

**A MULTI-OBJECTIVE OPTIMIZATION OF ECONOMIC,
ENVIRONMENTAL AND SOCIAL ASPECTS FOR ENERGY AND
MATERIAL INDUSTRIAL SYMBIOSIS WITH SUPPLIER DISRUPTION**

BY

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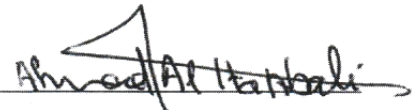


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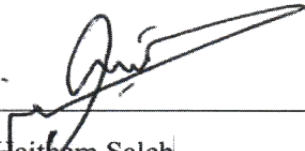
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LIST OF ABBREVIATIONS

IS	:	Industrial Symbiosis
EIPs	:	Eco-Industrial Parks
WMREN	:	Waste Material Recycling and Exchanging Network
MOO	:	Multi-Objective Optimization
DM	:	Distance Method

]

ABSTRACT

Full Name : Mustafa Yousef Alabandi

Thesis Title : A Multi-objective Optimization of Economic, Environmental and Social Aspects for Energy and Material Industrial Symbiosis with Supplier Disruption

Major Field : Industrial & Systems Engineering

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Industrial symbiosis, which allows companies and other entities to cooperate symbiotically by exchanging material, energy, waste water and by-products, can play a substantial role in improving economic, environmental and social aspects of the supply chain. Afshari et al. (2020) considered an energy symbiosis network where parties participating in the network exchange energy symbiotically. They formulated the problem as a multi-objective mixed-integer linear programming model. In this research, we extend the work of Afshari et al. (2020) to account for more realistic aspects of the industrial symbiosis network by considering material exchange as well as energy exchange. The material exchange is incorporated through a variation of the waste material recycling and exchanging network (WMREN) discussed by Haung et al. (2020). In addition, we consider supplier disruptions in the model which is modeled using chance constraints. The model is formulated as a multi-objective mixed-integer linear programming model and solved using a suitable optimization methodology. Epsilon-constraint method in conjunction with the distance method is used to handle the multi-objective nature of the model. Sensitivity analysis is also provided by varying important parameters and studying the impact on the model. Results prove that participating in a symbiosis network is economically, environmentally and socially advantageous.

ملخص الرسالة

الاسم الكامل: مصطفى يوسف العبندي

عنوان الرسالة: تبادل الطاقة والمواد الخام في الصناعة التكافلية مع أخذ الاعتبارات الاقتصادية والبيئية والاجتماعية

التخصص: الهندسة الصناعية

تاريخ الدرجة العلمية: جمادى الثاني، ١٤٤٤ هـ

تتناول هذه الرسالة ما يسمى بالصناعة التكافلية، حيث تقوم المصانع بتبادل الطاقة والمواد الخام تكافلياً، ليتم الاستفادة من الموارد وعدم هدرها. أولاً، سيتم صياغة النموذج الرياضي الحديث، أخذاً بعين الاعتبار تبادل المواد الخام بالإضافة لتبادل الطاقة بين المصانع المشاركة في التكافل. ثانياً، سيتم إضافة ما يسمى بالاضطرابات في التوريد إلى النموذج الرياضي ثم سيتم حله بالطرق المناسبة. تُشير نتائج هذا البحث أن المشاركة في الصناعة التكافلية لها جوانب إيجابية عدة، من ضمنها الاقتصادية والبيئية والاجتماعية. [

CHAPTER 1

INTRODUCTION

1.1 Background

The growth of industrialization and urbanization over the last few decades has most certainly improved civilization, but it comes with consequences. Global warming, and its negative impact on the environment is one of these consequences, which has attracted the attention of many researchers, environmental activists and industry leaders. Companies and enterprises around the globe are leaning more towards greening their supply chains to reduce the harmful emissions affecting the environment. While doing so, they also try to optimize their total costs.

One of the most effective ways to achieve these objectives simultaneously is industrial symbiosis (IS). Symbiosis, in biological terms, is defined by Paracer & Ahmadjian (2000) as a mutually beneficial association between two or more species of organisms. In the context of industrial synergies, however, IS allows companies and other entities to cooperate symbiotically by exchanging material, energy, wastewater, and by-products. Research shows that IS can play a prominent role in greening existing industries and in improving economic, environmental, and social aspects of the supply chain (Neves et al.,

2020). The complex nature of such symbiotic networks makes it a challenge to model, and it has become the interest of many researchers. Most research in the literature focuses primarily on the environmental impact alone, or the economic aspect of such networks. Some researchers, however, aimed at encompassing the three pillars of sustainability; economic, environmental, and social impacts (Demartini et al., 2022).

Afshari et al. (2020) considered an energy symbiosis network where parties participating in the network exchange energy symbiotically. They filled a gap in the literature by incorporating the social aspect when optimizing an industrial symbiotic network. They formulated the problem as a multi-objective mixed-integer linear programming model while taking the important aspects in the optimal design of energy symbiosis; economic, environmental, and social impacts. They also accounted for seasonality in the energy demand throughout the year. They implemented the distance method to rank the solutions of the multi-objective optimization problem, then used the epsilon-constraint method to verify the solutions obtained from the distance method, which was solved using a commercial solver.

In this thesis, we extend the work of Afshari et al. (2020) by incorporating material exchanges between industrial users as well as energy exchange. According to Branca et al. (2020), one of the vital objectives of IS networks is that waste material and by-products resulting from the production process of one industry, may become the input material used for the production process of another industry. That said, we consider material/by-product

symbiosis in this thesis by incorporating a variation of the WMREN model discussed by Haung et al. (2020) where demand industries require raw material for their production, which may be comprised of the different by-products and waste material resulting from other industries in the IS network.

Furthermore, Supply chains and logistics systems are subject to various sorts of disruptions. These disruptions could cause a severe drop (or total stoppage) in the supply of material, products, energy, and other resources in the system. Several books and research papers in the literature have discussed how vulnerable supply chains are to disruptions, and the need to systematically analyze their security and resiliency (Mehrotra et al., 2012; Snyder et al., 2006). Researchers have developed different models that mitigate this type of risk by taking supplier disruptions into account during the strategic planning phase. For instance, Snyder et al. (2006) designed eleven different models for designing supply chains that are resilient to disruptions. Their models considered facility location and network design models for designing networks from scratch, or modifying an existing network to reduce (or prevent) disruptions at some facilities. In the model developed in this thesis, we consider random supplier disruptions that may arise due to technical difficulties facing the supplier industries.

The resulting model becomes a novel IS network where both energy and material are exchanged symbiotically, while taking supplier disruptions into consideration through chance constraints. The model is formulated as a multi-objective, mixed-integer linear

programming model. The epsilon-constraint method, in conjunction with the distance method will be employed to handle the multiple objective nature of the model, which is an efficient methodology to tackle such problems (Laumanns et al., 2006).

1.2 Thesis Questions

In short, the questions that will be addressed in this thesis are as follows:

- Considering the economic, environmental, and social aspects; how to formulate a mathematical model representing the symbiotic network where suppliers face random disruptions?
- How to optimize an energy and material symbiotic network where suppliers face random disruptions?
- What are most important parameters of the proposed IS model and what is the impact of the changes of their values on the model performance?

1.3 Thesis Objectives

The objective of this thesis is fourfold:

1. We include material exchanges between the industrial users into the IS model instead of focusing only on energy symbiosis.
2. We incorporate energy supply disruptions.

3. We propose solution methodology to handle the obtained multi-objective mathematical model of the IS.
4. We conduct sensitivity analyses on the most important parameters of the model and study their impact.

1.4 Thesis Methodology

Therefore, the methodology that will be used to address the questions of the thesis is as follows:

- 1- The model will be extended to account for other types of symbiotic relationships than energy such as the exchange of material, wastewater and by-products. This will be accomplished by assuming that the industrial users considered in Afshari et al. (2020) allow for the exchange of by-products through a WMREN model. The network will be modified accordingly, and the effect of this extension on the assumptions, objective functions and constraints will be captured.
- 2- Once the necessary adjustments on the model are made, suppliers will be assumed to have intermitent disruptions in the supply of energy and by-products, and this will be accomplished by assuming random loss of the total supply and modeled using chance constraints.
- 3- Now that all the extensions have been applied, the problem becomes a multi-objective, mixed-integer linear programming model. The model will be solved using a solution methodology that invloved independent optimization of objectives (solving for each objective function seperatly), the distance method and the ϵ -

constraint method. That is, the solutions of the independent optimization models will be used as input for the distance method, and the optimal solution obtained from the distance method will be used as lower and upper bounds to the ε -constraint method.

- 4- Sensitivity analysis will be conducted on the most important parameters. First, a comparison between the model before and after considering supplier disruptions will be provided. Then, the effect on the objective values and the total network configuration will be studied when the demand and the selling prices are varied.

The rest of this report is organized as follows: In chapter 2, we provide a comprehensive literature review of the related topics in IS, grouped by commonality. In chapter 3, we articulate the problem discussed in the thesis by explaining the material exchange, the energy exchange and the supplier disruptions. We then provide the notations used and the full optimization model. Then, the case study used to assess the applicability of the proposed model is provided in chapter 4. Moreover, chapter 5 contains the solution of the proposed model using the case study, and also contains the sensitivity analyses by varying important parameters in the model, as well as complexity analyses. Finally, chapter 6 summarizes the contributions of this thesis, and provides the work limitations as well as the future research directions emerging from this work. Figure 1 below summarizes the research process.

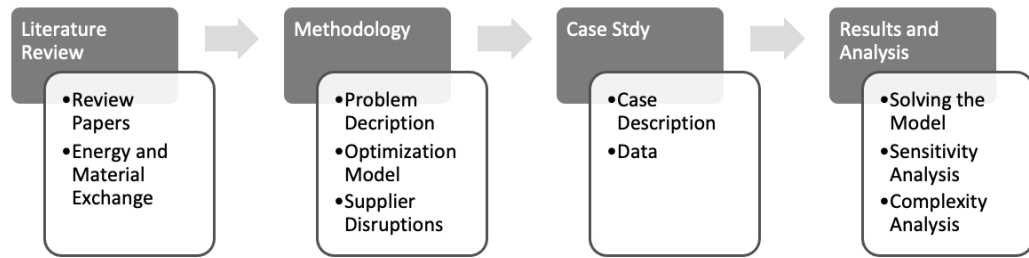


Figure 1: Research Process and Work

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[CHAPTER 2]

[LITERATURE REVIEW

In this chapter, we review the literature of the related topics to our proposed study to define the scope of this research, and we group them by commonality under the following areas:

1) review papers on IS, 2) optimization of energy and material exchange in IS.

2.1 Review Papers in IS

Several comprehensive reviews were conducted in the field of industrial symbiosis, each considering a different aspect such as IS strategy, policies, tools, theory, trends and optimization methods. Demartini et al. (2022) presented a systematic literature review of to investigate and categorize the most commonly used modeling techniques to tackle industrial symbiosis. These modeling techniques include agent-based modeling (AB), material flow analysis (MFA), network analysis (NA), mixed-integer linear programming (MILP) and system dynamics. Based on their findings and the set of reviewed papers, agent-based system dynamics is the most appropriate technique for modeling IS and the authors encouraged using this technique in future IS works.

Another comprehensive literature survey was conducted by Neves et al. (2020). The authors reviewed around 584 publications in the area of IS. They assessed the main lines

of research in IS, and studied the different published case studies by focusing on various aspects such as location, industry type and modeling technique. Moreover, they provided distributions of the studied articles based on type, year of publication, content type (review, case studies, theoretical and others), and the country of publication. Their results show that China tops the list of the highest number of publications in IS, followed by the US. As possible future areas of investigation, they suggested developing a method that encompasses the three pillars of sustainability (economic, environmental and social) in a way the supports decision-making activities in the optimal design of IS, which is the main focus of this thesis.

2.2 Optimization of Energy and Material in IS

Afshari et al. (2020) considered an energy symbiosis network where parties participating in the network exchange energy symbiotically. They filled a gap in the literature by incorporating the social aspect when optimizing an industrial symbiotic network. They formulated the problem as a multi-objective mixed-integer linear programming model while taking the important aspects in the optimal design of energy symbiosis; economic, environmental and social impacts. They also accounted for seasonality in the energy demand throughout the year. They implemented the distance method to rank the solutions of the multi-objective optimization problem, and the was solved using a commercial solver. They also conducted some sensitivity analysis by varying the supply and demand parameters to study the effect on cost, environmental impact and social value preference. Their results suggest that social value preference is inversely proportional to cost and

environmental impact since it encourages building symbiotic connections between parties. This paper is the base paper of this thesis in which the proposed extensions will be applied.

Suzanne et al. (2021) formulated an Industrial Symbiosis (IS) network including two production units as a two-level single-item lot-sizing problem (ULS-IS). The IS network consisted of two production units (PU1 and PU2), where each production unit produces a product to meet a deterministic demand. PU1 produces a product that generates a certain by-product, and this by-product is used as raw material in PU2 to produce their final product. They proposed two different formulations to model the two-level single-item lot-sizing problem in a centralized coordination policy manner, and these two formulations are Straightforward Formulation (AGG) and Facility Location Formulation (FAL). They proved that the resulting model is NP-Hard, and proposed a Lagrangian-decomposition-based solution methodology. They proceeded to conduct extensive numerical experiments to study the tractability and competitiveness of the proposed solution method, which proved to be very efficient in solving the ULS-IS problem.

Fair and stable allocation of the cost of maintaining the information system between the parties participating in an IS system is a problem addressed by Yazdanpanah et al. (2020). They studied the nature of transaction costs (TC) that exist in the context of IS, and model it as a game-form that can result in game theoretic solution concepts for the TC allocation problem. The utilization of game theory as a modeling approach to the TC allocation problem provides advantages such as capturing both the physical and institutional

contributions of the participating firms. The IS is modeled as a graphical game to reflect the established relations among the firms and allows the application of standard fair division methods for sharing the TC, and this modeling technique resulted in a tractable algorithm for the TC allocation problem.

Most of IS related paper in the literature focus on strategic decisions level, and few such as Daquin et al. (2019) paid attention to the tactical decisions level and studied the production planning as a lot sizing problem in an IS network containing two actors. It is assumed that each actor faces a deterministic demand, and each has an external supplier of raw material while actor 2 also uses the waste of actor 1 as raw material. They formulated the production planning problem of the two actors in IS network as a centralized multi-period lot-sizing optimization problem. A numerical example was solved using a software and it is concluded that participating in the industrial symbiotic scheme is more efficient in terms of cost and environmental impact.

Iron and steel industry is considered as an energy-intensive sector with huge environmental impacts and carbon dioxide emissions. Norbert et al. (2018) developed a new methodology and a new tool to evaluate, over time, the environmental and economic impacts of constructing industrial symbiotic relationships for this sector. The whole network was modeled using SD to simulate the model in order to support the decision-making process and provide a systematic approach for assessing the overall IS system performance. The SD model was then validated and applied to a real case study of an iron and steel industry,

and the simulation model was run on different scenarios for 2 years to study the environmental and economic impacts of applying IS in the iron and steel industry.

Demartini et al. (2018) proposed a hybrid approach based on Agent Based Modeling (ABM) and System Dynamics (SD) in order to model an IS system and improve the modeling insight by converting from the traditional static representation to a more complex dynamic system. The authors claim that employing an integrated approach of ABM and SD will address the complexities of IS systems such as non-linear behavior and non-rational interacting behavior in a more efficient way, since both of these approaches are simulation methods used to study the leverage points of complex systems. The IS system examined in the paper consists of 4 firms, namely, a mechanical components plant, a steel plant, a cement plant and paper factory, each producing a single product and can send and receive waste from any firm in the network. The mathematical model governing the SD of the IS system was developed, and it was assumed that each firm acts as an agent that can decide whether or not to construct a symbiotic relationship with the other firms. Results show that establishing industrial symbiotic relationships among the firms results in an overall higher profit.

Cui et al. (2018) employed System Dynamics (SD) to build an IS model in the application of Hai Hua Industrial Symbiosis (HHIS). IS is a non-linear complex problem, and formulating it as an SD model can be extremely helpful to gain insight and visualization on the effect of changing different system parameters. The paper adapted a software called

Vensim software to model the SD of the HHIS, which consists of around 9 interrelated plants exchanging energy, solid waste and wastewater. The aim is to simulate different system scenarios based on different input variables to study the behavior changes of energy consumption, solid waste stock, wastewater stock and symbiotic benefits in HHIS. Based on the various analysis and different scenarios conducted in the paper, the SD model helped illustrate the benefits on the reduction of energy consumption, solid waste stock, wastewater stock that was achieved through the establishment of symbiotic relationships between the parties of the supply chain during the evolution of HHIS.

Brondi et al. (2018) discuss a methodology to quantify the ease of forming symbiotic relationships between parties in an existing industry cluster. They developed a Java tool aimed at and optimizing possible material/energy exchanges within the symbiosis network. This Java tool named Symbioptima provides a company with reliable assessments based on numeral KPIs in order to identify possible beneficial symbiotic relationships with other companies in the same industry cluster. Their approach is based off of the Life Cycle Thinking (LCT) concept. Once different IS scenarios are constructed, they are modeled as a multi-criteria optimization problem and solved via heuristic approaches.

