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Identifying Industrial Symbiosis Options for Energy Reuse

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Abstract: *Industrial symbiosis (IS), emerges when diverse organizations interact to share resources with each other in order to improve their overall economic outcomes and simultaneously reducing the overall environmental impact. This paper addresses the issue of identifying the most relevant energy reuse technologies for existing ecosystem of companies with energy HAVES (Sellers) and WANTS (Buyers) to facilitate Industrial symbiosis. Agent-based modelling was used to simulate the industrial ecosystem. The computational development was performed in Réseau.py. Simulations were carried out on twenty different companies with and without waste conversion technologies. The simulation results show that waste conversion technology should be included in the industrial ecosystem so as to increase sustainability.*

Keywords: *Industrial Symbiosis, ecosystem, simulation, computational development, agent-based modelling.*

1. INTRODUCTION

Since the emergence of industrial ecology in the 1950s and its take-off during the 1990s, much progress, in theory, policy and practice has been achieved for designing a fruitful and sustainable eco-industrial park. Almost all research into industrial symbiosis (IS) involves either proposing a frame work, [1] or mathematical model, [2] to design of IS or industrial ecosystem (IES). There are few works, see [3 - 5] that focus on the simulation of IS to understand its complexity. Progress is still being made in the area of computational modelling of the actions and interactions of the autonomous agents that formed the ecosystem. Major problems to unravel the complexity of IS include but not limited to price, profit and supply-demand fluctuations. Also, part of the problem that exist in the design of industrial ecosystems is the difficulties that companies face in identifying each other's resources. When such opportunities are energy related, conversion technologies are typically required depending on nature of the energy resource. To change the process, alternative resources with additional capital are required and will generate the same product, but different quantities of waste and profit as shown in Pr (1. This offers opportunities for sustainable supply chain management for instance through the design of new symbiotic Industrial parks where the waste of one company becomes a resource for another. Here the term symbiotic is used in a positive sense, as in both companies benefit.

$$R + Ca = P + W + Pr \tag{1}$$

R is resources, Ca is capital, P is product, W is waste and Pr is profit

Literarily, companies need to make decision on what quantity of waste resources are available for disposing, exchanging for money or that will cost them money in the company and know possibly the demand available in the next sales season. Because of the mismatch in the demand and supply of resources, the implication is that that there will generally be periods of excess supply (supply greater than demand) and shortage (demand exceeds supply). Agent-based model (ABM) also known as bottom-up modelling according to [6] has proved to be a promising tool to simulate the evolution of eco-industrial parks [3; 7].

There are many approaches of simulating a complex system and one of the applicable methods is through agent-based modelling (ABM). ABM is extensively used within complexity theory and springs from object-oriented programming and distributed artificial intelligence. ABM is not comprehensive solution to explain all aspects of the complexity theory and complex systems, instead it should be seen as a useful tool to gain insight [8].

ABM is a way to address these challenges as it offers a proactive problem-solving tool. The focus of ABM is on agents and their relationships with other agents or entities. In comparison to other, more traditional programming methods, the agents in an agent-based model determine independently the best way to solve a problem in order to achieve an overall objective.

This paper addresses the issue of identifying the most relevant energy reuse technologies for an ecosystem of companies with energy HAVES and WANTS to facilitate Industrial symbiosis. An agent-based model, Réseau [9] is used to simulate the industrial ecosystem, generate demand and supply profiles. We analyse IS considering materials and energy flows and the related supply-demand match for the output products (finished goods, by-products, useful waste) becoming primary input for entirely new processes that are co-located or within the same vicinity. Two different case studies will be utilised to illustrate the effectiveness of the proposed methodology in order to gain some managerial insights.

In Section 2, the different waste conversion technologies in industry are introduced, leading to the description of the problem statement and the proposed solution method in Section 3. In Section 4 a set of case studies are introduced to illustrate the application of Réseau and MERIT in a range of different scenarios and the simulation results presented. Conclusions are given in Section 5.

1.1 Waste Treatment

Cost and financials attribute is one of the deciding factors in the choice of conversion technologies [10; 11]; it forms the base of the cost model. The technologies are presented in terms of Capital Cost (CAPEX), Operations and Maintenance Cost (OPEX) and the fuel cost on per installed capacity and per unit output is scored based on comparison to similar technologies for same functionality. Furthermore, it contains business model indicators for process integration, industrial symbiosis and/or sharing with the wide energy network. The waste to energy technology is evaluated based on following cost and financials attributes.

- Capital Cost: CAPEX is scored based on comparison to similar technologies for same functionality.
- Operations and Maintenance Cost (Non-Energy): OPEX is scored based on comparison to similar technologies for same functionality.
- Fuel cost: It describes the cost of fuel used to convert the by-products to useful resources.

1.2 Waste Conversion Technologies

In this work three waste to energy technologies were used. These technologies were selected based on typical industrial applications; industries reviewed include: glass manufacturing, cement manufacturing, iron and steel manufacturing, aluminium production, metal casting, industrial boilers and ethylene furnaces. Brief descriptions for the selected waste to energy technologies are discussed next.

