. 4. Technology interaction scheme.

IV. Demonstration: Application Example

With this approach, inter-company symbioses can be mapped in the same way as internal ones. A practical example for an inter-company symbiosis is the use of waste heat from an electric arc furnace (EAF) in a steel mill in Riesa near Dresden, which is operated in three shifts per day. From 140.000 $^{m^3}/_{h}$ exhaust gas (up to 1,100 °C) 30 $^{t}/_{h}$ of steam are produced. 20 $^{t}/_{h}$ of the total are used to operate a 3 MWel Organic Rankine Cycle (ORC) process. The remaining 10 $^{t}/_{h}$ of steam is transferred to a continuous working tire plant via a district heating pipeline coupled with the district heating supply of the public utility Stadtwerke Riesa, where the heat is used to operate a steam process to generate electricity for own purposes. The melting pauses of approx. 20 min. are bridged with a steam accumulator. Although little information is publicly available [20], [21], we can create a model for this approach.

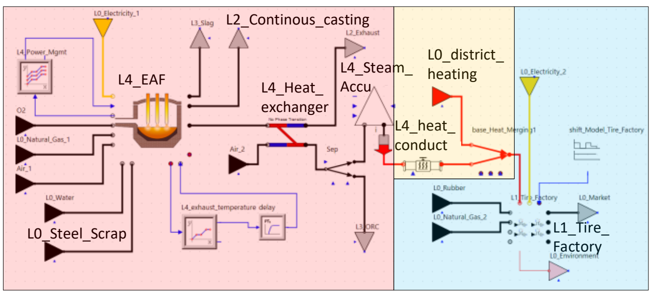

Fig. 5. Inter-company symbiosis.

The model (Fig. 5) contains an EAF we could reuse from another model coupled with the steam accumulator, the district heating and the heat sink in the tire factory. The sinks for the symbiosis resources are the material sink representing the ORC in the steel mill and the tire factory itself.

Because of the lack of publicly available information a model verification is not possible. Nevertheless, it shows the possibility of evaluation different scenarios, especially with and without symbiotic reuse of resources. The dimension of components in the process can be estimated and with that an economic evaluation of a symbiosis for potential partners is possible.

The following example (Fig. 6) shows an internal symbiosis with the use of waste heat in biogas combined heat and power plants (CHP) in the downstream of a wastewater treatment. The activity of microorganisms in a biogas reactor is strongly linked to the temperature. In order to increase the activity, the wastewater flow is heated by a few degrees, whereby a higher chemical oxygen demand (COD) degradation takes place in a shorter time and more biogas can be generated.

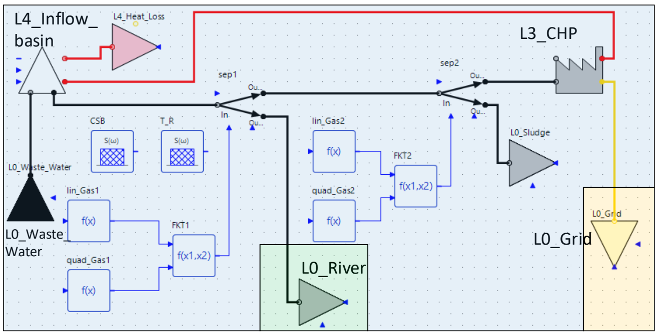

Fig. 6. Internal symbiosis.

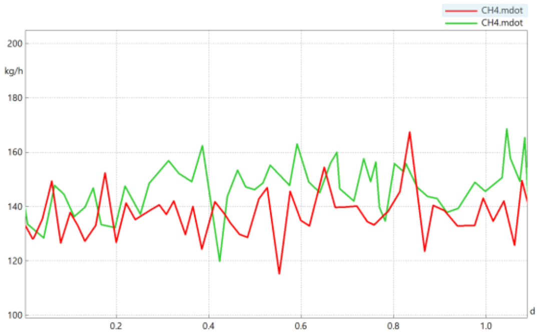

Fig. 7. CH4 output.

The model includes a simplified biogas plant, which is reduced to the effect of biogas output as a function of temperature. As shown above, mainly basic components (storage, heat exchanger, material separation, Modelica signal blocks) are used for the model. Waste water is collected in the inflow basin and split in several stages into sewage sludge, purified waste water and biogas. The biogas is then disposed in a cogeneration plant, where the electrical energy is fed into the grid and the thermal energy is transferred to the inflow of the biogas reactor. In order to increase the effect, the biogas reactor is additionally insulated.

As a result, a higher activity in the biogas reactor can be observed due to the temperature increase of around 4.2 K, which leads to an output increase of biogas of up to 18 %, which is also the electricity generation increase. The output increase depends on the temperature of the waste water inflow, where lower temperature leads to a relatively higher temperature increase, the effect is stronger. The graph in Fig. 7 shows the upper and lower envelope curve and is based on 210 t/h water inflow with a COD between 14 and 22 t/d and 33 – 37 °C temperature. It can be seen that the best results in the non-symbiosis scenario outscores the worst results of the symbiosis scenario in in total 2 hours in one day.

The models contain only physical effects and therefore do not allow any conclusions about the economic value of a symbiosis yet. Thus, the savings effects need be compared with investment costs for infrastructure like heat exchangers, heat conductions pipes and controls.

V. Conclusion and Further Research

In this article we have given a brief overview of current approaches to model and simulate industrial symbiosis. We propose a new modeling method for dynamic simulation. The approach is modular (object-oriented), bottom-up (technology-oriented), demand-based (pull-oriented) using the non-proprietary, object-oriented, equation-based modeling language Modelica. Hereby we show how to apply an acausal equation-based language in the given context (e.g. pull-orientation). The aim is not a tool to simulate and investigate the emergence of industrial symbiosis, but a tool to model real and future scenarios to assess the fit and benefit (economic and environmental) of potential synergies to support decisions for or against it.

To understand our approach, we have presented the underlying principles and assumptions. At present, basic components and common compound technologies for the representation of transport (e.g. power grid, conveyor technology), production (e.g. furnace) or energy generation (e.g. CHP) have been developed.

Currently, a holistic analysis has to be done manually. Individual model elements can be analyzed quickly using the tools given in SimulationX, but a comprehensive analysis method of the overall model is missing as well as economic data. In future, an evaluation option must be provided either within the tool (e.g. an analysis component) or by data export and querying in database. This requires the definition of performance indicators. Since the economic situation depends on a variety of factors such as disposal costs, procurement costs or operating costs of each plant, contractual agreements, etc., it is difficult to assign prices within the model components themselves. Costs for investments, e.g. in infrastructure or energy technologies, should initially not be passed on to existing companies, but to a third party. This avoids disproportionate allocation. In addition, users can then view the total costs incurred and conclude contractual agreements with which the parties involved agree. Therefore, we consider a subsequent analysis using a database to be useful.

Although we focus on the technology level, we will provide company modules that can act as placeholders in case there is not enough information available about technological units. It also enables rough symbiosis simulations if desired or required.

Furthermore, the validation of the model components, in particular compound technologies, is pending. This will be done by comparing other simulations with our own or with data from the literature or from the associated companies.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Martin Maiwald developed the modules for the simulation and the control logic. Furthermore, he carried out and evaluated the simulation experiments. Linda Kosmol conceptualized the topic and structured the approach. Christoph Pieper provided the physical basics for the creation of the modules and especially complex models. Thorsten Schmidt supervised and reviewed the work.

Acknowledgment

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