One way of constructing symbiotic collaboration between parties of the supply chain as opposed to the independent SC network is through waste material recycling and exchanging. Huang et al. (2020) is one example of such case, where they proposed an IS optimization model based on waste material recycling and exchanging, and formulated the

problem as a mixed-integer programming model incorporating the three pillars of sustainability: economy, environment and society. They tested the validity of their work on the WMREN model, and solved it using the Epsilon-constraint method. Their model provides managers with greater insight to make better decisions based on various objective priorities.

Moreover, Ren et al. (2016) proposed an innovative mechanism to support better decision making in the design of IS in a chemical complex where sustainability measures are taken into consideration. They did so by incorporating emergy theory (sustainability index function for a given process or economy) and formulating the problem as a multi-objective optimization problem where the objectives are maximizing the economic aspect and the sustainability performance. The model was then solved using the Particle Swarm Algorithm (PSA) where their model was implemented on an illustrative case of a chemical complex. This algorithm provides the decision makers with a pool of feasible Pareto solution that they can pick from, which can be accomplished through the satisfaction degree method.

Most of the papers in the literature discussed IS assuming deterministic demand. Chamani et al. (2021) extended the work on IS by considering a two-stage IS supply chain collaboration with stochastic demand. They focus on the production planning level and formulate the problem as an integrated capacitated lot-sizing problem where the second plant uses the by-product waste of the first plant as raw material. At first, they formulated

the problem under demand uncertainty (Gamma and normally distributed) and solved the resulting mixed-integer linear program using the Sample Average Approximation (SAA). Then, they reformulated the model as a plant location problem as a mean to providing better relaxation gaps as compared to the original formulation. Their results show that the reformulated version performs better in terms of optimality gap but leads to higher computational time.

Industrial Symbiosis (IS) has mostly been implemented in industrial contexts such as the oil industry and the manufacturing industry. Alternatively, Afshari et al. (2018) discussed the opportunities and challenges of energy symbiosis for non-industrial purposes, specifically, residential buildings. They proposed a multi-objective mixed integer linear programming mathematical model under stochastic considerations, where the first objective is minimizing the total cost required to establish the symbiosis network, and the second objective function aims at minimizing the collective environmental impact from consuming energy supplied by internal and external IS sources. Their proposed mathematical model was used on a case study in Western Europe that consists of residential users, industrial users and energy suppliers. They considered different scenarios for potential uncertainties over a long-term period. Based on the results of the model, they concluded that the active contribution of residential buildings in the IS network helps in overcoming financial and cultural barriers, and helps reducing the environmental impact.

Gonela et al. (2015) discussed an IS approach to shed light on the various types of bioethanol plant configurations in order to design an optimal, sustainable and robust hybrid-generation bioethanol supply chains. They formulated the model as a stochastic mixed integer linear programming that maximizes profit under some green sustainability indicator constraints. The problem was then solved using the Sample Average Approximation (SAA) method and the results show that there is a great trade-off between how strong the sustainability standards are, and the economic performance of the IS supply chain.

Up to the best of our knowledge, this research is considered the first in the direction of optimizing the three dimensions of sustainability; economic, environmental and social of an industrial symbiosis network where both the energy and material exchanges are considered while addressing supply disruptions. Table 1 below summarizes the literature pertinent to energy and material symbiosis.

Table 1: Classification of key literature related to this thesis

Reference	IS Exchange ^a		Modeling Technique ^b		Objective Function ^c			Supplier Disruptions
	M	E	MILP	Other	Ec.	En.	S.	
Afshari et al. (2020)		√	√		√	√	√	
Huang et al. (2020)	√		√		√	√	√	
Suzanne et al. (2021)	√		√		√			
Daquin et al. (2019)	√		√		√			
Norbert et al. (2018)	√			√	√	√		
Demartini et al. (2018)	√			√	√			
Cui et al. (2018)	√	√		√	√			
Brondi et al. (2018)	√		√		√	√		
Ren et al. (2016)	√		√		√	√		
Chamani et al (2021)	√		√		√			
Gonela et al. (2015)	√			√	√			
This Thesis	√	√	√		√	√	√	√

^a M: Material, E: Energy

^b Other: Systems dynamics, agent-based modeling, simulation

^c Ec: Economic, En: Environmental, S: Social

CHAPTER 3

METHODOLOGY

Before presenting the proposed model, it is essential to articulate the problem discussed in this thesis. The problem can be viewed from different aspects, starting at explaining the entire symbiosis network as a whole, and then dissecting it into the main types of synergies that exist in the system, which are energy exchange network and the by-product exchange network. Symbiosis, in the context of industrial synergies, has been mainly categorized in two main models: planned EIPs, and self-organized symbiosis (Chertow, M.R., 2007). In the latter, established industries in a close geographic location seek potential opportunities to exchange energy/by-products amongst them, in order to achieve a more cost-efficient and sustainable eco-industrial systems.

Prior to these negotiations between industries, each industry operates independently. Meaning, the raw materials demand will be satisfied from external suppliers, and the energy demand of each industry will be generated internally through an energy generation facility using fossil fuel.

3.1 Problem Description

3.1.1 Material Exchange

According to Haung et al. (2020), the core decision-making factors pertaining the IS network design are the short-term concerns, such as the exchange of material and the recycling/reprocessing of by-products. Therefore, designing a structure that optimizes the core activities in the waste material recycling and exchanging network (WMREN) is a primary objective of this thesis. Given a potential IS network, supplier industries and demand industries strive to move from an independent supply chain network, to an integrated IS network through the exchange of material and the recycling/reprocessing of by-products, which promotes the reuse of what was originally considered waste. The structure of the WMREN model discussed in this thesis is represented in Figure 2, which is a variation of the model developed by Haung et al. (2020).

In a supplier industry, the production process results in different by-products and waste materials. On the other hand, demand industries purchase raw material from external markets to satisfy their demand. However, part of these raw materials can be supplied by recycling/reprocessing different by-products purchased from supplier industries. Therefore, the demand of raw material can either be satisfied from the external raw material market, or processed in the demand industry from the constituting by products. For example, assume that raw material 1 ($r1$) requires by-products $b1$, $b2$ and $b3$ to make, and each by-product has a 50% reprocessing rate. Therefore, in order to make one ton of $r1$, we require two tons $b1$, $b2$ and $b3$.

In Figure 2, supplier industries are denoted by i and demand industries are denoted by j . The blue arrow represents the flow of raw material purchased from external markets. The green arrow refers to by-product flow from supplier industries to demand industries, which are then reprocessed into raw material at the site of demand industries (represented by the green cycle). The remaining by-products gone unprocessed and the secondary by-products that result from the reprocessing activities are moved to the landfill site, which is represented by the yellow arrow.

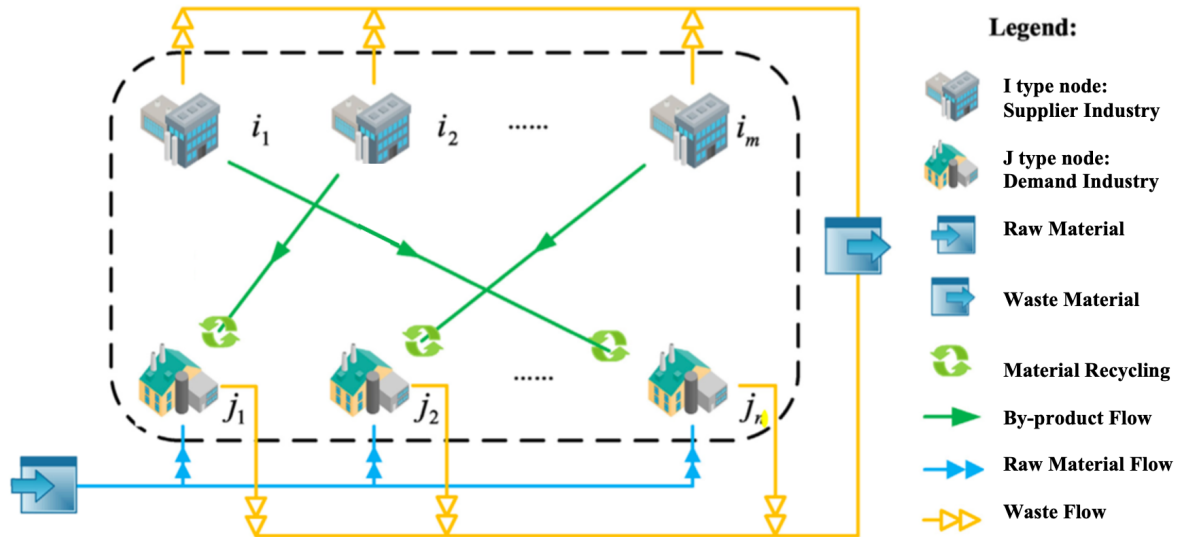


Figure 2: WMREN model for material exchange ([Haung et al., 2020](#))

One of the main challenges concerning the material exchange between industries is the need of energy required by the thermodynamic consumption of internal processes (Afshari et al., 2016). A raising concern to industries is the uncertainties in fuel prices, which makes the use of energy from recovered heat (whether internally, or externally from the symbiosis

network) more cost-efficient. Therefore, industries consider the investment in infrastructure for exchanging the recovered energy symbiotically a desirable one.

3.1.2 Energy Exchange

Given a set of supplier and demand industries, each industry can supply its required energy either internally or externally. Internally means that energy will be generated in an energy generation facility within a demand industry using fossil fuel. On the other hand, externally means it will be purchased from external sources in the symbiosis network. Figure 3 shows a schematic view of an industry that depicts the energy generation facility, and the amount of wasted heat resulting from the different processes within its facility. According to Afshari et al. (2016), internal generation of energy for heat production can be especially expensive and produces harmful greenhouse gases to the environment, which makes establishing a symbiosis network to exchange energy between industries a profitable and a sustainable option.

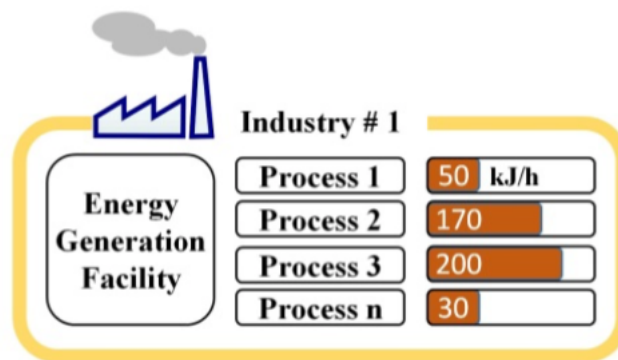


Figure 3: Schematic view of an industry with the energy generation facility ([Afshari et al., 2016](#))

In order for this symbiosis via heat exchange to be established, infrastructure investments in heat exchange networks (HENs) and pipelines to transfer heat must be made. Once HENs and pipelines are constructed, the suppliers of energy will recover the wasted/unused energy from their processes and transfer them to demand industries via the HEN. The demand industries will receive the energy (heat energy by transfer of fluids) in their conditioning facility, to alter the temperature to their required temperature. This process is depicted in Figure 4.

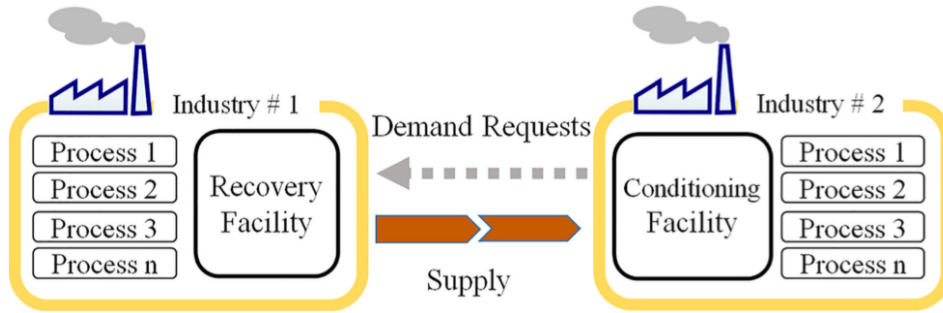


Figure 4: Energy exchange process ([Afshari et al., 2017](#))

Now, the IS network discussed in this thesis will build upon the model of Afshari et al. (2020) for energy exchange, by incorporating a variation of the WMREN model in Haung et al. (2020) to allow for the exchanges of by-products between industries. The problem becomes an integrated energy/by-product/material industrial symbiosis, with the objective of optimizing the flow of energy/by-products between industries, while satisfying the three pillars of sustainability – economic, environmental and social. The model also considers potential symbiosis between residential energy users and energy suppliers. The assumptions of the proposed model are as follows.

- The geographic location of supplier industries, demand industries, external raw material market and residential users and landfill is fixed and known in advance.
- The demand of raw material, whether purchased from external market or reprocessed from by-products, should be fully satisfied.
- The energy demand, whether generated within the demand industry or purchased from supplier industries, should be fully satisfied.
- Energy and by-products demands are known (deterministic) for each period.
- Suppliers of energy and by-products encounter random disruptions that reduce the total amount supplied.
- Infrastructure investments for energy exchange are financed by supplier industries, which will be recovered by selling the recovered energy to demand industries.
- The depreciation of infrastructure investment is considered, and once it reaches its useful life another investment will be made. The cost is charged every time the infrastructure is utilized in a period, and not incurred otherwise.
- The pollution of recovered energy is less than the pollution of generated energy ($PE_i^k < PI_j^k$).
- The infrastructure investment, reprocessing and purchasing cost of by-products should be less than the cost of raw material.
- No backlogging of any type of energy/material/by-product is allowed.
- Reprocessing activities of by-products occur only in demand industries.
- Raw materials are either purchased from an external supplier, or processed in the demand industry from the constituting by-products.

3.2 Optimization Model Without Supplier Disruptions

In this section, we introduce the notations that will be used throughout the modeling of the problem discussed in this thesis, which includes the sets, the decision variables and the parameters of the proposed model. After that, we provide the three objectives and the constraints of the model, followed by a detailed explanation of all the equations.

The notations of the developed model are as follows:

Sets of the proposed model

$1 \dots i \dots I$	Supplier Industries
$1 \dots j \dots J$	Demand Industries
$1 \dots k \dots K$	Energy Product types
$1 \dots b \dots B$	Set of by-products
$1 \dots r \dots R$	Set of raw materials
$1 \dots t \dots T$	Time periods

Decision variables of the proposed model:

x_{ijt}^k	Percentage demand of energy type k supplied by node i to j in period t
π_{jt}^k	Percentage demand of energy type k generated by node j in period t
$\varphi_{ijt}^{b,r}$	Percentage demand of by-product b supplied by i to j for r in period t
$\tau_{ijt}^{b,r}$	level demand of by-product b supplied by i to j to make r in period t
ω_{jt}^r	Percentage demand of raw material r bought by demand industry j from market in period t

y_{ijt}^k	Binary variable, 1 if symbiosis exists between nodes i and j for k in period t , 0 otherwise
n_{jt}^k	Binary variable, 1 if demand industry j generates energy internally in period t , 0 otherwise
z_{ijt}^b	Binary variable, 1 if symbiosis exists between nodes i and j for b in period t , 0 otherwise
g_{ijt}	Binary variable, 1 if symbiosis exists between nodes i and j in period t , 0 otherwise

Parameters of the proposed model

D_{jt}^k	Demand for energy type k by industry j in period t
DR_{jt}^r	Demand for raw material r (ton) by industry j in period t
λ_j^k	Binary parameter, 1 if industry j has a demand for energy type k , 0 otherwise
δ_j^r	Binary parameter, 1 if industry j has a demand for raw material r , 0 otherwise
SK_{it}^k	Fixed supply amount of industry i for energy type k in period t
SB_{it}^b	Fixed supply amount of industry i for by-product b (ton) in period t
$RR_j^{b,r}$	Reprocessing rate of one unit of by-product b into raw material r at demand industry j
$u^{b,r}$	Binary parameter, 1 if b can be used to make r , 0 otherwise
MC_j	Capacity of demand industry j for reprocessing by-products
PL_{ij}^k	Pipeline distance from industry i to j for product energy type k
RL_{ij}^b	Road distance from industry i to j for by-product type b
ML_j^r	Road distance from the source of raw material r (market) to demand industry j
LL_i	Distance from supplier-industry i to the waste landfill

LL_j	Distance from demand-industry j to the waste landfill
CES_{ijt}	Cost of establishing a symbiosis between i and j in period t (management and other costs)
U_{ij}^k	Unit (pipeline construction) cost for connecting i to j for k (if any)
CD_j^k	Fixed cost of generating energy type k by demand industry j
CC_{ij}^k	Fixed temperature conditioning cost for energy type k to supply to j from i
VCC_{ij}^k	Variable temperature conditioning cost for energy type k to supply to j from i
CE_{ij}^k	Unit selling price of energy type k recovered at i and sold to j
CI_j^k	Variable cost of generating energy type k by demand industry j
FRC_{ij}^k	Fixed cost of recovering energy type k for industry j in i
RC_{ij}^k	Variable cost of recovering energy type k for industry j in i
TC_j^k	Energy type k carbon tax imposed on industry j
TS_i^k	Tax saving amount industry i receives by exporting energy type k
$CBT_j^{b,r}$	Treatment cost of j when reprocessing one unit of by-product b into raw material r
CFT_j^b	Fixed reprocessing cost of b in demand industry j
CUT_{ij}^b	Unit transportation cost (per ton) of by-product b from i to j per kilometer
CUR_j^r	Unit transportation cost (per ton) of raw material r from external market per kilometer
CUW	Unit transportation cost (per ton) of waste from industries to landfill per kilometer
CR^r	Unit cost of purchasing raw material r from external market
CB_i^b	Unit price of by-product b at supplier-industry i
α_{ij}^k	Pipeline depreciation rate between nodes i and j