1) Cooling: there are different forms of waste that can be generated from cooling system e.g. steam at low or high pressure. To cool steam, different number of methods such as heat exchanger that takes place between flue gases and air through metallic or ceramic walls can be adopted. Duct or tubes carrying the air for combustion to be pre-heated, the other side contains the waste stream. For example, gas to gas heat exchanger is one type of waste to energy exchanger. This can be obtained from industrial process such as flue gases. It is applicable in pre-heating of combustion air and operating boundary conditions between 230 °C to 1650 °C. Furthermore, another type of heat exchanger is plate heat exchanger that consists of a series of separate parallel plates forming a thin flow pass. Each plate is separated from the next by gaskets and the hot stream passes in parallel through alternative plates while the liquid to be heated passes in parallel between the hot plates. To improve heat transfer, the plates are corrugated. For example, gas to gas and liquid to liquid heat exchange are typical plate heat exchanger. This can be obtained from boiler exhausts, incinerators and turbines, drying, curing, and baking ovens. It is applicable combustion air preheat, and space heat technology operating boundary conditions from 10 °C to 170 °C.
2) Incineration: there are a wide variety of waste treatment options that may be used as part of a waste management strategy to recover materials (for example furniture reuse, glass recycling or organic waste composting) or generate energy from the wastes (for example through incineration or digesting biodegradable wastes to produce usable gases). In this work, the term incineration is used to describe processes that combust waste material for landfill.
3) Combustion: One of the thermal incineration methods of waste is combustion where the waste materials are burnt for either energy recovery or disposal. In this work, the combustion process is not for energy recovery but as a form of treating the waste at a transfer cost.

1.3 Problem statement

Figure 1 illustrates the structure of the problem identified in the introduction of this work. The industrial ecosystem consists of two environments: (i) an external environment made up of buyers and sellers outside the ecosystem, and (ii) an internal environment made up of factories, utilities the external buyers and sellers can supply and buy without capacity limitation. The factories convert raw materials and energy from suppliers into products. The finished products are sold to the external buyers, and energy by-product are typically destroyed using waste technology, e.g. cooling towers and incinerators. The objective of this work is to match the energy demand from factories in the ecosystem with waste energy currently generated and identify whether the installation of energy conversion and storage technologies would deliver significant benefits. This paper addresses the issue of identifying the energy reuse technologies options for an existing ecosystem of companies with energy *HAVES* and *WANTS* to facilitate industrial symbiosis.

2. METHODOLOGY

The factories energy needs are provided from utilities with an assumed fixed cost. We define such energy need as a "WANT" (e.g. fuel, electricity, steam). The waste energy being destroyed is defined as a "HAVE" (e.g. flue gas, low pressure steam, calorific waste) and the destruction of this waste energy is done at a fixed cost per GJ. Table 1 gives the utility costs used in the simulations. The first step in the process allows factories to exchange matching energies. In other words, if factory A has excess IP Steam (HAVE) and company B requires IP steam (WANT) then IP Steam can be transferred from A to B, at a fixed cost per km. Assuming the transport costs are not prohibitive, the transaction reduces the utility cost of A and B. In this work we focus on three types of waste treatment processes: (i) cooling towers to condense steam, (ii) incineration of gaseous and aqueous streams and (iii) combustion of calorific waste. The waste treatment costs, and transportation costs are provided in Table 1. After exchange of matching energy WANTS and HAVES, there remains a residual Demand and Supply of energy types that require conversion. By adding conventional energy conversion technologies as service providers in the ecosystem energy HAVES can be converted to require energy WANTS. In this work 4 types of conversion technologies were identified: (i) direct steam injection loop to heat water, (i) waste heat exchangers for HP steam generation, (ii) a combustion plant to generate HP steam, (iii) electricity turbines to convert HP steam to electricity. Each technology has an energy efficiency, and an associated cost per GJ consumed, as well as a transport cost. The complexity of the problem lies in the fact that the energy HAVES and WANTS are time dependent. So not only the quantity needs to be matched, but also the time at which the energy is required/available. A second aspect is that the number of streams can be significant on a large site. To solve these problems, an agent-based model is adopted. The industrial ecosystem is made up of A (i = 1,2,3,…n) number of agents. Note that each agent is unique in that its state variables cannot be directly altered by other agents. The system allows agents to interact and this may result in a transaction through which variables in both agents can change (e.g Loss of energy by agent A is matched by a gain of energy in agent B). There are two basic types of agents: suppliers and buyers. External suppliers and buys and the utilities are basic agents. The factories, and the conversion services can both sell products and HAVES and can buy raw materials and energy WANTS. As such they combine the properties and methods of both the buyer and seller agents.