β_{ij}^k	Facilities depreciation rate between nodes i and j
γ_j^b	By-product reprocessing facility depreciation rate at j
PE_i^k	Environmental impact of recovering energy type k by industry i
PI_j^k	Environmental impact of generating energy type k by industry j
PB_i^b	Environmental impact of generating by-product b by industry i
γ	The maximum allowed distance between two industries
PV_i^k	Social value preference when producing energy type k by i
PV_i^b	Social value preference when producing by-product b by i
TMP_j	Temperature of energy type k supplied by industry i
TMP_i^k	Temperature of energy type k demanded by industry j
M	A large positive integer

Hence, the optimization model is as follows:

$$\begin{aligned}
& \min Z_1 \\
& = \sum_{k=1}^K \sum_{i=1}^I \sum_{j=1}^J \sum_{t=1}^T CD_j^k \beta_{ij}^k n_{jt}^k + \sum_{k=1}^K \sum_{j=1}^J \sum_{t=1}^T CI_j^k D_{jt}^k (\pi_{jt}^k) \\
& + \sum_{k=1}^K \sum_{i=1}^I \sum_{j=1}^J \sum_{t=1}^T [U_{ij}^k PL_{ij}^k \alpha_{ij}^k + (FRC_{ij}^k + CC_{ij}^k) \beta_{ij}^k] y_{ijt}^k \\
& + \sum_{k=1}^K \sum_{i=1}^I \sum_{j=1}^J \sum_{t=1}^T (RC_{ij}^k + VCC_{ij}^k) D_{jt}^k x_{ijt}^k + \sum_{k=1}^K \sum_{j=1}^J \sum_{t=1}^T TC_j^k D_{jt}^k \left(\pi_{jt}^k - \sum_{i=1}^I x_{ijt}^k \right) \\
& - \sum_{k=1}^K \sum_{i=1}^I \left(TS_i^k \sum_{j=1}^J \sum_{t=1}^T D_{jt}^k x_{ijt}^k \right) + \sum_{r=1}^R \sum_{j=1}^J \sum_{t=1}^T (CR^r + CUR_j^r ML_j^r) DR_{jt}^r \omega_{jt}^r \\
& + \sum_{r=1}^R \sum_{b=1}^B \sum_{i=1}^I \sum_{j=1}^J \sum_{t=1}^T (CB_i^b + CUT_{ij}^b RL_{ij}^b) DR_{jt}^r \tau_{ijt}^{b,r} + \sum_{r=1}^R \sum_{b=1}^B \sum_{i=1}^I \sum_{j=1}^J \sum_{t=1}^T CBT_j^{b,r} DR_{jt}^r \tau_{ijt}^{b,r} \\
& + \sum_{r=1}^R \sum_{b=1}^B \sum_{i=1}^I \sum_{j=1}^J \sum_{t=1}^T CUWLL_j (1 - RR_j^{b,r}) DR_{jt}^r \tau_{ijt}^{b,r} \\
& + \sum_{r=1}^R \sum_{b=1}^B \sum_{i=1}^I \sum_{j=1}^J \sum_{t=1}^T CUWLL_i (SB_{it}^b - DR_{jt}^r \tau_{ijt}^{b,r}) + \sum_{b=1}^B \sum_{i=1}^I \sum_{j=1}^J \sum_{t=1}^T CFT_j^b \gamma_j^b z_{ijt}^b \\
& + \sum_{i=1}^I \sum_{j=1}^J \sum_{t=1}^T CES_{ijt} g_{ijt} \tag{1}
\end{aligned}$$

$$\begin{aligned}
\min Z_2 = & \sum_{k=1}^K \sum_{i=1}^I PE_i^k \sum_{j=1}^J \sum_{t=1}^T D_{jt}^k x_{ijt}^k + \sum_{k=1}^K \sum_{i=1}^I \sum_{t=1}^T PI_j^k D_{jt}^k (\pi_{jt}^k) \\
& + \sum_{b=1}^B \sum_{i=1}^I PB_i^b \left(\sum_{t=1}^T SB_{it}^b - \sum_{r=1}^R \sum_{j=1}^J \sum_{t=1}^T DR_{jt}^r RR_j^{b,r} \tau_{ijt}^{b,r} \right) \tag{2}
\end{aligned}$$

$$\max Z_3 = \sum_{k=1}^K \sum_{i=1}^I \sum_{t=1}^T PV_i^k x_{ijt}^k + \sum_{b=1}^B \sum_{i=1}^I \sum_{t=1}^T PV_i^b \tau_{ijt}^{b,r} \tag{3}$$

Subject to the following constraints:

a. Demand Constraints:

$$\pi_{jt}^k + \sum_{i=1}^I x_{ijt}^k = \lambda_j^k \quad \forall k, j, t \quad (4)$$

$$\varphi_{ijt}^{b,r} = RR_j^{b,r} \tau_{ijt}^{b,r} \quad \forall i, j, b, r, t \quad (5)$$

$$\omega_{jt}^r \leq \delta_j^r \quad \forall j, r, t \quad (6)$$

$$\sum_{i=1}^I \varphi_{ijt}^{b,r} = \delta_j^r u^{b,r} (1 - \omega_{jt}^r) \quad \forall j, b, r, t \quad (7)$$

b. Supply and Capacity Constraints:

$$\sum_{j=1}^J \frac{D_{jt}^k x_{ijt}^k}{1 - \left(\frac{TMP_j}{TMP_i} \right)} \leq SK_{it}^k \quad \forall k, i, t \quad (8)$$

$$\sum_{j=1}^J \sum_{r=1}^R \tau_{ijt}^{b,r} DR_{jt}^r \leq SB_{it}^b \quad \forall b, i, t \quad (9)$$

$$\sum_{r=1}^R \sum_{b=1}^B \sum_{i=1}^I \tau_{ijt}^{b,r} DR_{jt}^r \leq MC_j \quad \forall j, t \quad (10)$$

c. Cost and Profitability Constraints:

$$\begin{aligned} & CD_j^k \sum_{i=1}^I \beta_{ij}^k y_{ijt}^k + CI_j^k D_{jt}^k \sum_{i=1}^I x_{ijt}^k + TC_j^k D_{jt}^k (\pi_{jt}^k) \\ & \geq \sum_{i=1}^I CE_{ij}^k D_{jt}^k x_{ijt}^k \quad \forall k, j, t \end{aligned} \quad (11)$$

$$\begin{aligned} & [U_{ij}^k PL_{ij}^k \alpha_{ij}^k + (FRC_{ij}^k + CC_{ij}^k) \beta_{ij}^k] y_{ijt}^k + (RC_{ij}^k + VCC_{ij}^k) D_{jt}^k x_{ijt}^k - TS_i^k D_{jt}^k x_{ijt}^k \\ & \leq CE_{ij}^k D_{jt}^k x_{ijt}^k \quad \forall k, i, j, t \end{aligned} \quad (12)$$

$$\begin{aligned} & [U_{ij}^k PL_{ij}^k \alpha_{ij}^k + (FRC_{ij}^k + CC_{ij}^k) \beta_{ij}^k] y_{ijt}^k + (RC_{ij}^k + VCC_{ij}^k) D_{jt}^k x_{ijt}^k - TS_i^k D_{jt}^k x_{ijt}^k \\ & \leq CI_j^k D_{jt}^k x_{ijt}^k \quad \forall k, i, j, t \end{aligned} \quad (13)$$

d. Symbiosis Logic and Restrictions:

$$x_{ijt}^k \leq y_{ijt}^k \quad \forall k, i, j, t \quad (14)$$

$$\sum_{i=1}^I x_{ijt}^k \geq \lambda_j^k (1 - n_{jt}^k) \quad \forall k, j, t \quad (15)$$

$$\varphi_{ijt}^{b,r} \leq z_{ijt}^b \quad \forall b, r, i, j, t \quad (16)$$

$$\varphi_{ijt}^{b,r} \leq u^{b,r} \quad \forall b, r, i, j, t \quad (17)$$

$$\sum_{b=1}^B z_{ijt}^b + \sum_{k=1}^K y_{ijt}^k \leq M g_{ijt} \quad \forall i, j, t \quad (18)$$

$$(PL_{ij}^k - \gamma) x_{ijt}^k \leq 0 \quad \forall k, i, j, t \quad (19)$$

$$0 \leq x_{ijt}^k, \varphi_{ijt}^{b,r}, \omega_{jt}^r, \pi_{jt}^k \leq 1, \quad \tau_{ijt}^{b,r} \geq 0, \quad y_{ijt}^k, n_{jt}^k, z_{ijt}^b, g_{ijt} \in \{0,1\} \quad \forall k, b, r, i, j, t \quad (20)$$

The first sub-objective function (Z_1) is aimed to minimize the total cost of establishing and operating the industrial symbiosis system for T periods. The total cost function includes the energy generation fixed cost of demand industries (term 1), the energy generation variable cost of demand industries (term 2), the fixed cost of energy transfer/recovery/conditioning by IS industries (term 3), the variable cost of energy recovery/conditioning by IS industries (term 4), the tax amount imposed on/saved by demand industries (term 5), and the tax savings received by the suppliers (term 6).

Furthermore, the function also includes the cost of purchasing and transporting raw material from external market (term 7), cost of purchasing and transporting by-products (term 8), treatment cost of turning by-products into raw material (term 9), cost of transporting the waste material, after reprocessing by-products into raw material at demand-industries, to the waste landfill node (term 10), the cost of transporting the waste material, resulting from extra by-products at supplier-industries, to the waste landfill node (term 11). Term 12 is incurred as a fixed cost of establishing a symbiosis between two nodes if there is either a by-product or energy exchange. Meaning, a fixed cost will be incurred only once regardless of the number of by-product/material exchanges between industries.

Minimizing the total amount of waste material and the environmental impact caused by energy consumption is a vital environmental objective of industrial symbiosis. The second sub-objective function (Z_2) is introduced to minimize the total environmental impact of the established IS. The first term in the function measures the environmental impact of producing energy at the supplier industries to be transferred to demand industries (energy symbiosis), while the second term measures that of internal energy production in the demand industries' facilities (generating energy using fossil fuels). The third term in Z_2 denotes the environmental impact of waste material resulting from unprocessed by-products that will be disposed of. More specifically, it is the environmental impact of difference between the total amount of by-products generated at supplier-industries and the total amount processed into raw material at demand industries.

This study aims to simultaneously optimize the three pillars of sustainability: economic, environmental and social impact. Both the economic and environmental impacts are quantitative measures captured by Z_1 and Z_2 , respectively. On the other hand, the social sub-objective (Z_3) is a qualitative measure that needs to be quantified in order to optimize it. As suggested by Afshari et al. (2020), a multiple criteria decision-making approach called the analytic network process (ANP) will be employed to prioritize suppliers based on their values perceived by customers. The qualitative social value will be converted into a quantitative measure (PV) based on the suppliers' environmental practices, utilization of eco-technology and their social contribution. Therefore, the first term measures the total social value preference of produced energies, and the second measures that of generated by-products.

As for the model constraints, they are divided into different blocks based on their logic. Equations (4)-(7) are demand-related constraint, where equation (4) ensures that the energy supplied by supplier industries does not exceed the energy demand of demand industries. Equation (5) establishes the relationship between the demand level and demand percentage of by-products supplied to industries. The demand level is defined as the percentage of by-product that is used to make r in terms of the demand of r itself, taking into consideration the reprocessing rate of the by-product. Equation (6) makes sure that the raw material purchased from external suppliers does not exceed the raw material demand. This is complemented by Equation (7), which ensures that the demand of by-products constituting a raw material is satisfied from the symbiosis network. Equations (5)-(7) are a novel formulation that is considered one of the contributions of this thesis.

Equations (8)-(10) are supply and capacity constraints, where equation (8) forces the amount of fulfilled demand to be within the supplier industries capacity. Both these equations take into consideration the difference between temperatures of supplied and demanded energy. Equation (9) ensures that the amount of by-product supplied to all buyer-firms does not exceed the capacity of that by-product in seller-firms. Equation (10) represents the capacity cap for each buyer-firm for by-product reprocessing into raw material.

Moreover, equations (11)-(13) are cost constraints where equation (11) makes sure that participating in energy symbiosis is more cost-effective than internal energy generation by fossil fuel consumption. Equation (12) guarantees a profitable symbiosis investment for each supplier industry. Meaning, revenues from supplying recovered energy should cover all investments in a given period. Equation (13), on the other hand, investigates the profitability of the demand industries for each energy symbiosis.

Equations from (14)-(20) represent the symbiosis logic and restrictions, where energy flows are restricted to the selected symbiosis network by equation (14). Equation (15) ensures that if the energy demand is not fully satisfied from the symbiosis, the energy demand industry will generate the full (or remaining) demand internally. Equation (16) guarantees that if symbiosis is not established between industries for a certain by-product, then the flow between them for that by-product will be zero. Equation (17) ensures that the by-product exchange is equal to zero if by-product b is not used to make raw material r .

and equation (18) ensures that the fixed cost of establishing a symbiosis between two industries will be incurred only once, regardless of the number of energy/material exchanges between industries. Equation (19) ensures that energy symbiosis only exists if the distance between industries is within the maximum allowable distance. Finally, equation (20) defines the decision variables in the proposed model.

3.3 Incorporating Supplier Disruptions

In the model presented in this thesis, there are potentially two types of supply disruptions: one associated with the supply of energy (waste water) through pipelines, and the other for the supply of material/by-products. Water distribution networks are prone to multiple types of failures, and there are several factors contributing to pipeline failures such as pipe geometry, material type, internal loads and material deterioration (Wilson et al., 2017). According to Kleiner & Ragani (2001), several statistical models exist to predict the frequency of water pipeline failures, most of which require knowledge and data specific to the pipelines and their history. Since none of this data exists, the disruptions in the supply of energy in this thesis will be modeled as a random decrease in the supply of energy at period t due to disruptions. This way, the uncertainty of the supply of energy and by-products will be considered in the model without delving into the technicalities of the failure causes and models.

Inspired by Aghaie & Heidary (2019), the disruption in the total supply of suppliers will be modeled as a loss percentage of the deterministic supply of each supplier in the system at a given period t due to an event. That is, a new random variable with a specific distribution function will be introduced in the model, that reduces the supply of the suppliers by a percentage determined by the distribution of the random variable. Evidently, the introduction of this random variable to the model will transform it from deterministic to stochastic optimization. Chance constraints have been first introduced by Charnes & Cooper (1959) to tackle stochastic considerations in optimization, and later on Charnes & Cooper (1963) discussed the concept of obtaining the deterministic equivalent of the chance constraint, which eliminates all random elements from the model. In this thesis, chance constraints will be utilized to model the supplier disruptions, where the deterministic equivalent to the chance constraint exists and can be obtained. The following notations are introduced to formulate the problem:

Table 2: Parameters of the supplier disruptions

κ_{it}	Loss percentage of the fixed supply amount of supplier i as a result of a disruption in an event at time t (random variable)
μ_{it}	Mean loss percentage of the fixed supply amount of supplier i as a result of a disruption in an event at time t
σ_{it}^2	Variance of loss percentage of the fixed supply amount of supplier i as a result of a disruption in an event at time t
α_i	Service level; level of probability that percentage demand to be supplied by i to all demand industries does not exceed the fixed supply amount of the supplier
$F_{SK_{it}^k}^{-1}$	Inverse probability distribution function for random energy supply for a given α_i

$F_{SB_{it}^b}^{-1}$	Inverse probability distribution function for random by-product supply for a given α_i
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Now, given the loss percentage κ_{it} , the supply of energy SK_{it}^k and the supply of by-products SB_{it}^b , the new capacities after an event occurs causing a disruption in the supply become

$$SK'_{it}^k = (1 - \kappa_{it})SK_{it}^k \quad (21)$$

$$SB'_{it}^b = (1 - \kappa_{it})SB_{it}^b \quad (22)$$

The above expressions for the new capacities are flexible in the sense that κ_{it} may be defined as a binary random variable that denotes complete elimination of supply when $\kappa_{it} = 1$, or it may be defined as the proportion of the total supply that is affected by the disruptions.

Assuming κ_{it} follows a cumulative distribution function $F_{\kappa_{it}}$, it follows that SK'_{it}^k follows the same distribution denoted $F_{SK'_{it}^k}$. For instance, assume $\kappa_{it} \sim N(\mu_{it}, \sigma_{it}^2)$, now since $SK'_{it}^k = (1 - \kappa_{it})SK_{it}^k$, it follows that $SK'_{it}^k \sim N\left[(1 - \mu_{it})SK_{it}^k, (SK_{it}^k)^2 \sigma_{it}^2\right]$. We can model this situation with the chance constraint applied to equation (8) as given below:

$$P \left(\sum_{j=1}^J \frac{D_{jt}^k x_{ijt}^k}{1 - \left(\frac{TMP_j}{TMP_i} \right)} \leq SK'_{it} \right) \geq \alpha_i \quad \forall k, i, t \quad (23)$$

The deterministic equivalent to the chance constraint presented above will be

$$\begin{aligned} & P \left(\sum_{j=1}^J \frac{D_{jt}^k x_{ijt}^k}{1 - \left(\frac{TMP_j}{TMP_i} \right)} \geq SK'_{it} \right) \leq 1 - \alpha_i \quad \forall k, i, t \\ & \Leftrightarrow F_{SK'_{it}} \left(\sum_{j=1}^J \frac{D_{jt}^k x_{ijt}^k}{1 - \left(\frac{TMP_j}{TMP_i} \right)} \right) \leq 1 - \alpha_i \\ & \Leftrightarrow \sum_{j=1}^J \frac{D_{jt}^k x_{ijt}^k}{1 - \left(\frac{TMP_j}{TMP_i} \right)} \leq F_{SK'_{it}}^{-1}(1 - \alpha_i) \quad \forall k, i, t \end{aligned} \quad (24)$$

Note that the deterministic equivalent in equation (24) preserves the linearity of equation (23), and the model remains a mixed-integer linear programming model. Applying the same procedure for the supply of by-products, equation (9) in section 3.2 becomes:

$$\sum_{j=1}^J \sum_{r=1}^R \tau_{ijt}^{b,r} DR_{jt}^r \leq F_{SB'_{it}}^{-1}(1 - \alpha_i) \quad \forall b, i, t \quad (25)$$

Finally, the new model after incorporating supplier disruptions becomes:

$$\begin{aligned}
& \min \mathcal{Z}_1 \\
& = \sum_{k=1}^K \sum_{i=1}^I \sum_{j=1}^J \sum_{t=1}^T CD_j^k \beta_{ij}^k n_{jt}^k + \sum_{k=1}^K \sum_{j=1}^J \sum_{t=1}^T CI_j^k D_{jt}^k (\pi_{jt}^k) \\
& + \sum_{k=1}^K \sum_{i=1}^I \sum_{j=1}^J \sum_{t=1}^T [U_{ij}^k PL_{ij}^k \alpha_{ij}^k + (FRC_{ij}^k + CC_{ij}^k) \beta_{ij}^k] y_{ijt}^k \\
& + \sum_{k=1}^K \sum_{i=1}^I \sum_{j=1}^J \sum_{t=1}^T (RC_{ij}^k + VCC_{ij}^k) D_{jt}^k x_{ijt}^k + \sum_{k=1}^K \sum_{j=1}^J \sum_{t=1}^T TC_j^k D_{jt}^k \left(\pi_{jt}^k - \sum_{i=1}^I x_{ijt}^k \right) \\
& - \sum_{k=1}^K \sum_{i=1}^I \left(TS_i^k \sum_{j=1}^J \sum_{t=1}^T D_{jt}^k x_{ijt}^k \right) + \sum_{r=1}^R \sum_{j=1}^J \sum_{t=1}^T (CR^r + CUR_j^r ML_j^r) DR_{jt}^r \omega_{jt}^r \\
& + \sum_{r=1}^R \sum_{b=1}^B \sum_{i=1}^I \sum_{j=1}^J \sum_{t=1}^T (CB_i^b + CUT_{ij}^b RL_{ij}^b) DR_{jt}^r \tau_{ijt}^{b,r} + \sum_{r=1}^R \sum_{b=1}^B \sum_{i=1}^I \sum_{j=1}^J \sum_{t=1}^T CBT_j^{b,r} DR_{jt}^r \tau_{ijt}^{b,r} \\
& + \sum_{r=1}^R \sum_{b=1}^B \sum_{i=1}^I \sum_{j=1}^J \sum_{t=1}^T CUWLL_j (1 - RR_j^{b,r}) DR_{jt}^r \tau_{ijt}^{b,r} \\
& + \sum_{r=1}^R \sum_{b=1}^B \sum_{i=1}^I \sum_{j=1}^J \sum_{t=1}^T CUWLL_i (SB_{it}^b - DR_{jt}^r \tau_{ijt}^{b,r}) + \sum_{b=1}^B \sum_{i=1}^I \sum_{j=1}^J \sum_{t=1}^T CFT_j^b \gamma_j^b z_{ijt}^b \\
& + \sum_{i=1}^I \sum_{j=1}^J \sum_{t=1}^T CES_{ijt} g_{ijt}
\end{aligned} \tag{26}$$

$$\begin{aligned}
\min \mathcal{Z}_2 = & \sum_{k=1}^K \sum_{i=1}^I PE_i^k \sum_{j=1}^J \sum_{t=1}^T D_{jt}^k x_{ijt}^k + \sum_{k=1}^K \sum_{i=1}^I \sum_{t=1}^T PI_j^k D_{jt}^k (\pi_{jt}^k) \\
& + \sum_{b=1}^B \sum_{i=1}^I PB_i^b \left(\sum_{t=1}^T SB_{it}^b - \sum_{r=1}^R \sum_{j=1}^J \sum_{t=1}^T DR_{jt}^r RR_j^{b,r} \tau_{ijt}^{b,r} \right)
\end{aligned} \tag{27}$$

$$\max \mathcal{Z}_3 = \sum_{k=1}^K \sum_{i=1}^I \sum_{t=1}^T PV_i^k x_{ijt}^k + \sum_{b=1}^B \sum_{i=1}^I \sum_{t=1}^T PV_i^b \tau_{ijt}^{b,r} \tag{28}$$

Subject to the following constraints:

e. Demand Constraints:

$$\pi_{jt}^k + \sum_{i=1}^I x_{ijt}^k = \lambda_j^k \quad \forall k, j, t \quad (29)$$

$$\varphi_{ijt}^{b,r} = RR_j^{b,r} \tau_{ijt}^{b,r} \quad \forall i, j, b, r, t \quad (30)$$

$$\omega_{jt}^r \leq \delta_j^r \quad \forall j, r, t \quad (31)$$

$$\sum_{i=1}^I \varphi_{ijt}^{b,r} = \delta_j^r u^{b,r} (1 - \omega_{jt}^r) \quad \forall j, b, r, t \quad (32)$$

f. Supply and Capacity Constraints:

$$\Leftrightarrow \sum_{j=1}^J \frac{D_{jt}^k x_{ijt}^k}{1 - \left(\frac{TMP_j}{TMP_i} \right)} \leq F_{SK_{it}^k}^{-1} (1 - \alpha_i) \quad \forall k, i, t \quad (33)$$

$$\sum_{j=1}^J \sum_{r=1}^R \tau_{ijt}^{b,r} DR_{jt}^r \leq F_{SB_{it}^{b}}^{-1} (1 - \alpha_i) \quad \forall b, i, t \quad (34)$$

$$\sum_{r=1}^R \sum_{b=1}^B \sum_{i=1}^I \tau_{ijt}^{b,r} DR_{jt}^r \leq MC_j \quad \forall j, t \quad (35)$$

g. Cost and Profitability Constraints:

$$\begin{aligned} & CD_j^k \sum_{i=1}^I \beta_{ij}^k y_{ijt}^k + CI_j^k D_{jt}^k \sum_{i=1}^I x_{ijt}^k + TC_j^k D_{jt}^k (\pi_{jt}^k) \\ & \geq \sum_{i=1}^I CE_{ij}^k D_{jt}^k x_{ijt}^k \quad \forall k, j, t \end{aligned} \quad (36)$$

$$\begin{aligned} & [U_{ij}^k PL_{ij}^k \alpha_{ij}^k + (FRC_{ij}^k + CC_{ij}^k) \beta_{ij}^k] y_{ijt}^k + (RC_{ij}^k + VCC_{ij}^k) D_{jt}^k x_{ijt}^k - TS_i^k D_{jt}^k x_{ijt}^k \\ & \leq CE_{ij}^k D_{jt}^k x_{ijt}^k \quad \forall k, i, j, t \end{aligned} \quad (37)$$

$$\begin{aligned} & [U_{ij}^k PL_{ij}^k \alpha_{ij}^k + (FRC_{ij}^k + CC_{ij}^k) \beta_{ij}^k] y_{ijt}^k + (RC_{ij}^k + VCC_{ij}^k) D_{jt}^k x_{ijt}^k - TS_i^k D_{jt}^k x_{ijt}^k \\ & \leq CI_j^k D_{jt}^k x_{ijt}^k \quad \forall k, i, j, t \end{aligned} \quad (38)$$

h. Symbiosis Logic and Restrictions:

$$x_{ijt}^k \leq y_{ijt}^k \quad \forall k, i, j, t \quad (39)$$

$$\sum_{i=1}^I x_{ijt}^k \geq \lambda_j^k (1 - n_{jt}^k) \quad \forall k, j, t \quad (40)$$

$$\phi_{ijt}^{b,r} \leq z_{ijt}^b \quad \forall b, r, i, j, t \quad (41)$$

$$\phi_{ijt}^{b,r} \leq u^{b,r} \quad \forall b, r, i, j, t \quad (42)$$

$$\sum_{b=1}^B z_{ijt}^b + \sum_{k=1}^K y_{ijt}^k \leq M g_{ijt} \quad \forall i, j, t \quad (43)$$

$$(PL_{ij}^k - \gamma) x_{ijt}^k \leq 0 \quad \forall k, i, j, t \quad (44)$$

$$0 \leq x_{ijt}^k, \phi_{ijt}^{b,r}, \omega_{jt}^r, \pi_{jt}^k \leq 1, \quad \tau_{ijt}^{b,r} \geq 0, \quad y_{ijt}^k, n_{jt}^k, z_{ijt}^b, g_{ijt} \in \{0,1\} \quad \forall k, b, r, i, j, t \quad (45)$$

CHAPTER 4

CASE STUDY

The case study used to examine the applicability of the proposed model is inspired by the case study discussed by Afshari et al. (2020). However, this thesis extends the model to incorporate material/by-product considerations, which is captured by the case study of the WMREN model by Haung et al. (2020). Research data is employed and modified from these two sources. Therefore, the assumed scenario (case study) solved in this thesis is a mixture of two real-life cases. Namely, an energy symbiosis network for a set of industries in France, and a WMREN model located in Sweden. The integrated network is found in Figure 5. The problem consists of 3 energy suppliers, 6 industrial energy users, 3 residential energy users, 3 by-product suppliers, 3 by-product users, one external raw material market and one waste landfill.

The energy suppliers/users and by-product suppliers/users overlap, meaning that one industry may demand energy and supply by-products concurrently. If an industry supplies and demands at the same time, these activities are enclosed in one rectangle as in Figure 5. For example, industry “S1, D8” in the figure supplies energy, and demands certain by-products for its own production process. Moreover, industry “D4, S5” demands energy and supplies by-products in the network while industry “D3” demands both energy and by-products from the symbiosis network.

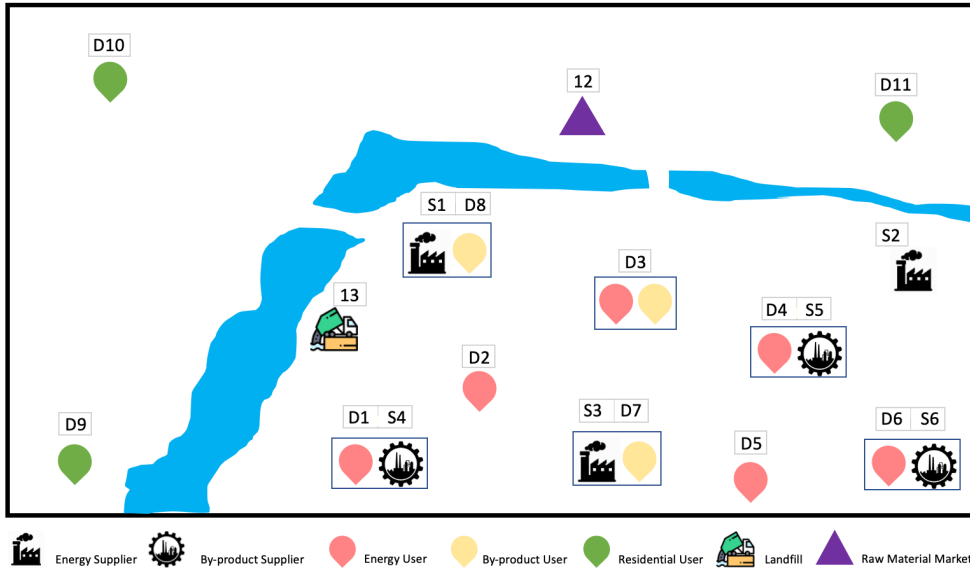


Figure 5: Topography of the case study

The pipeline and road distances between industries can be found in Tables 3 and 4, respectively.

Table 3: Pipeline distance (km) between industries

Energy Supplier	Industrial Energy Users						Residential Energy Users		
	D1	D2	D3	D4	D5	D6	D9	D10	D11
S1	7	4	6	8	6	17	18	7	15
S2	13	11	7	4	3	2	22	25	7
S3	3	5	2	10	3	8	9	21	19

Table 4: Road distance (km) of WMREN model

	D1	D8	D3	D7	D4	D6	Landfill (13)	Market (12)
S4	0	7	8	8	12	21	6	
D8	7	0	5	11	13	9	4	10
D3	8	5	0	5	5	7	7	14
D7	8	11	5	0	11	6	8	19

S5	12	13	5	11	0	7	10
S6	21	9	7	6	7	0	14
Landfill (13)	6	4	7	8	10	14	0
Market (12)		10	14	19			0

As per the data employed from the sources, the new configuration contains one energy product type (wasted heat), 3 by-product types (e.g., bark and fiber sludge) and 3 raw material types which are exchanged in the symbiosis. For example, Industry “S1, D8” requires raw material 1 for one of its processes, which can be acquired as by-products 1, 2 and 3 from the symbiosis then reprocessed inside the facility. In principle, the process in which by-products are reprocessed into raw materials corresponds to a reprocessing rate (the actual amount of the by-product utilized to constitute a recycled raw material) and a treatment cost. This data is shown in Table 5 below.

Table 5: Types of parameters involved in the model

B	R	Reprocessing Rate	Treatment Cost (\$/ton)
b1	r1	0.45	5.1
b1	r2	0*	0
b1	r3	0.65	5.1
b2	r1	0.56	5.0
b2	r2	0.46	7.3
b2	r3	0	0
b3	r1	0.65	5.1
b3	r2	0.56	7.4
b3	r3	0.46	9.3

*Note: if the reprocessing rate is zero, it means that by-product *b* cannot be converted into recycled raw material *r*.

Other parameters involved in the model such as energy demand, raw material demand, capacities and costs are found in Table 6 below.

Table 6: Major parameters used in the optimization model

I = 6*	$U_{ij}^k = 2,653,300$	$TC_j^k = 0.0042$	$PV_i^k = (0.5, 0.2, 0.3, 0, 0, 0)$	$CUT_{ij}^b = 1$
J = 11**	$CD_j^k = 500,000$	$TS_i^k = 0.0042$	$PV_i^b = (0, 0, 0, 0.35, 0.35, 0.3)$	$CUR_j^r = 1.3$
K = 1	$CC_{ij}^k = 400,000$	$CES_{ijt} = 12,000$	$PI_j^k = 0.074 \text{ kg CO}_2/\text{kWh}$	$CUW = 0.4$
R = 3	$CE_{ij}^k = 0.056$	$CFT_j^b = 350,000$	$PE_i^k = 0.06 \text{ kg CO}_2/\text{kWh}$	$CR^r = (412, 321, 430)$
B = 3	$CI_j^k = 0.07$	$VCC_{ij}^k = 0.008$	$PB_i^b = (200, 240, 190) \text{ kg CO}_2/\text{ton}$	$CB_i^b = (44, 39, 54)$
T = 4	$RC_{ij}^k = 0.028$	$\alpha_{ij}^k = 0.05$		
	$FRC_{ij}^k = 300,000$	$\beta_{ij}^k = 0.1$	$M_j = (0, 0, 50000, 0, 0, 0, 50000, 50000, 0, 0, 0)$	
	$\lambda_j^k = (1, 1, 1, 1, 1, 1, 0, 0, 1, 1, 1)$	$\gamma_j^b = 0.05$	$u^{b,r} = [(1, 0, 1), (1, 1, 0), (1, 1, 1)]$	
	$\delta_j^r = [(0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0), (0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0), (0, 0, 1, 0, 0, 0, 1, 0, 0, 0, 0)]$			

Note*: there are 3 energy suppliers (i.e., i=1, 2, 3) and 3 by-product suppliers (i.e. i=4, 5, 6).

Note**: there are 9 energy users (6 industrial and 3 residential) and 3 by-product users.

The fixed energy supply and demand specifications are found in Table 7 below.

Table 7: Energy supply and demand specifications

		Heat (Ton/period)	Energy (kWh/period) x10 ³		Temperature (K°)
Supplier Industries	S1	90	SK_{it}^k	1414000	673
	S2	70		1514000	523
	S3	100		1314000	473
Demand Industries	D1	70	D_{jt}^k	459900	403
	D2	10		65700	443

	D3	60		394200	423
	D4	35		229950	403
	D5	30		197100	383
	D6	25		164250	373
	D9	6.97		(45800, 54960, 46258, 43510)	322
	D10	14.13		(92810, 111372, 93738, 88169)	322
	D11	10.46		(68700, 82440, 69387, 65265)	322

Moreover, the fixed material supply and demand specifications are enlisted in Table 8.