- Transactions logic (system, randomised buyers checks all sellers and completes transactions; system stores history
- UTILITY Buyer: fixed price, infinite capacity
- Raw Material (RM) Seller: supplies RM at fixed costs, and infinite supply
- Product buyer: buys products but limited constant supply.
- Electricity buyer, buys any available at fixed price
- Factory
    - Calculates required RM and buys the lowest costs
    - Calculates required input utilities for production (WANTS), and buys from market (utilities, other factories and Conversion services)
    - Calculates required excess energy (HAVE) for production, and sells on market but all must be sold at any cost (to utilities and conversion Services) including transport costs
    - The energy needs and waste streams have demand/supply profiles, RM material is constant per period
- Conversion Technology Services
    - Buys all available HAVES at fixed price and transport cost
    - Sells its product to the highest bidder and transport costs

Note that the buyers and sellers are not related. For example, there are $\boldsymbol{n}$ number of HAVES, WANTS, conversion technologies and utilities (internal); i.e. each agent can be represented as $\boldsymbol{C_1}, \boldsymbol{C_2}, \boldsymbol{C_3}, \ldots \boldsymbol{C_n}$ in the ecosystem. The structure of this work contains of two cases with increasing complexity as explained below.

- Case I – In this case study, the industrial ecosystem is made of only companies with HAVES and treatment companies. The assumption here is that the by-product(s) (solid, liquid, gas) has no economic value but need to be treated to reduce environmental pollution. The treatment thus has associated cost. This cost includes; capital cost (CAPEX), operational cost (OPEX) and fuel cost.

- Case II is Case I with the addition of the WANTS companies. The HAVES and WANTS companies interact with each other to generate raw demand and supply as well as residual demand and supply. The essence of this is to evaluate the benefit of trading the by-products with the WANTS companies as against treating it that is required an extra cost.

At the beginning, each of the WANTS agents' source for resources (energy/materials). If the required resource, the WANTS agents makes the offer and the HAVES agents accept the offer and the demand is fulfilled. If the input type quantity available from the HAVES agent is less than the input type demand by the WANTS agent, the remainder is source from the market selling agent, and if the demand is less than the availability from the plants, the HAVES agent sells it out to market buyers. The environment is assumed to be an infinite source and sink. It can provide any inputs requested within the park and can absorb any excess output from the park. Our model is to ensure that the flow of inputs (materials/energy) from the environment into the parks is minimised while outputs (energy) flow from the park to the environment is maximised with optimal synergy in the park. The main problem is to generate the raw demand and supply, residual demand and supply over the period of simulation so as to identifying the most relevant energy reuse technologies that can foster industrial symbiosis.

2.1 Agent-based Modelling

There are many approaches of simulating a complex system and one of the applicable methods is through agent-based modelling (ABM). ABM is extensively used within complexity theory and springs from object-oriented programming and distributed artificial intelligence. The agent formulations used in this work extend on the basic formulation by [12]. The model was named Réseau, which means a network. The Overview, Design Concepts and Details (ODD) protocol proposed by [13] is used for its description. It was designed so that ABM publications would be more complete, quick and easy to understand, and organized in a manner that allows for presenting information in a consistent order [13]. The detail of ODD adaptation in Réseau can be find in the extra supplement information (ESI) section. The model is an integrated agent-based model and input-output approach and was developed using Python platform, which is a general-purpose programming language.

2.2 Simulation Flow

The logic flow of Réseau agent-based model for the problem identified above is described below. The logic flow is divided into four distinct heading and the high level of how the mode runs is explained below for each of the header.

2.2.1 System logic flow

- Initialised agents
- Load all agent parameters from external file

Begin trading

Step 1

- Randomise all agents in the list
- Agents produce
- Agents predict requirements

Step 2

- Randomise all buyers
- Each buyer checks all sellers and complete transaction

Step 3

- Randomise all sellers
- Each seller checks all buyers and complete transaction

Step 4

- The histories are collated and stored

Step 5

- Each agent records its transaction in an external file

2.2.2 Seller logic flow

Step 1 – Production

- The production quantity for each product is assumed equivalent to the production quantity.

Step 2 - Predict requirement

For each product:

- Product sales quantity SQ_i is asummed to follow Gaussian distribution with mean, μ and sigma, σ.

For each product

- Check history and get average price in the market over 10 periods
- If condition is random: product price p_i is asummed to follow Gaussian distribution with mean, μ and sigma, σ.
    - If condition is risk based and average price equal zero: delta p equal p_i
    - If condition is risk based: get product price

Step 3 – Sell product

- Create an empty list to append buyers
- For each product, if the storage capacity is less than sales quantity
    - Randomize all the buyers
    - For buyer in buyers list: make deal for each product
    - If deal is valid
    - Append buyer in the list of deals
    - Sort the deal based on highest price: Initialize the count n = 0
    - While the sales quantity is greater than storage capacity and n is Less than length of the deals list: execute trading and increase n by 1

2.2.3 Buyer logic flow

Step 1 - Production

For each raw material: If list of raw material equal empty then raw material quantity equal zero

Step 2 - Predict requirement

- The raw material demand Di is asummed to follow Gaussian distribution with mean, μ and sigma, σ.