Table 8: Material supply and demand specifications

		Material (ton) x10³			
			b=1	b=2	b=3
Supplier Industries	S4	SB_{it}^b	7000	7000	0
	S5		0	7300	10300
	S6		7300	0	13000
			r=1	r=2	r=3
Demand Industries	D3	DR_{jt}^r	0	0	4000
	D7		0	3500	3000
	D8		3200	0	0

Finally, at each period, the energy suppliers face random disruptions in the supply due to pipeline failures, maintenance and inspection. Also, by-product supplier industries in the IS network face random disruptions due to process failures, maintenance and inspections. The parameters related to supplier disruptions are presented in Table 9 below.

Table 9: Parameters of the suppliers disruptions

	$i = 1, 2, 3$	$i = 4, 5, 6$
$\kappa_{it} \sim N(\mu_{it}, \sigma_{it}^2)$	$N(0.1, 0.01^2)$	$N(0.05, 0.006^2)$
α_i	0.95*	0.95

* the reliability level for the supply is set to $\alpha_i = 0.95$, meaning that the supply will cover the demand 95% of the time.

Therefore, the supply of energy becomes as shown in Table 10 below.

Table 10: Distribution of energy supply

		Energy (kWh/period)	
Supplier Industries	S1	SK_{it}^k	$N[(1 - 0.1)1414000000, (1414000000)^2 0.01^2]$ $= N(1272600000, 14140000^2)$
	S2		$N[(1 - 0.1)1514000000, (1514000000)^2 0.01^2]$ $= N(1362600000, 15140000^2)$
	S3		$N[(1 - 0.1)1314000000, (1314000000)^2 0.01^2]$ $= N(1182600000, 13140000^2)$

Now, taking the inverse of the normal distribution yields the values in Table 11 below.

Table 11: New deterministic values of the energy supply

Supplier	S1	S2	S3
$F_{SK_{it}^k}^{-1}(1 - \alpha_i)$	1249341769	1337696916	1160986623

Similarly, the supply of by-products becomes as presented in Table 12 below.

Table 12: Distribution of by-product supply

		Material (ton)			
			b=1	b=2	b=3
Supplier Industries	S4	SB_{it}^b	$N(6650, 42^2)$	$N(6650, 42^2)$	0
	S5		0	$N(6935, 43.8^2)$	$N(9785, 61.8^2)$
	S6		$N(6935, 43.8^2)$	0	$N(12350, 78^2)$

And taking the inverse of the normal distribution yields the results in Table 13.

Table 13: New deterministic values of the by-product supply

		Material (ton)			
Supplier			b=1	b=2	b=3
S4	$F_{SB_{it}^b}^{-1}(1 - \alpha_i)$		6581	6581	0
S5			0	6863	9683
S6			6863	0	12221

CHAPTER 5

RESULTS AND ANALYSIS

5.1 Solution Approach

The optimization problem discussed in this thesis is a multi-objective (or multi-criterion) optimization problem. Meaning, the problem involves multiple conflicting objectives (economic, environmental and social) that need to be considered simultaneously. The goal of multi-objective optimization is to minimize a set of objective functions such that the optimal value of a single objective function does not deteriorate when minimizing another objective function (Collette and Siarry, 2004). Hundreds of solution methods have been proposed to handle multi-objective optimization, and they are categorized based on the nature of the objective functions themselves, or the solution procedure. Collette and Siarry (2004) categorized the solution methods into exact methods (such as goal programming), interactive methods (such as the STEP method), fuzzy methods (such as the Reardon method), and metaheuristic methods (such as the ε -constraint method). In this thesis, we will use two different methods in conjunction with each other, which are the L_p -Metric method, the ε -constraint method.

5.1.1 L_p -Metric Method

Also known as the distance method (Ravindran and Warsing Jr, 2016), because mathematically speaking, the L_p -metric is defined as the distance between two vectors, $\mathbf{x}$ and $\mathbf{y}$, where $\mathbf{x}, \mathbf{y} \in \mathbb{R}^n$, and is given by:

$$\|\mathbf{x} - \mathbf{y}\|_p = \left[\sum_{j=1}^n |x_j - y_j|^p \right]^{\frac{1}{p}} \quad (46)$$

In optimization context, the distance method can be applied to minimize the summation of weighted differences (distance) between each objective function and its optimal value obtained from solving the model for each objective function separately (Mirzapour et al., 2011). That is, we solve the model for each objective (economic, environmental and social) as a single objective model, we obtain the optimal values (Z_1, Z_2 and Z_3), then formulate a single objective (Z) that represents the weighted sum of the differences between each objective and its optimal value. This objective function is represented as:

$$\min Z = \left[w_1^p \left(\frac{Z_1 - Z_1^*}{Z_1^*} \right)^p + w_2^p \left(\frac{Z_2 - Z_2^*}{Z_2^*} \right)^p + w_3^p \left(\frac{Z_3 - Z_3^*}{Z_3^*} \right)^p \right]^{\frac{1}{p}} \quad (47)$$

Here, Z_i^* represents the optimal value of each objective function when solved independently, and w_i are the weight factors given to each objective. The idea of equation (47) is to minimize the deviation from the targets (Z_1^*, Z_2^* and Z_3^*) that are obtained from the independent optimization of each objective. Each objective is then divided by the optimal value to make the objective function values consistent, since the cost,

environmental impact and social value preference values have different level of magnitudes.

According to Ringuest (1997), the most commonly used values for p are $p = \infty$ (Tchebycheff metric), $p = 2$ (geometric or Euclidean distance) and $p = 1$ (Manhattan distance). The L_1 metric will be used in this thesis since it minimizes the sum of the absolute changes in the multi-objective value function weights. The resulting optimization problem becomes:

$$\min Z = w_1 \left(\frac{Z_1 - Z_1^*}{Z_1^*} \right) + w_2 \left(\frac{Z_2 - Z_2^*}{Z_2^*} \right) + w_3 \left(\frac{Z_3 - Z_3^*}{Z_3^*} \right) \quad (48)$$

Subject to Equations (29) to (45).

5.1.2 ϵ -Constraint Method

According to Miettinen (2001), the basic concept of the ϵ -constraint method is to choose one objective function as the main objective to be minimized/maximized, while treating the other objective functions as constraints. The general form of this method is:

$$\begin{aligned} & \text{minimize } f_l(x) \\ & \text{subject to } f_j(x) \leq \varepsilon_j \quad \forall j = 1, \dots, k, \quad j \neq l \\ & x \in S \end{aligned} \quad (49)$$

where $l \in \{1, \dots, k\}$ and k is the number of objective functions, S is the feasible region, and ε_j are upper bounds for the objectives $j \neq l$ set by some method.

In this thesis, the ε -constraint method will be utilized to verify the solutions obtained from the distance method described above. The economic aspect will be treated as an objective function, while the other objectives (environmental and social) become constraints where the upper bounds (ε_j) will be the optimal values of Z_2 and Z_3 obtained from the distance method, denoted by Z_2^{**} and Z_3^{**} , respectively. The optimization model becomes:

$$\min Z = Z_1 \tag{50}$$

Subject to:

$$Z_2 \leq Z_2^{**} \tag{51}$$

$$Z_3 \geq Z_3^{**} \tag{52}$$

Equations (28) – (44)

5.2 Results

5.2.1 Solving the Model for Each Objective Independently

The first step in the solution process is to solve three single-objective models, each without considering the other two objectives. The proposed model has been modeled in GAMS

24.7.4 and solved using the IBM ILOG CPLEX 12.6.3.0 solver for mixed-integer linear programming (MIP), consisting of 12,036 constraints, 4,736 variables, 1,364 are discrete variables. The computer used to run all executions was a personal laptop Core i7-7600 CPU, 2.8 GHz, 8 GB of RAM operating a Windows 10 Pro system. The problem was solved in less than one second CPU time. The model has been solved for each objective independently, and the optimal values are shown in Table 14 below:

Table 14: Optimal solution for economic, environmental and social objectives (solved independently)

Objective				Economic			
Optimal Value				381,361,566			
Configuration of Network							
π_{jt}^k							
$\pi_{1t}^1 = (0, 0.096, 0.067, 0)$				$\pi_{3t}^1 = (1, 1, 1, 1)$			
$\pi_{4t}^1 = (0.099, 0.011, 0, 0.068)$				$\pi_{5t}^1 = (1, 1, 1, 1)$			
x_{ijt}^k							
$i = 1$	$x_{11t}^1 = (0.850, 0.733, 0.724, 0.721)$			$x_{1,10,t}^1 = (1, 1, 1, 1)$			
$i = 2$	$x_{24t}^1 = (0.901, 0.989, 1, 0.932)$	$x_{26t}^1 = (0.417, 0.214, 0.183, 0.380)$		$x_{2,11,t}^1 = (1, 1, 1, 1)$			
$i = 3$	$x_{31t}^1 = (0.065, 0, 0, 0.058)$			$x_{32t}^1 = (1, 1, 1, 1)$			
	$x_{36t}^1 = (0.583, 0.786, 0.817, 0.620)$			$x_{39t}^1 = (1, 1, 1, 1)$			
ω_{jt}^r							
$\omega_{7t}^2 = (0.098, 0.098, 0.098, 0.098)$				$\omega_{8t}^1 = (1, 1, 1, 1)$			
$\varphi_{ijt}^{b,r}$							
$i = 4$	$j = 3$	$\varphi_{43t}^{1,3} = (1, 1, 1, 1)$					
$i = 5$	$j = 3$	$\varphi_{53t}^{3,3} = (1, 1, 1, 1)$					

	$j = 7$	$\varphi_{57t}^{2,2} = (0.902, 0.902, 0.902, 0.902)$		
$i = 6$	$j = 7$	$\varphi_{67t}^{1,3} = (1, 1, 1, 1)$	$\varphi_{67t}^{3,2} = (0.902, 0.902, 0.902, 0.902)$	$\varphi_{67t}^{3,3} = (1, 1, 1, 1)$
Objective			Environmental	
Optimal Value			468,727,484	
Configuration of Network				
π_{jt}^k				
$\pi_{1t}^1 = (1, 0, 0, 0)$		$\pi_{2t}^1 = (1, 0, 0, 0)$		$\pi_{3t}^1 = (1, 1, 1, 1)$
$\pi_{4t}^1 = (1, 0.203, 0.091, 0.056)$		$\pi_{5t}^1 = (1, 1, 1, 1)$		$\pi_{6t}^1 = (1, 0, 0, 0)$
$\pi_{9t}^1 = (1, 0, 0, 0)$		$\pi_{10t}^1 = (1, 0, 0, 0)$		$\pi_{11t}^1 = (1, 0, 0, 0)$
x_{ijt}^k				
$i = 1$	$x_{11t}^1 = (0, 0.505, 0.479, 0.470)$		$x_{14t}^1 = (0, 0.797, 0.909, 0.944)$	$x_{1,10,t}^1 = (0, 1, 1, 1)$
$i = 2$	$x_{21t}^1 = (0, 0.495, 0.521, 0.530)$		$x_{26t}^1 = (0, 0.214, 0.183, 0.173)$	$x_{2,11,t}^1 = (0, 1, 1, 1)$
$i = 3$	$x_{32t}^1 = (0, 1, 1, 1)$		$x_{36t}^1 = (0, 0.786, 0.817, 0.827)$	$x_{39t}^1 = (0, 1, 1, 1)$
ω_{jt}^r				
$\omega_{7t}^3 = (0.961, 0.961, 0.961, 0.961)$				
$\varphi_{ijt}^{b,r}$				
$i = 4$	$j = 7$	$\varphi_{47t}^{2,2} = (0.098, 0.098, 0.098, 0.098)$		
	$j = 8$	$\varphi_{48t}^{1,1} = (0.925, 0.925, 0.925, 0.925)$		$\varphi_{48t}^{2,1} = (1, 1, 1, 1)$
$i = 5$	$j = 3$	$\varphi_{53t}^{3,3} = (1, 1, 1, 1)$		
	$j = 7$	$\varphi_{57t}^{2,2} = (0.902, 0.902, 0.902, 0.902)$		
$i = 6$	$j = 3$	$\varphi_{63t}^{1,3} = (1, 1, 1, 1)$		
	$j = 7$	$\varphi_{67t}^{1,3} = \varphi_{67t}^{3,3} = (0.039, 0.039, 0.039, 0.039)$		$\varphi_{67t}^{3,2} = (1, 1, 1, 1)$

	$j = 8$	$\varphi_{68t}^{1,1} = (0.075, 0.075, 0.075, 0.075)$	$\varphi_{68t}^{3,1} = (1, 1, 1, 1)$
Objective			Social
Optimal Value			22.34
Configuration of Network			
π_{jt}^k			
$\pi_{1t}^1 = (0.621, 0.690, 0.624, 0.604)$			$\pi_{3t}^1 = (1, 1, 1, 1)$
x_{ijt}^k			
$i = 1$	$x_{12t}^1 = (1, 1, 1, 1)$		$x_{15t}^1 = (0.775, 0.658, 0.769, 0.804)$
	$x_{16t}^1 = (1, 1, 1, 1)$	$x_{1,10,t}^1 = (1, 1, 1, 1)$	
$i = 2$	$x_{21t}^1 = (0.379, 0.310, 0.376, 0.396)$		$x_{24t}^1 = (0.345, 0.364, 0.346, 0.341)$
	$x_{25t}^1 = (0.225, 0.342, 0.231, 0.196)$		
$i = 3$	$x_{34t}^1 = (0.655, 0.636, 0.654, 0.659)$		$x_{39t}^1 = (1, 1, 1, 1)$
ω_{jt}^r			
$\omega_{3t}^3 = (0.721, 0.721, 0.721, 0.721)$			
$\varphi_{ijt}^{b,r}$			
$i = 4$	$j = 3$	$\varphi_{43t}^{1,3} = (0.279, 0.279, 0.279, 0.279)$	
	$j = 7$	$\varphi_{47t}^{1,3} = (1, 1, 1, 1)$	$\varphi_{47t}^{2,2} = (0.098, 0.098, 0.098, 0.098)$
	$j = 8$	$\varphi_{48t}^{1,1} = (0.035, 0.035, 0.035, 0.035)$	$\varphi_{48t}^{2,1} = (1, 1, 1, 1)$
$i = 5$	$j = 7$	$\varphi_{57t}^{2,2} = (0.902, 0.902, 0.902, 0.902)$	$\varphi_{57t}^{3,2} = (0.762, 0.762, 0.762, 0.762)$
	$j = 8$	$\varphi_{58t}^{3,1} = (1, 1, 1, 1)$	
$i = 6$	$j = 3$	$\varphi_{67t}^{3,3} = (0.279, 0.279, 0.279, 0.279)$	

	$j = 7$	$\varphi_{67t}^{3,2} = (0.238, 0. 0.238, 0. 0.238, 0. 0.238)$	$\varphi_{67t}^{3,3} = (1, 1, 1, 1)$
	$j = 8$	$\varphi_{68t}^{1,1} = (0.965, 0.965, 0.965, 0.965)$	

The optimal value for the total cost function is \$381,361,566, and as can be seen from the table, both industry 3 and industry 5 generate their full energy demand internally using fossil fuels. Industries 1 and 4 generate a small portion of their energy demand internally, and the rest is provided from the symbiosis network. As for the raw material demand, industry 8 purchases the full amount of its raw material 1 demand from the external raw material market, while the rest of the industries acquire their raw material demands as by-products from the symbiosis network, and then process them into raw material inside their own facilities. Apparently, the economic model encourages more symbiosis for both energy and material.

Moreover, the optimal value for the environmental function when optimized independently is 484,232,270 kg CO₂. Just as in the economic case, both industry 3 and 5 generate their demand internally. Additionally, the energy demand in the first period for all industries is generated internally, while in the other periods the energy is exchanged in the symbiosis. As for the material exchange, industry 7 purchases 96.1% of its raw material 3 demand from the external market, while all the other industries fulfill their raw material demand from the symbiosis network as by-products. Since the environmental impact of generating energy internally using fossil fuels is higher than recovering and exchanging it in the

symbiosis network, and since not re-processing by-products harms the environment, it is evident that the environmental objective also encourages more symbiotic exchanges between industries.

When maximizing the social value preference objective independently, the resulting optimal value is 22.34. As defined, maximizing the social value preference means more symbiotic relationships. As can be observed from Table 14 above, only industry 3 generates its full energy demand internally, while all the other industries participate actively in the symbiosis. Supplier industry 1 has five different connections with demand industries 2, 5, 6, 10 and 11. It has the highest number of connections since it has the highest social value preference of 0.5 (compared to 0.2 for supplier industry 2 and 0.3 for supplier industry 3). On the raw material side, only 72.1 % of demand industry 3 demand of raw material 3 is purchased from the external raw material market, while the rest of demand industries obtain the raw material as by-products from the symbiosis.

5.2.2 Solving the Model Using the Distance Method

Since the objectives in our model (economic, environmental and social) are clearly conflicting (optimization of one objective may cause the deterioration of another's value), obtaining a global minimum is nearly impossible. Therefore, we look for Pareto optimal solutions. According to Miettinen (2001), a solution vector $\mathbf{x}^*$ is Pareto optimal if and only if there does not exist another solution vector $\mathbf{x}$, satisfying the model constraints, and

$Z(x) \leq Z(x^*)$ for all the objective functions in the model, and $Z(x) < Z(x^*)$ for at least one objective function.

For the optimization model provided in (48), solving the model with specified weights results in one Pareto optimal solution. In order to obtain several Pareto optimal solutions, all weights need to be considered in order to construct the Pareto front, which is the set of all pareto optimal solutions (Jin et al., 2001). In order to generate different weights that result in Pareto optimal solutions, the Dynamic Weighted Aggregation (DWA) method, introduced by Jin et al. (2003) is used. The pseudo-code of the weights generation algorithm is shown below:

```

begin
t1 = 0; t2 = 0; t = t1 + t2;
  for t1 = 0 to  $\frac{F}{2}$ 
    w1(t) =  $\left| \sin\left(\frac{2 * \pi * t1}{F}\right) \right|$ ;
    for t2 = 0 to  $\frac{F}{2}$ 
      w2(t) =  $(1 - w1(t)) * \left| \sin\left(\frac{2 * \pi * t2}{F}\right) \right|$ ;
      w3(t) =  $1 - w1(t) - w2(t)$ ;
    endf;
  endf;
end

```

(52)

where F is the number of generations.

Due to time limitations, only 28 random weights obtained from the above algorithm with $F = 20$ will be used to construct an approximation of the Pareto front. The selected weights, and the resulting objective values after solving the model in GAMS using the model in (48) and the optimal results from the independent optimization (5.2.1) are listed in Table 15 below:

Table 15: Weights and objective values of the distance method

Weights (w_1, w_2, w_3)	Values		
	Economic	Environmental	Social
(0.00, 0.89, 0.11)	412,233,600	471,220,900	22.16
(0.00, 0.16, 0.84)	423,252,000	472,637,100	22.34
(0.00, 0.59, 0.41)	423,099,000	471,993,000	22.31
(0.16, 0.75, 0.09)	397,312,900	470,214,800	21.70
(0.16, 0.13, 0.71)	409,546,200	471,898,400	22.29
(0.16, 0.49, 0.35)	400,882,900	470,901,200	22.17
(0.31, 0.62, 0.08)	383,894,300	469,272,100	19.39
(0.31, 0.11, 0.58)	400,882,900	470,901,200	22.17
(0.31, 0.41, 0.28)	399,313,000	470,998,000	22.08
(0.45, 0.49, 0.06)	382,768,900	469,078,600	18.99
(0.45, 0.09, 0.46)	399,338,700	471,309,300	22.09
(0.45, 0.32, 0.23)	395,980,700	471,068,000	21.77
(0.59, 0.37, 0.04)	381,740,900	469,345,500	18.52
(0.59, 0.06, 0.35)	396,819,000	471,508,900	21.86
(0.59, 0.24, 0.17)	389,600,500	470,455,000	20.67
(0.71, 0.26, 0.03)	381,740,900	469,345,500	18.52
(0.71, 0.05, 0.25)	393,760,900	471,545,500	21.54

(0.71, 0.17, 0.12)	383,181,500	469,242,400	19.17
(0.81, 0.17, 0.02)	381,740,900	469,345,500	18.52
(0.81, 0.03, 0.16)	384,412,300	469,323,300	19.55
(0.81, 0.11, 0.08)	381,816,600	469,345,500	18.57
(0.89, 0.10, 0.01)	381,247,800	471,143,800	17.54
(0.89, 0.02, 0.09)	381,816,600	469,345,500	18.57
(0.89, 0.06, 0.05)	381,740,900	469,345,500	18.52
(0.95, 0.04, 0.01)	381,247,800	471,143,800	17.54
(0.95, 0.01, 0.04)	381,740,900	469,345,500	18.52
(0.95, 0.03, 0.02)	381,247,800	471,143,800	17.54
(1.00, 0.00, 0.00)	381,361,566	473,204,300	16.49

It can be observed from Table 15 that similar results for the objectives are repeating as we increase the weight of the economic objective function. Also, we notice the results of the economic objective function converging to the optimal value of the independent optimization ($Z_1^* = 381,361,566$) as its weight increases, whereas it performs relatively poorly with lower values of w_1 . Using the results in the above table, an approximation of the Pareto front is plotted, and can be found in Figure 6 below:

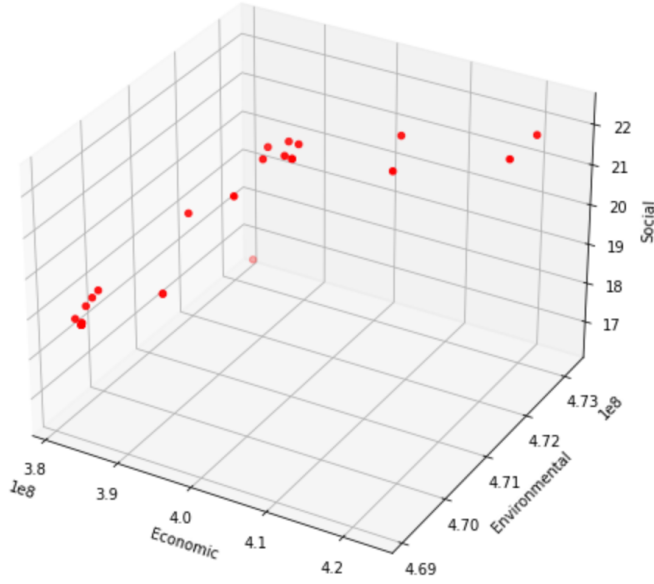


Figure 6: Approximation of Pareto front for the multi-objective model using the distance method

In order to gain more insight, the projections of the 3D Pareto front onto the 2D planes are provided in Figure 7. As can be observed from the figure, the projections follow a concave trend, which can be more noticeable with more data points. This trend can also be observed from Table 15. Evidently, maximizing the social objective results in an increase in both the economic and environmental objectives, which is undesirable. On the other hand, the first plot in Figure 7 is more scattered, but it is rather apparent that the economic and environmental objective are positively proportional. Meaning, minimizing one of them results in the minimization of the other, and vice versa. The outliers in the upper-left corner in the Economic vs. Environmental plot and the bottom-right corner in the Environmental vs. Social plot is the optimal value of the economic function given a weight equal to one, which is the same result obtained from the independent optimization.

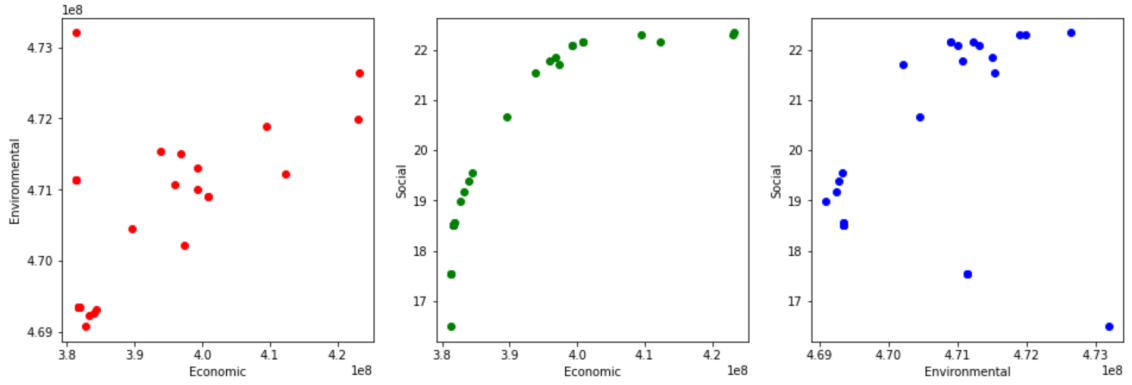


Figure 7: 2D projections of Pareto front using the distance method

Three of the optimal solutions obtained from the distance method will be chosen, and analyzed further in the following sections, and they are listed in Table 16 below. Decision makers and shareholders may select the appropriate weights based on their priorities, whether economic, environmental or social.

Table 16: Chosen solutions computed by the distance method

#	Weights (w_1, w_2, w_3)	Values		
		Economic	Environmental	Social
1	(0.81, 0.11, 0.08)	381,816,600	469,345,500	18.57
2	(0.16, 0.75, 0.09)	397,312,900	470,214,800	21.70
3	(0.31, 0.11, 0.58)	400,882,900	470,901,200	22.17

5.2.3 Solving the Model Using the ε -Constraint Method

As mentioned in (5.1.2), the ε -constraint method will be used in conjunction with the distance method. This has been done in many research papers, such as Afshari et al. (2020) and Lima et al. (2017). The optimal values for the environmental and social objectives

obtained from the distance method (Z_2^{**} and Z_3^{**}) will be used as upper and lower bounds to the constraints (51) and (52), and the economic aspect will be the objective function. The model will be solved three times, for each solution provided in Table 16. The results of optimizing the model in (50) for the three solutions is provided in Table 17 below.

Table 17: Objective values computed by the distance method

#	ε_2	ε_3	New Values		
			Economic	Environmental	Social
1	469,345,500	18.57	383,805,320	428,989,300	18.80
2	470,214,800	21.70	397,590,764	429,902,000	21.70
3	470,901,200	22.17	401,178,030	430,591,300	22.17

Comparisons between the solutions obtained from the distance method and the ε -constraint method are shown in Table 18 below.

Table 18: Comparisons between solutions of the distance method and the ε -constraint method

#	Method	Economic	Environmental	Social
1	distance method	381,816,600	469,345,500	18.57
	ε -constraint method	383,805,320	428,989,300	18.80
	Percentage difference %	0.52% increase	8.60% decrease	1.24% increase
2	distance method	397,312,900	470,214,800	21.70
	ε -constraint method	397,590,764	429,902,000	21.70
	Percentage difference %	0.07% increase	8.57% decrease	0%

3	distance method	400,882,900	470,901,200	22.17
	ε -constraint method	401,178,030	430,591,300	22.17
	Percentage difference %	0.07% increase	8.56% decrease	0%

For the first solution, we notice a slight increase in the economic objective, a noticeable increase in the social objective, and a great improvement in the environmental objective value. This trend continues for all solutions except from the social objective, where the value witnesses zero change in the second and third solutions. Apparently, the ε -constraint method gives a much better value of the environmental objective, which is due to the fact that the economic and environmental objectives are positively proportional. That is, once they are both minimized, they will perform better than the independent optimization. This can also be concluded from the Pareto front graph of the ε -constraint method, which is shown in the Figures 8 and 9 below. As can be seen in the figures, the concave trend is more recognizable for all the combinations of objective functions than the ones obtained by the distance method.

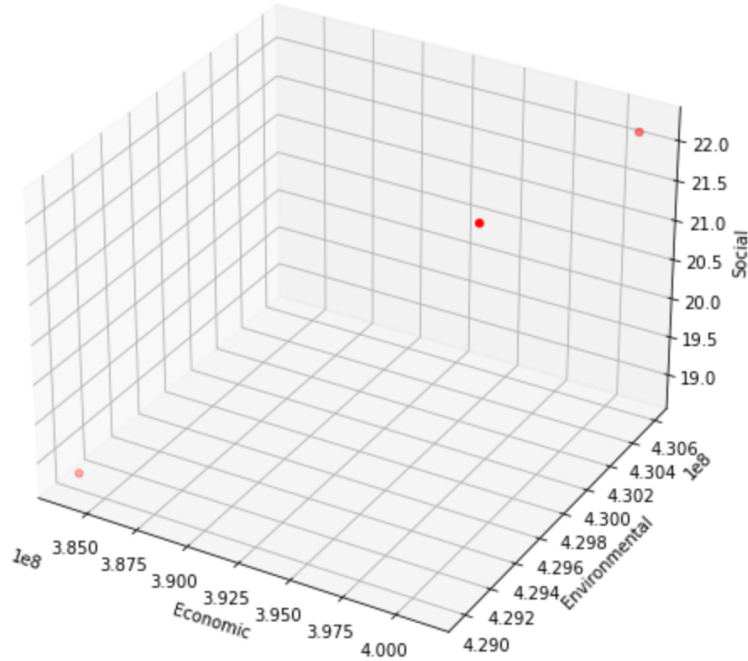


Figure 8: Approximation of Pareto front for the multi-objective model using the ε -constraint method

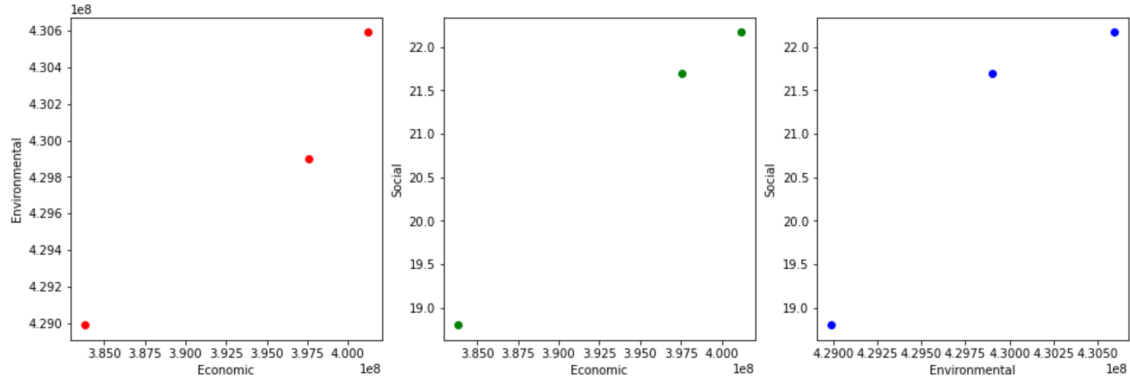


Figure 9: 2D projections of Pareto front using the ε -constraint method

The three solutions in Table 17 are all optimal solutions, and it is up to the decision maker to choose the plan that is most convenient. Choosing a specific solution has a substantial impact on the configuration of the symbiosis network, both on the energy symbiosis and the material symbiosis. Table 19 below shows the configuration of the symbiosis network

for solution 1. This configuration will be utilized throughout the rest of the discussion and analyses.

Table 19: Configuration of network for solution 1

Objective		Economic	Environmental	Social
Optimal Value		383,805,320	428,989,300	18.80
Configuration of Network				
π_{jtk}				
$\pi_{1t}^1 = (0.065, 0.145, 0, 0)$			$\pi_{3t}^1 = (1, 1, 1, 1)$	
$\pi_{4t}^1 = (0, 0, 0.105, 0.068)$			$\pi_{5t}^1 = (1, 1, 1, 1)$	
x_{ijt}^k				
$i = 1$	$x_{11t}^1 = (0.935, 0.855, 0.933, 0.942)$		$x_{12t}^1 = (0, 0.378, 0, 0)$	$x_{1,10,t}^1 = (1, 1, 1, 1)$
$i = 2$	$x_{24t}^1 = (1, 1, 1, 1)$	$x_{26t}^1 = (0.181, 0.084, 0.424, 0.380)$		$x_{2,11,t}^1 = (1, 1, 1, 1)$
$i = 3$	$x_{31t}^1 = (0, 0, 0.067, 0.058)$		$x_{32t}^1 = (1, 622, 1, 1)$	
	$x_{36t}^1 = (0.819, 0.916, 0.576, 0.620)$		$x_{39t}^1 = (1, 1, 1, 1)$	
ω_{jt}^r				
$\omega_{3t}^3 = (0.571, 0.571, 0.571, 0.571)$			$\omega_{7t}^3 = (0.084, 0.084, 0.084, 0.084)$	
$\omega_{8t}^1 = (0.075, 0.075, 0.075, 0.075)$				
$\tau_{ijt}^{b,r}$				
$i = 4$	$j = 7$	$\tau_{47t}^{2,2} = (0.369, 0.369, 0.369, 0.369)$		
	$j = 8$	$\tau_{48t}^{1,1} = (2.057, 2.057, 2.057, 2.057)$		$\tau_{48t}^{2,1} = (1.653, 1.653, 1.653, 1.653)$
$i = 5$	$j = 3$	$\tau_{53t}^{3,3} = (0.932, 0.932, 0.932, 0.932)$		
	$j = 7$	$\tau_{57t}^{2,2} = (1.805, 1.805, 1.805, 1.805)$		

	$j = 8$	$\tau_{58t}^{3,1} = (1.424, 1.424, 1.424, 1.424)$	
$i = 6$	$j = 3$	$\tau_{63t}^{1,3} = (0.659, 0.659, 0.659, 0.659)$	
	$j = 7$	$\tau_{67t}^{1,3} = (1.409, 1.409, 1.409, 1.409)$	$\tau_{67t}^{3,2} = (1.786, 1.786, 1.786, 1.786)$
		$\tau_{67t}^{3,3} = (1.990, 1.990, 1.990, 1.990)$	
$\varphi_{ijt}^{b,r}$			
$i = 4$	$j = 7$	$\varphi_{47t}^{2,2} = (0.170, 0.170, 0.170, 0.170)$	
	$j = 8$	$\varphi_{48t}^{1,1} = (0.925, 0.925, 0.925, 0.925)$	$\varphi_{48t}^{2,1} = (0.925, 0.925, 0.925, 0.925)$
$i = 5$	$j = 3$	$\varphi_{53t}^{3,3} = (0.429, 0.429, 0.429, 0.429)$	
	$j = 7$	$\varphi_{57t}^{2,2} = (0.830, 0.830, 0.830, 0.830)$	
	$j = 8$	$\varphi_{58t}^{3,1} = (0.925, 0.925, 0.925, 0.925)$	
$i = 6$	$j = 3$	$\varphi_{63t}^{1,3} = (0.429, 0.429, 0.429, 0.429)$	
	$j = 7$	$\varphi_{67t}^{1,3} = (0.916, 0.916, 0.916, 0.916)$	$\varphi_{67t}^{3,2} = (1, 1, 1, 1)$
		$\varphi_{67t}^{3,3} = (0.916, 0.916, 0.916, 0.916)$	

The selected connections in the energy symbiosis network provided in Table 19 above are highlighted in different colors for each period in Figure 10 below.