Step 3 – Buy raw material

- Create an empty list to append sellers
- For each raw material, randomize all the sellers
- For seller in sellers list, make deal for each raw material. If deal is valid, append seller in the list of deals and then sort the deal based on lowest price
- Initialize the count n = 0. While raw material demand is greater than zero and n is less than length of the deals list then executes trading and increase n by 1

2.2.4 Factory logic flow

Step 1 - Production

- For each raw material obtain

$$PC = minimum(\frac{RMQ}{RMU}, RMC) \quad (2)$$

- For each raw material obtain

$$RMQ_i = RMQ_i - PC \times RMU_i \quad (3)$$

- For each raw material

$$\boldsymbol{SQ_i = SQ_i + PC \times PU_i} \quad (4)$$

$$\boldsymbol{PQ = SQ} \quad (5)$$

Step 2 - Predict requirement

Total capacity C is asummed to follow Gaussian distribution with mean (μ) and sigma (σ).

- For each product sales quantity

$$SQ_i = SQ_i + C \times PU_i \quad (7)$$

- For each raw material demand

$$RD_i = C \times RMU_i \times SQ_i - RMQ_i \quad (8)$$

- For each product
    - Check history and get average price in the market over 10 periods
    - If condition is random
        - Product price p_i is asummed to follow Gaussian distribution with mean, μ and sigma, σ.
        - If condition is risk based and average price equal zero
            - Delta p equal p_i
    - If condition is risk based
        - Get product price

Step 3 – Buy raw material

- Create an empty list to append sellers
- For each raw material, randomize all the sellers.
- For seller in sellers list: make deal for each raw material
- If deal is valid, append seller in the list of deals and sort the deal based on lowest price.
- Initialize the count n = 0. While raw material demand is greater than zero and n is less than length of the deals list then executes trading and increase n by 1

Where PC is production capacity, RMQ is all raw material quantity, RMU is all raw material usage, RMC is all raw material capacity, RMQ_i is each raw material quantity, RMU_i is each raw material usage, RD_i is each raw material demand, SQ_i is each sales quantity, PU is product usage, PQ all product quantity and SQ all sales quantity.

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2.3 Data Gathering

One of the numerous challenges facing the facilitation of industrial symbiosis is the inability of companies to share their data. Real data were gathered for 7 companies that participated in the SHAREBOX project [14]. A further 13 companies are simulated. These have demands and needs set to demonstrate the modelling approach. Table 1 shows the details of the 20 energy streams. The status of a company describes whether the energy stream is required, or in excess of requirement. For example, company 01 (comp 01) needs high pressure steam (WANT). Company 3 process generates HP Steam but has no immediate use for it (HAVE).

Table 1: demand and supply data

Company Name	**Resource**	**Status**	**Capacity (GJ/Y or MWhr/y)**
comp1	HP steam	Want	1388.89
comp2	Calorific FUEL	Have	960.00
comp3	HP steam	Have	1000.00
comp4	Calorific FUEL	Want	1600.00
comp5	HP steam	Want	1666.67
comp6	HP steam	Want	1388.89
comp7	Calorific FUEL	Have	2000.00
comp8	Calorific FUEL	Want	fuel 4000
comp9	HP Stream	Want	1500.00
comp10	HP Stream	Want	800.00
comp11	flue gas	Have	650.00
comp12	flue gas	Have	630.00
comp13	flue gas	Have	570.00
comp14	flue gas	Have	820.00
comp15	lp steam	Have	5555.56
comp16	lp steam	Want	5555.56
comp17	lp steam	Want	3055.56
comp18	lp steam	Have	3611.11
comp19	lp steam	Have	2916.67
comp20	Hot water	Want	6850.00

3. BASE CASE INTERNAL UTILITIES TO GENERATE ENERGY AND DEAL WITH WASTE ENERGY STREAM

Based on the problem statement in section 1.3, this phase addresses the case in which the industrial ecosystem is made up of several companies with HAVES and WANTS to interact with each other. From Figure 1, there are set of n companies that their status is ether HAVES or WANTS. The HAVES companies have capacity to generate a waste resource over a set period and the WANTS companies needs waste resources over a period time. The problem therefore is to match the HAVES and WANTS together over this period and generate the demand and supply profiles, residual demand and residual supply profile over this period.

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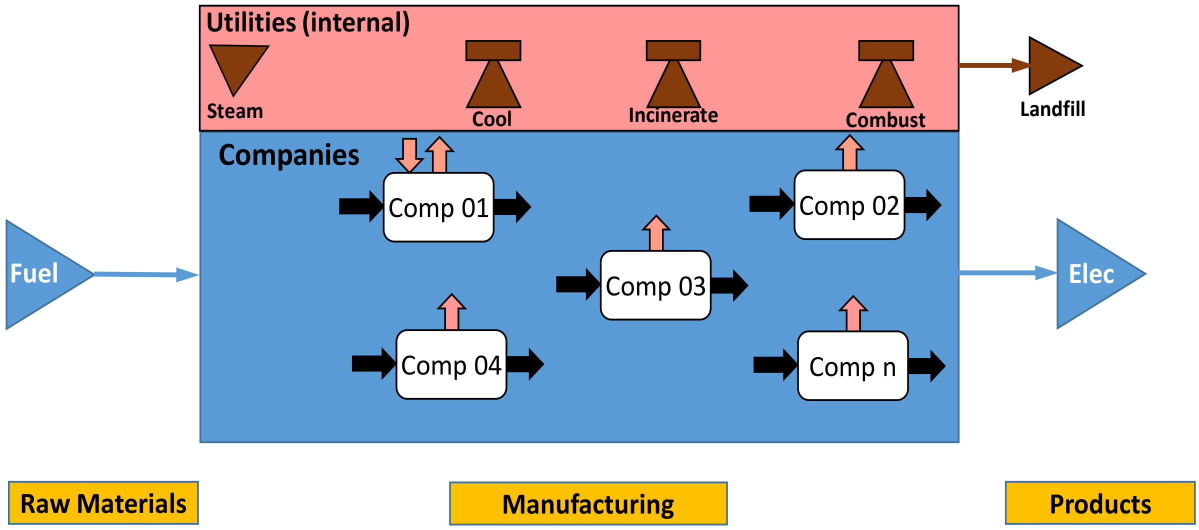

Figure 1: Problem statement (Base case: internal utilities to generate energy and deal with waste energy streams)

The results of a single simulation run for phase 1 as described in **Error! Reference source not found.** are shown in Figure - Figure . These results represent the total raw demand profile, total supply profile and total residual profile for the HAVES and WANTS companies. The simulation run was done for 500 periods to show that the profiles can be generated for any length of period that is required. The number of waste resources being shared among the participating companies in the ecosystem is four, i.e., High pressure (HP) steam, plastic waste, flue gas and low pressure (LP) steam. Over the period of simulation, the demand does not meet for all the materials except for the LP steam. The quantity available over the period for the LP steam meet the capacity of the WANTS companies and still have some residual supply. Therefore, there is a need for additional facilities that can utilize LP steam for its daily production activities. Also, inclusion of other companies that can generate HP steam, plastic waste and flue gas at a desirable amount in the ecosystem may make the system more sustainable. This can be observe in Figure - Figure 4 that the demand is more than supply.