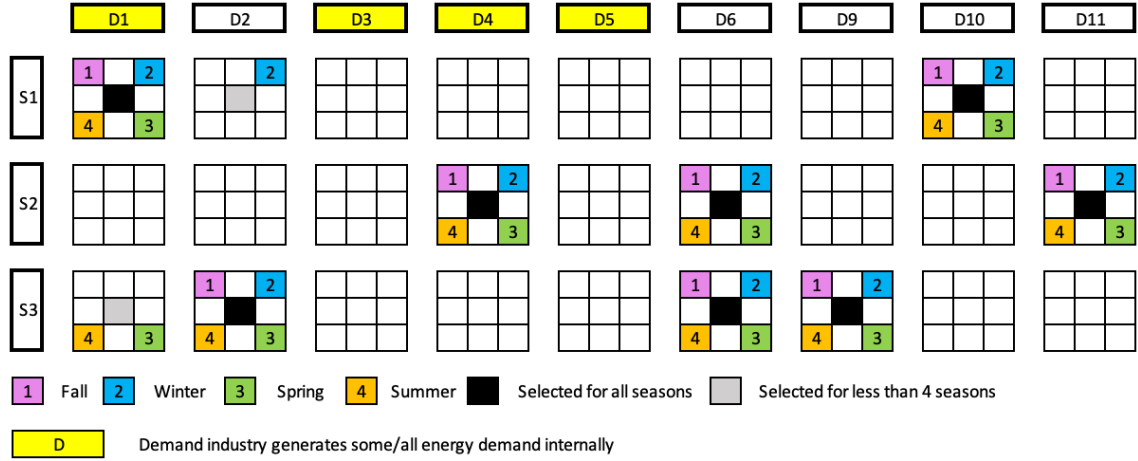


Figure 10: Selected energy connections for solution 1

As can be seen from Table 19 and Figure 10, demand industries 1 and 4 generate a small percentage of their demands internally using fossil fuels, while demand industries 3 and 5 generate their full demand within their facilities and do not participate in the energy symbiosis. Moreover, supplier 1 is selected to exchange energy with demand industry 1 for all seasons, demand industry 2 only for winter, and residential area 10 for all seasons. Supplier 2 is selected for demand industries 4 and 6 along with residential area 11 for all seasons. Finally, supplier industry 3 provides energy for demand industry 1 for spring and summer, and demand industries 2 and 6 as well as residential area 9 for all seasons. A larger proportion of demand industries tend to acquire their energy from the symbiosis network as opposed to generating it internally when the objective is to minimize the cost.

One contribution of this work is considering the energy generated internally in the model, to make sure the energy demand is fully satisfied. Taking demand industry 1 for example, it generates 6.5% of its energy demand within its facility, and 93.5% is obtained from supplier industry 1 for the fall season. Similarly for the winter, it generates 14.5% of the

energy demand internally, and acquires the remaining 85.5% from supplier 1. For the spring and winter seasons, no energy is generated internally. A large percentage is obtained from supplier 1, and the rest from supplier 3.

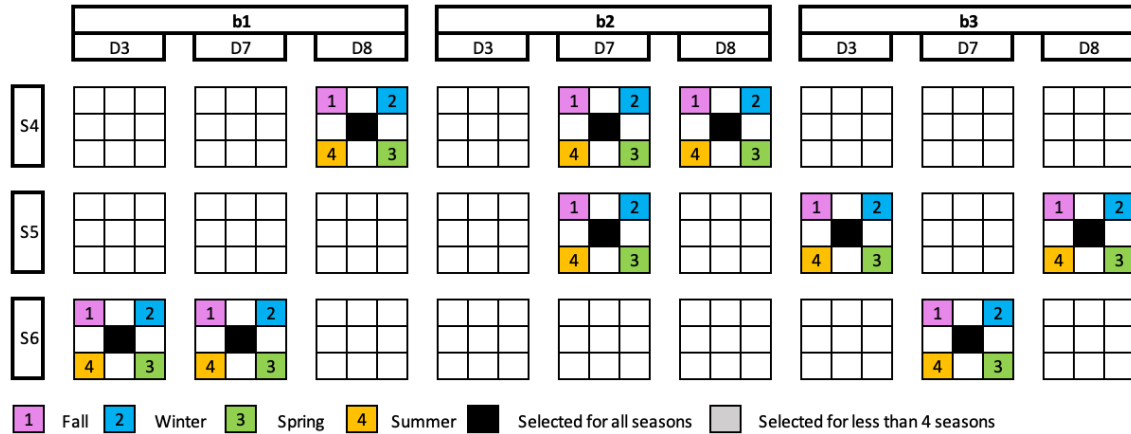


Figure 11: Selected by-product connections for solution 1

The selected connections for the by-product symbiosis are shown in Figure 11 above. Demand industry 3 requires raw material 3 for its production, demand industry 7 requires raw materials 2 and 3, and demand industry 8 require raw material 1 for its processes. As mentioned in Table 5, raw material 1 is comprised of by-products 1, 2 and 3, raw material 2 is comprised of by-products 2 and 3, while raw material 3 requires by-products 1 and 3 to be produced. One significant contribution of this thesis is equations (6) and (7) in section (3.2), which take into consideration the reprocessing rate and the constituting by-products in the demand of raw materials. Meaning, 1 ton of r1 requires $\frac{1}{0.45} = 2.22$ tons of b1, $\frac{1}{0.56} = 1.79$ tons of b2, and $\frac{1}{0.65} = 1.54$ tons of b3, and so on and so forth. The values 2.22, 1.79

and 1.54 are defined as the level demand of by-product b supplied by i to j to make r in period t ($\tau_{ijt}^{b,r}$).

In Table 19, we observe that the level demands and the percentage demand of by-products are proportionate (based on the reprocessing rate), and the raw material demand is fully satisfied. Let us take the demand of r3 by industry 3 for instance, we can see that $\omega_{3t}^3 = (0.571, 0.571, 0.571, 0.571)$, which means that 57.1% of r3 demand is satisfied from the external raw material market. The remaining 42.9% of the raw material demand is acquired as by-products from the symbiosis. Since 1 ton of r3 requires $\frac{1}{0.65} = 1.54$ tons of b1 and $\frac{1}{0.46} = 2.17$ tons of b3, it follows from equation (6) that we need $0.429 * 1.54 = 0.659$ tons of b1 and $0.429 * 2.17 = 0.932$ tons of b3 for all seasons, which is given by $\tau_{63t}^{1,3} = (0.659, 0.659, 0.659, 0.659)$ and $\tau_{53t}^{3,3} = (0.932, 0.932, 0.932, 0.932)$, respectively. These given values of τ translate to percentage demand as $\varphi_{63t}^{1,3} = (0.429, 0.429, 0.429, 0.429)$ and $\varphi_{53t}^{3,3} = (0.429, 0.429, 0.429, 0.429)$, respectively, when multiplied by their respective reprocessing rates.

We can see from Figure 9 that supplier industry 4 is selected to provide b1 to demand industry 8 for all seasons, and b2 to demand industries 7 and 8 for all seasons as well. Also, Supplier industry 5 exchanges b2 with demand industry 7, and b3 with demand industries 3 and 8 for all seasons. Finally, supplier industry 6 provides b1 for demand industries 3 and 7, and b3 for demand industry 7 for all seasons. Evidently, the model in this thesis

guarantees that the raw material demand for all demand industries is satisfied, whether from the external material market, or as by-products from the material symbiosis network.

Furthermore, to analyze the effect of prioritizing an objective over the other, the optimal energy and by-product connections for solutions 2 and 3, respectively, are provided in Figures 12 and 13 below. Apparently, the network configuration witnesses a significant change between solution 1 (where the economic objective is prioritized) and solutions 2 and 3. One notable difference is the number of energy demand industries supplied by supplier industry 1. In solution 1 (Figure 10), supplier 1 provides energy with only 3 demand industries, one of which only for one season. However, in solutions 2 and 3 (Figures 12 and 13), supplier 1 provides energy to 5 different energy users, which are demand industries 2, 4 and 5, and residential users 10 and 11.

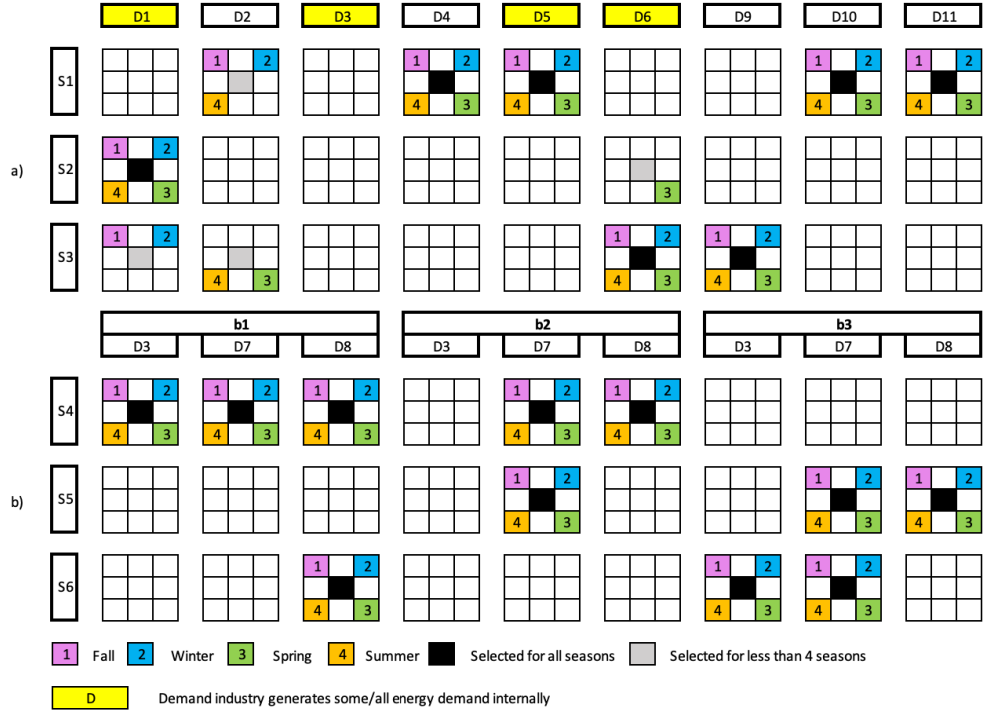


Figure 12: Selected connections for solution 2. a) energy network, b) by-product network

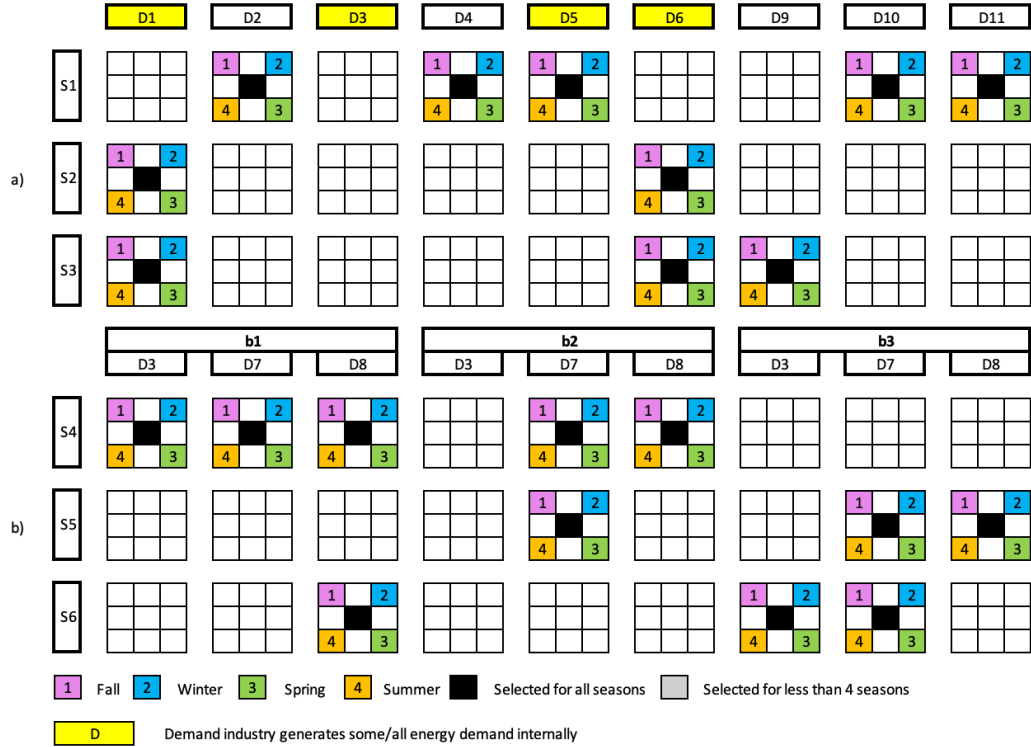


Figure 13: Selected connections for solution 3. a) energy network, b) by-product network

5.3 Sensitivity Analysis

Also referred to as parameter robustness analysis, this section will explore the effect of varying important parameters in the model to study the effect they have on the optimal objective functions values and the optimal configuration of the network. Intuitively, symbiosis networks face various uncertainties. Afshari et al. (2017) categorized these uncertainties into four different categories; uncertainty related to tax, prices, supply and demand. The uncertainty of supply has already been incorporated into the model as supplier disruptions, in which chance constraints were used to model this behavior.

In this section, we will start by comparing the results of the model with/without supplier disruptions, and the demand followed by the cost parameters will be investigated after that. The uncertainty degree (%change) is set to three different levels: 0, $\pm 15\%$ and $\pm 30\%$. The relationship of the new values with respect to the old values is given by

$$Value_{new} = Value_{old} * (1 + \%change) \quad (54)$$

For all the scenarios that will be investigated, the solution methodology explained in (5.2.1), (5.2.2) and (5.2.3) and used for solutions 1, 2 and 3 will be followed. That is, the independent optimization models will be solved, their results will be used as inputs for the distance method, and finally the results from the distance method will be used as upper and

lower bounds of the ε -constraint method. Only weights used in solution 1 (0.81, 0.11, 0.08) will be used for all the analysis in this section. Meaning, all model solutions considering the uncertainties will be compared with solution 1 from Table 17.

5.3.1 Uncertainty in the Supply

As explained in section (3.3), the suppliers face random disruptions that cause a percentage loss of the total fixed supply of each supplier industry, given by κ_{it} . In the case study, κ_{it} was assumed to follow a normal distribution provided in Table 9. Using chance constraints and the properties of the normal distribution, this caused a decrease in the energy supply of roughly 12% for all energy suppliers, and about 6% in the by-product supply. Although it is a relatively small drop in the supply, the effect on the economic, environmental and social objective, and the overall network configuration was significant. Table 20 below contains a comparison of the results of solution 1 with and without considering supply disruptions. Evidently, increasing the supply is advantageous to the symbiosis network, as the total cost decreases, the environmental impact increases (due to less carbon emissions produced by fossil fuels), and the social value increases since increasing the supply encourages more symbiosis.

Table 20: Comparison between the objective values with and without supplier disruptions

	Economic	Environmental	Social
With supplier disruptions	383,805,320	428,989,300	18.80
Without supplier disruptions	362,914,900	421,624,600	19.94
Percentage difference %	5.44% decrease	1.72% decrease	6.06% increase

The configuration of the network without considering supplier disruptions is shown in Figure 14 below. The most notable differences between the energy network with supplier disruptions and without supplier disruptions (Figures 10 and 11) is that demand industry 1 no longer generates some of its energy demand internally since energy supply from the symbiosis is available, and that demand industry 5 now acquires some of its energy demand from the symbiosis network, as opposed to total internal energy generation in Figure 10. Suppliers 1 and 2 provide demand industry 5 with energy, which makes a total of 4 connections with each supplier.

On the other hand, the by-product network also witnessed a substantial change in its configuration. For instance, supplier 4 now provides demand industries 7 and 8 with b1, while it only provided demand industry 8 previously. One more difference is that demand industries that require b1 now purchase their by-products for each period from different suppliers, as is the case for demand industries 7 and 8. Therefore, a small change in the total supply, results in a significant change in the configuration of the energy and by-product networks.