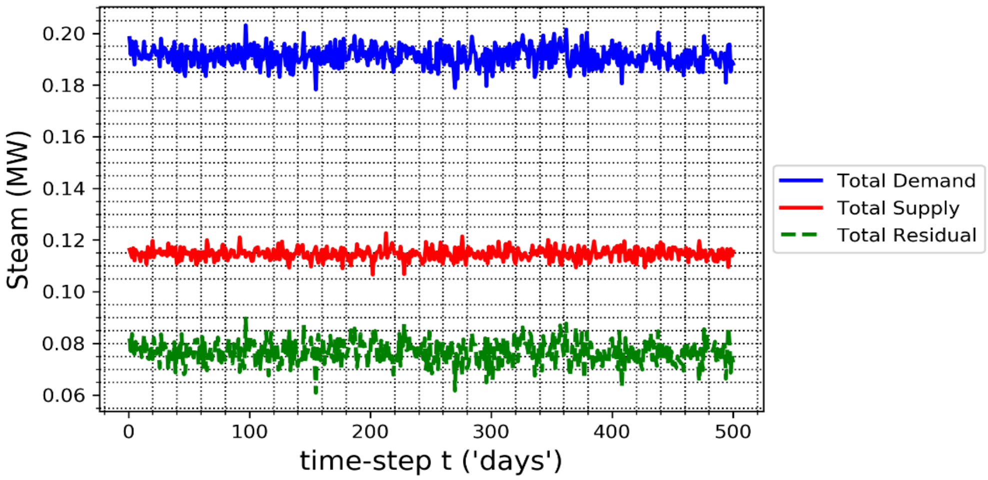

Figure 2: Steam demand and supply profile

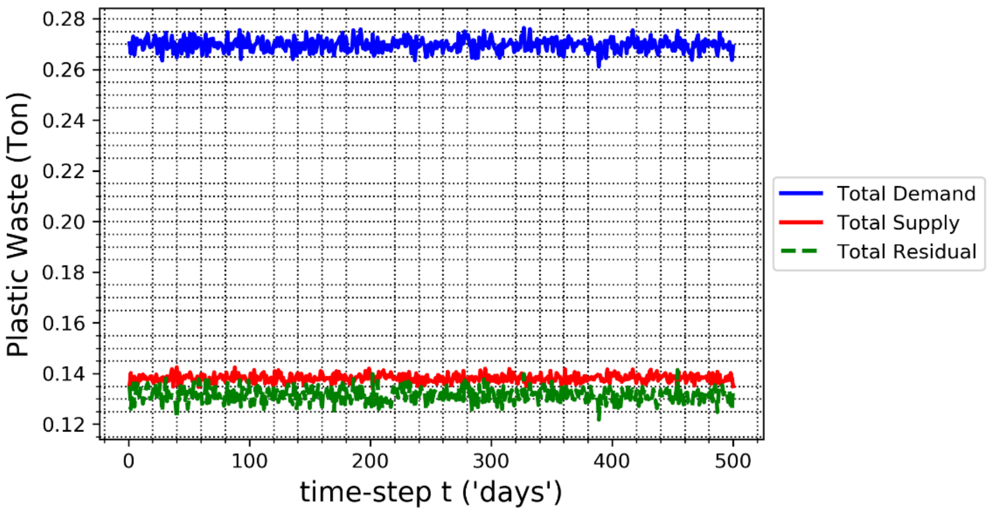

Figure 3: Plastic waste demand and supply profile

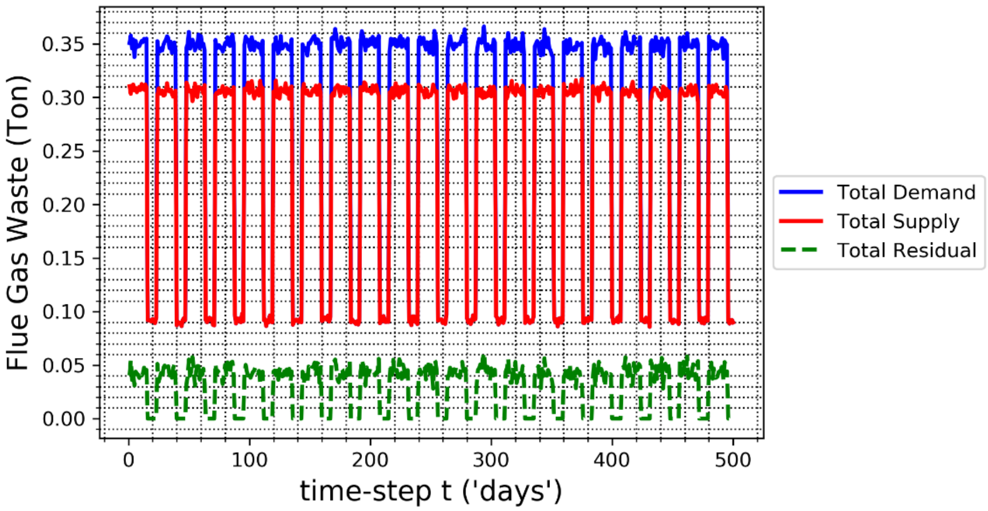

Figure 4: Flue Gas demand and supply profile

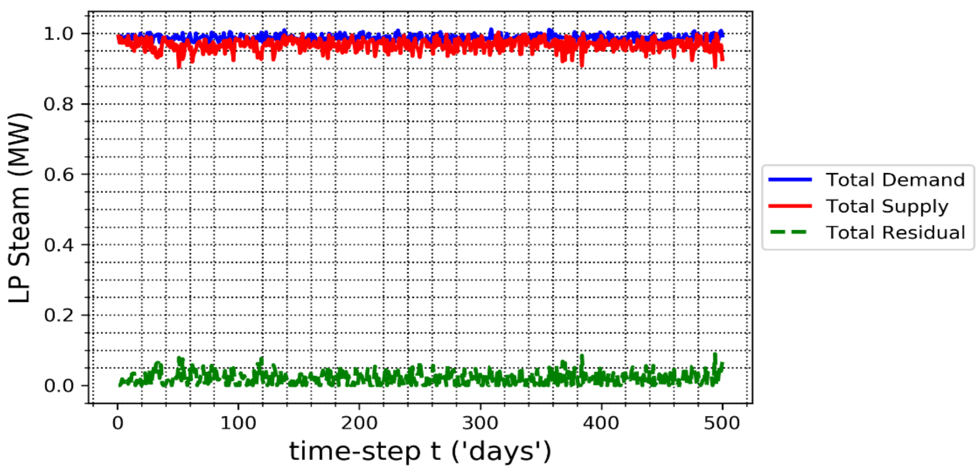

Figure 5: LP Steam demand and supply profile

4. WASTE ENERGY REUSE BY INTERNAL TRADING

This section focuses on phase I with the addition of some energy conversion technology systems that convert the waste stream to useful resources. The possibilities of refining the waste energy first by a conversion technology before using the output by another stream. Figure describes this phase 2. Phase 2 has set of n companies that their status is ether HAVES or WANTS with inclusion of some conversion technologies. The conversion technologies act as factory that buys raw material produce and sell later. The HAVES companies have capacity to generate a particular waste resource over a set period of time and the WANTS companies is in need of waste resources over a period time. The problem in this case is to study if with the inclusion of conversion technologies, the resources in the ecosystem will be fully utilized at any period.

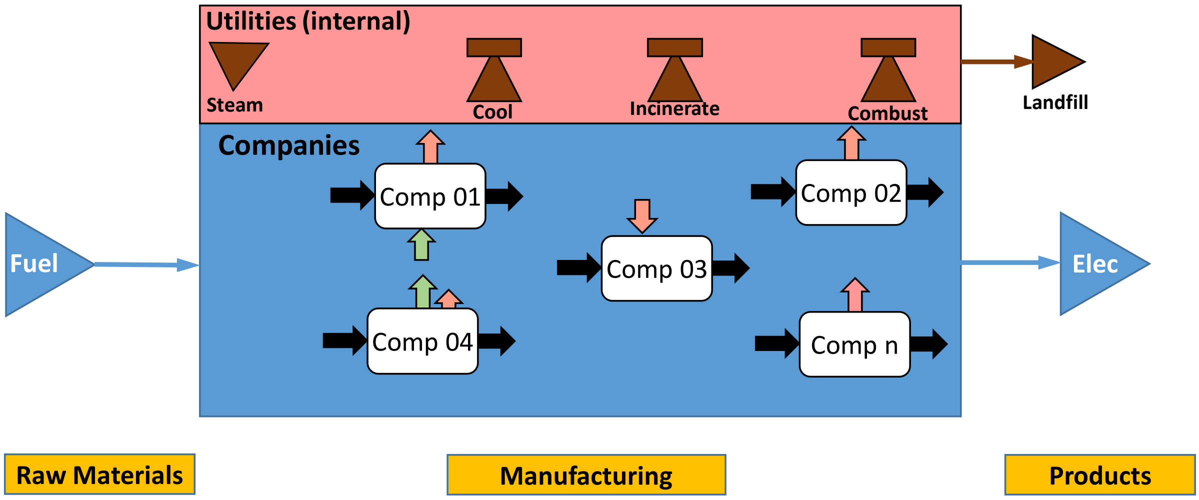

Figure 6: Waste energy reuse by internal trading leading to residual demand and supply still requiring utilities

Figure - Figure show the results of the simulation run for problem in phase 2, described in Figure 6. The number of waste resources shared among the participating companies in the ecosystem for phase 2 is same as in phase 1. Over the period of simulation, for each of the waste generated, the total demand is met by the supply except for plastic waste. Even though the demand for plastic waste is not completely met, compared to the problem in phase 1, it can be observed that the supply increases considerably due to the inclusion of conversion technologies. The demand for the HP and LP steam are adequately met and no residue (demand/supply) remain. It can be inferred that the inclusion of conversion technologies increase the level of sustainability of the ecosystem.

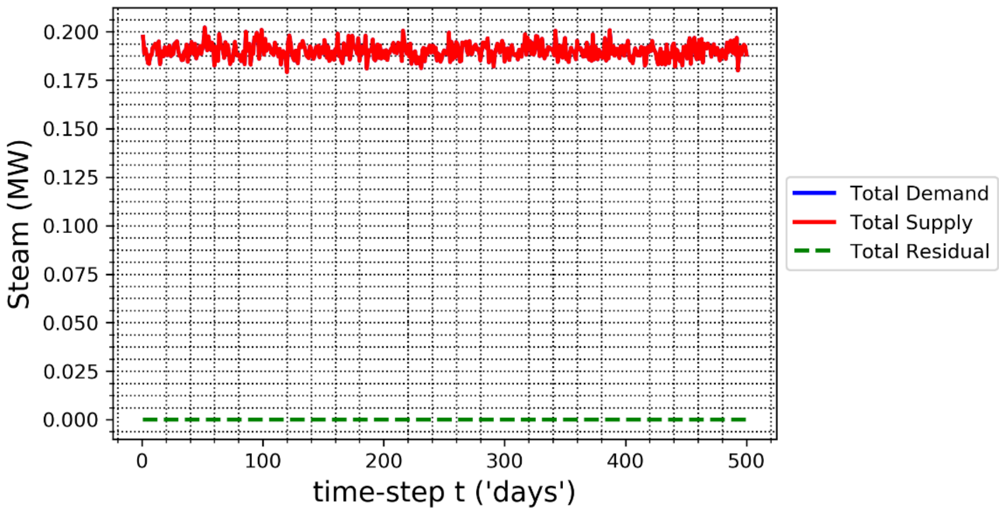

Figure 7: Steam demand and supply profile

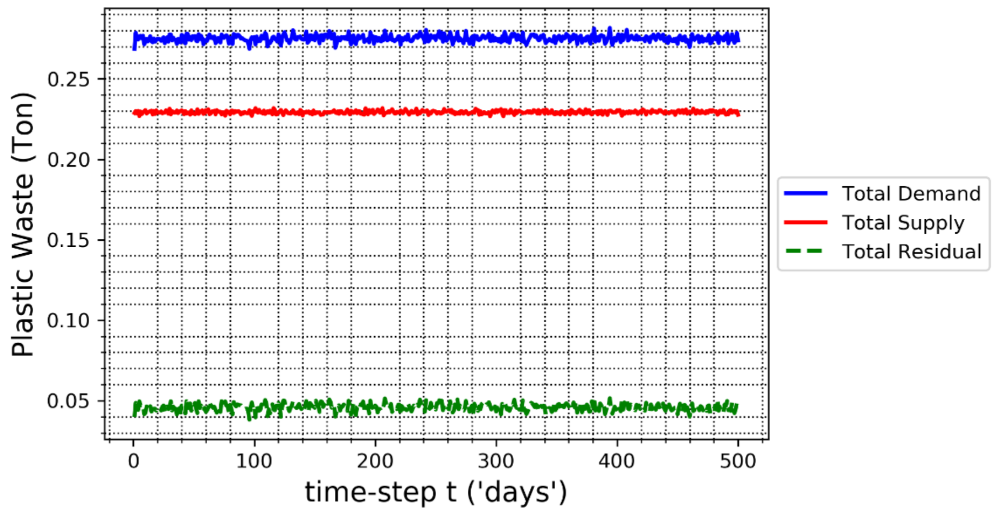

Figure 8: Plastic waste demand and supply profile

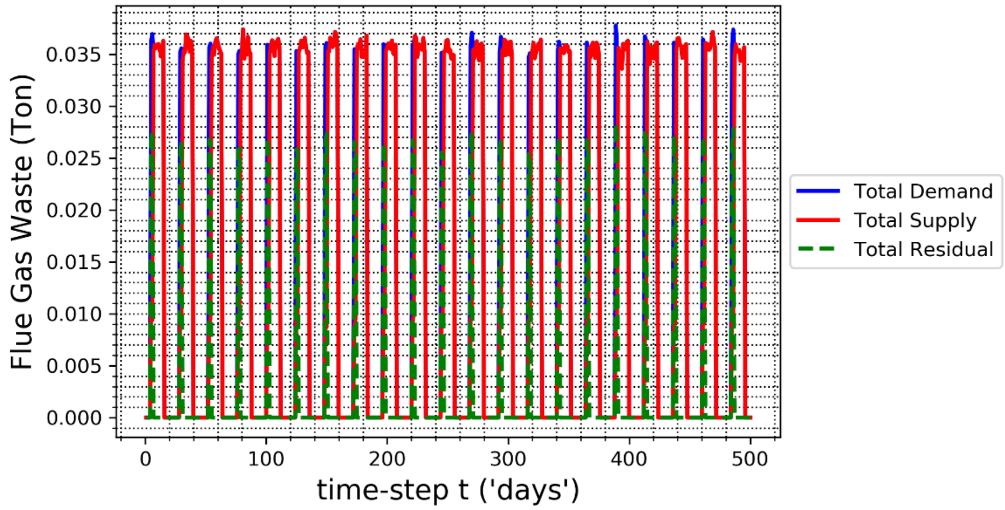

Figure 9: Flue Gas demand and supply profile

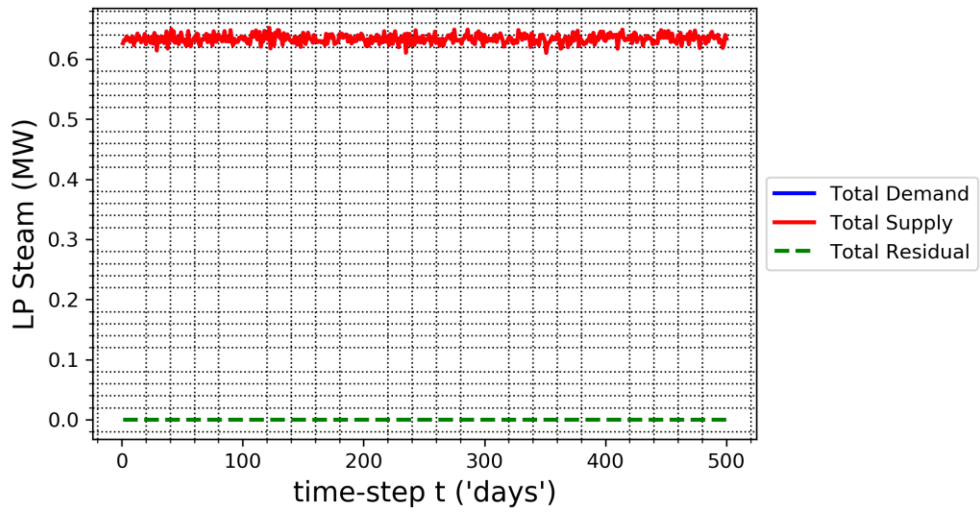

Figure 10: LP Steam demand and supply profile

5. CONCLUSION

The issue of identifying the most relevant energy reuse technologies for an existing ecosystem of companies with energy HAVES and WANTS to facilitate Industrial symbiosis is the focus of this paper. Reseau was used to simulate the selected eco-industrial parks. In order to gain insight on the interaction that exists within the ecosystem, an EIP system consisting of twenty different process companies is simulated. Two different case studies with and without inclusion of waste conversion technologies were studied. In conclusion, this study shows that the ABM is a useful tool that can be used in simulating periodic demand and supply. With the focus being basically on the reuse of waste generated in the ecosystem and the possibility of accessing conversion technologies, an IS with materials and energy flows and the related supply-demand match for each output products (finished goods, by-products, useful waste) was studied. Outputs become primary input for entirely new processes that are co-located or within the same vicinity. The focus was basically on the reuse of waste generated in the ecosystem and the possibility of accessing conversion technologies.

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