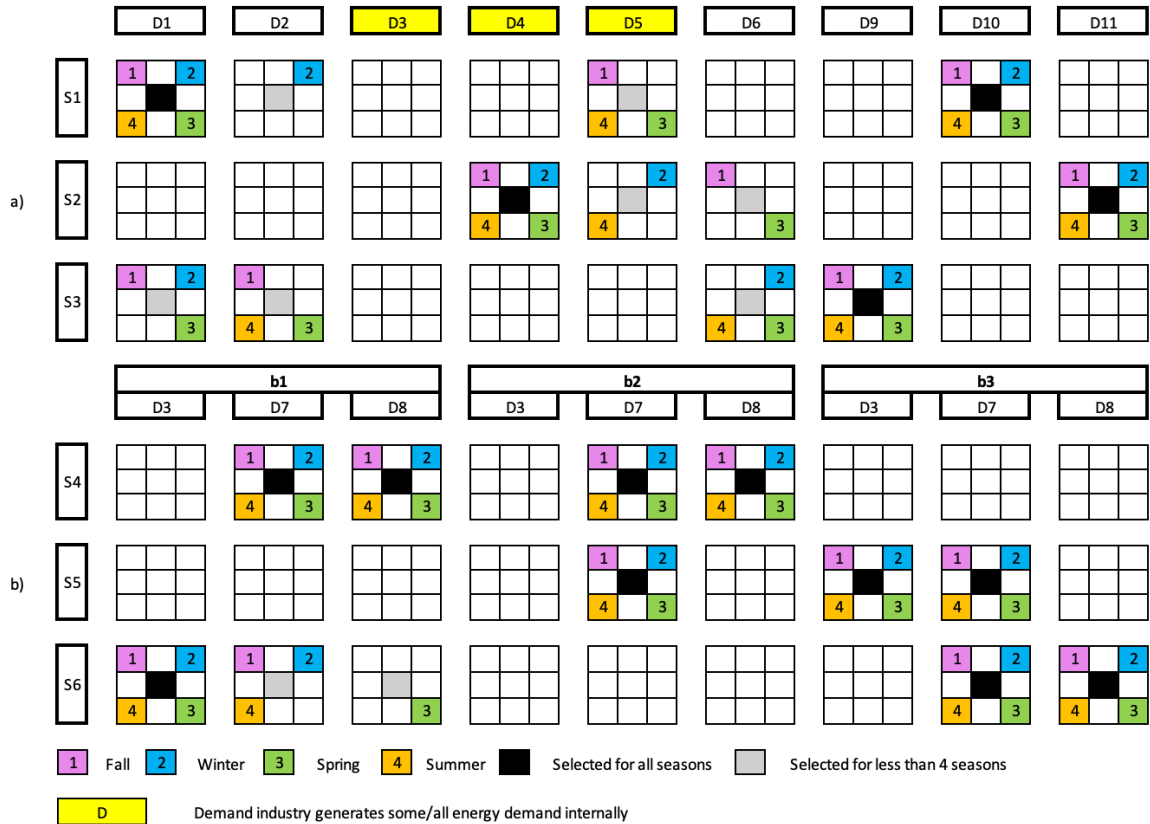


Figure 14: Selected connections without supplier disruptions. a) energy network, b) by-product network

To gain a deeper insight into the effect of supply variation on the values of the objective functions, we solve the original model, where no supplier disruptions are considered, while varying the total supply of energy and by-products by 15% and 30%. The results are presented in Table 21 below, and reflected on the bar chart provided in Figure 15.

Table 21: Comparison of objective values for supply uncertainty scenarios

Scenario	Objective Values			%Change		
	Economic	Environmental	Social	Econ.	Env.	Social
-30% in Supply	419,987,300	445,074,100	16.65	15.7%	5.6%	-16.5%
-15% in Supply	386,752,100	432,050,000	18.00	6.6%	2.5%	-9.7%

Original solution	362,914,900	421,624,600	19.94	0.0	0.0	0.0
+15% in Supply	339,367,600	410,941,900	21.78	-6.5%	-2.5%	9.2%
+30% in Supply	317,824,800	401,482,900	23.05	-12.4%	-4.8%	15.6%

The results in the above table confirm the trend observed in Table 20, where the total cost increases as an effect of a drop in the supply amount, and it decreases as a result of an increase in the supply. The environmental impact value witnesses the same behavior, whereas the social value preference value has the opposite effect. Moreover, the impact of supply variation has a stronger impact on the economic and social objectives, as compared to the environmental objective. As can be seen in Figure 15, the change in all objective function values is almost linear with respect to the variation in the supply.

The increase in the economic objective is attributed to the fact that when the total supply drops, the demand industries will resort to generating the energy demand internally and purchasing raw material from the external market, which is more economically consuming, and vice versa. As for the social objective, the drop in the supply causes less symbiosis connections to be constructed, which is the sole contributor to the value of the social objective. On the other hand, the relatively small change in the environmental impact is due to the small difference between the environmental impact parameters of generating energy internally (PI_j^k) and recovering energy (PE_i^k).

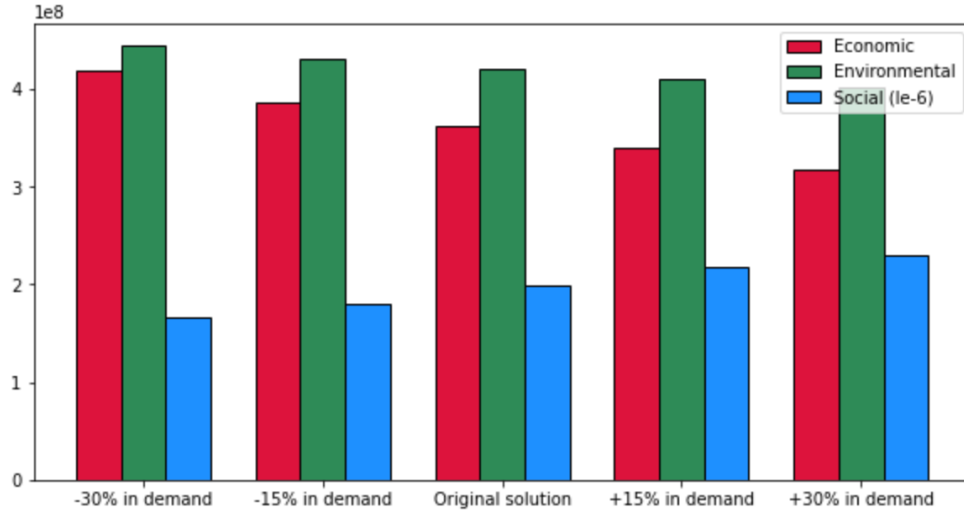


Figure 15: Impact of supply variability on the objective function values

5.3.2 Uncertainty in the Demand

Demand uncertainty is one of the most widely discussed stochastic parameter in the supply chain/industrial symbiosis context. Many researchers have addressed this type of uncertainty, and modeled their problems as a stochastic optimization problem to handle this behavior (Chamani et al., 2021; Huang et al., 2020. Afshari et al., 2018). In most cases, taking demand variability into consideration is more representative of the real-world situations. In our model, demand uncertainty may originate from the fact that some demand industries are expanding their processes and production, which causes their demand to increase. The objective values when the demand increases/decreases by 15% and 30% are presented in Table 22. All the solutions were obtained using the approach discussed in sections (5.2.1), (5.2.2) and (5.2.3)

Table 22: Comparison of objective values for demand uncertainty scenarios

Scenario	Objective Values			%Change		
	Economic	Environmental	Social	Econ.	Env.	Social
-30% in demand	243,430,100	284,186,800	22.05	-36.6%	-33.8%	17.3%
-15% in demand	308,494,500	356,239,500	20.05	-19.6%	-17.0%	6.6%
Original solution	383,805,320	428,989,300	18.80			
+15% in demand	462,530,600	503,849,200	18.15	20.5%	17.5%	-3.5%
+30% in demand	543,112,100	579,591,200	16.82	41.5%	35.1%	-10.5%

Based on the results in Table 22 and Figure 16 below, increasing the demand increases the total cost almost linearly, and decreasing the demand results in a decrease in the total cost function. This relationship is rather intuitive, since the demand is directly proportional to the cost parameters in the economic objective. The environmental objective also follows a similar trend, with less percentage increase compared to the economic objective. For example, increasing the demand by 30% results in a 41.5% increase in the economic objective value, compared to a 35.1% increase in the environmental objective. Conversely, the social objective seems to increase when the demand decreases, and vice versa. Note that for better representation of the social value preference, its values have been multiplied by 10^6 .

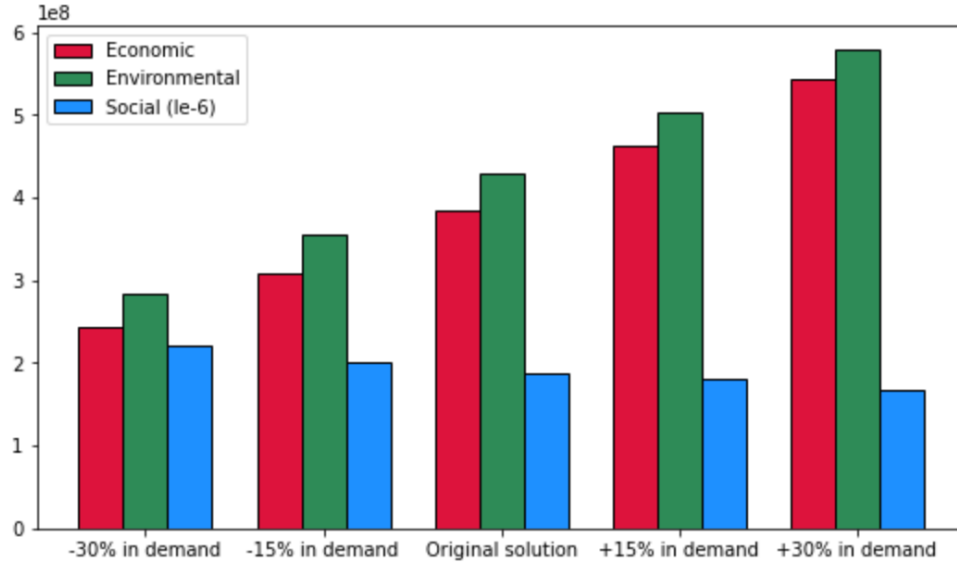


Figure 16: Impact of demand variability on the objective function values

5.3.3 Uncertainty in the Cost Parameters

One of the key parameters in our model are the cost parameters. Specially, the selling prices of both the energy and the by-products in the symbiosis network. In real life supply chains and industrial symbioses, many opportunities for the increment or decrement of prices may arise. For instance, technology improvements may lead to cheaper prices, and increased tax may result in more expensive prices (Perez-Valdes et al., 2012). We study the effect of variations in the selling prices of both energy (CE_{ij}^k) and by-products (CB_i^b) in the symbiosis network. The objective values when the selling prices increase/decrease by 15% and 30% are presented in Table 23. All the solutions were obtained using the approach discussed in sections (5.2.1), (5.2.2) and (5.2.3).

Table 23: Comparison of objective values for selling prices uncertainty scenarios

Scenario	Objective Values			%Change		
	Economic	Environmental	Social	Econ.	Env.	Social
-30% in selling prices	390,544,900	435,334,100	15.10	1.8%	1.5%	-19.7%
-15% in selling prices	384,339,300	430,230,800	17.61	0.1%	0.3%	-6.3%
Original solution	383,805,320	428,989,300	18.80			
+15% in selling prices	384,863,300	429,014,300	18.57	0.3%	0.0%	-1.2%
+30% in selling prices	413,327,700	433,524,300	17.55	7.7%	1.1%	-6.6%

Based on the results in Table 23, there is no obvious trend in the behavior of the objective values with respect to variations in the selling prices. One observation, though, is that the objective values seem to worsen more when they move away from the original solution. For example, the total costs increase by 0.1% and 1.8% when the selling prices are reduced, and decreases by 0.3% and 7.7% when the selling prices are increased. Decreasing the selling price should intuitively encourage more symbiosis, but more symbiosis induces more cost since energy transfer pipelines need to be constructed. This is a result of the complications that exist in the objective functions, and the economic profitability constraints. A bar chart reflecting the values in Table 23 is shown in Figure 17.

Moreover, there is a significant impact on the amount purchased from the external raw material market when the by-product purchasing cost is decreased. For example, when the by-product cost is decreased by 15%, demand industry 8 purchases only 68.4% of its r1 demand from the external market, as opposed to 100% in the original case. This shows how sensitive the material symbiosis is to a small change in the by-product prices.

Also, the social value preference witnesses a significant decrease in its value when the selling price is reduced by 30%. This is because when the selling price is reduced, the symbiosis becomes unprofitable for the suppliers, resulting in a large number of demand industries generating their energy internally, which in turn reduces the social value preference. This behavior is determined by equations (11)-(13).

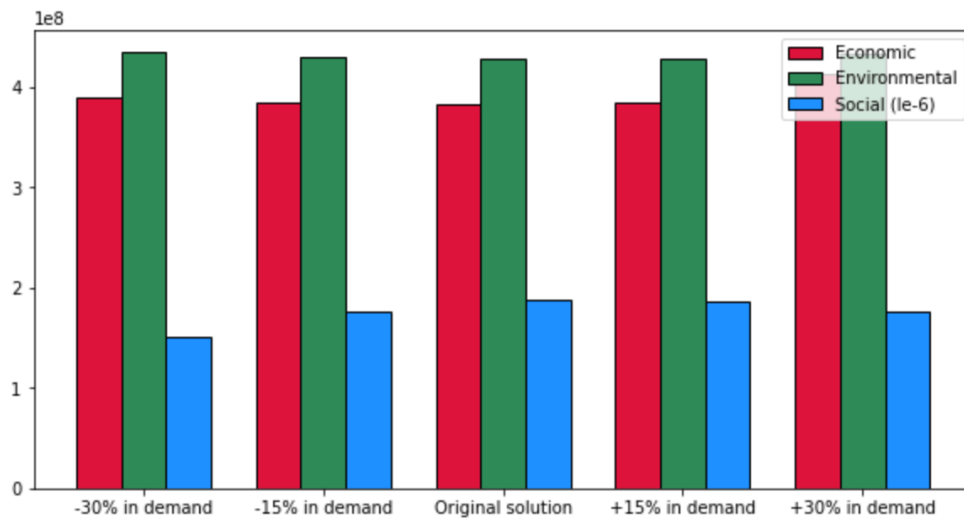


Figure 17: Impact of selling price variability on the objective function values

5.4 Complexity Analysis

In this section, we provide a computational experiment to study the complexity of the model, in terms of runtime, with respect to increasing the size of the model's sets. We conduct the analysis to investigate how the computational time of solving the proposed model increases with the increase in the size of the model parameters that affect the state space. Specifically, we select the number of time periods (T), and the number of industries (I, J) in the model.

5.4.1 Increasing Time Periods

In our model, the greater the time periods, the larger the data set, which in turn leads to slower computational time. We choose time periods as an important parameter since with every increase in the number of time periods, the data changes significantly. Table 24 below shows the runtime (in seconds) of the model using the IBM ILOG CPLEX 12.6.3.0 solver in GAMS 24.7.4 for different instances of time periods.

Table 24: Runtime results for different numbers of time periods

	Runtime (s)
$T = 4$ (original model)	0.688
$T = 5$	0.701
$T = 6$	0.764
$T = 7$	0.839

$T = 8$	0.868
$T = 9$	0.916
$T = 10$	0.941
$T = 20$	1.286
$T = 30$	1.607
$T = 40$	1.930
$T = 80$	2.776
$T = 100$	3.350
$T = 200$	6.376
$T = 365$	12.602
$T = 500$	14.997
$T = 750$	43.317
$T = 1000$	66.693
$T = 2000$	183.017
$T = 5000$	779.825
$T = 7500$	1719.689
$T = 10000$	2882.877

For better representation of the data, the results are plotted in Figure 18 below. The runtime values seem witness a parabolic increase with increasing the number of time periods, and the percent change starts to increase more rapidly after one-thousand periods. Evidently, the given model performs computationally well with the increase of time periods, since higher numbers of T are highly uncommon in the IS context.

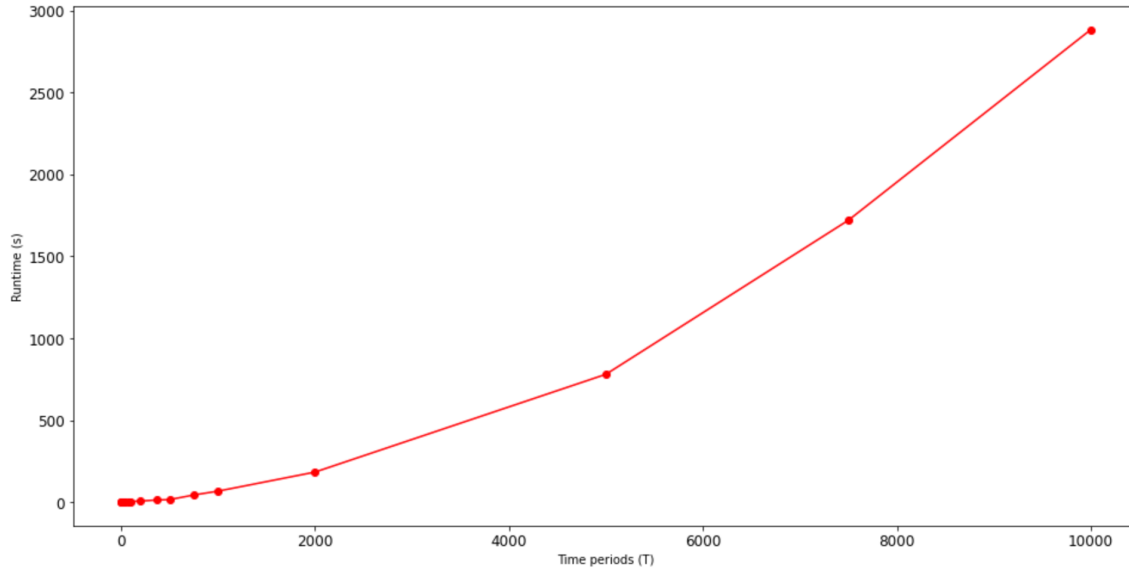


Figure 18: Runtime (s) vs. Time Periods (T)

5.4.2 Increasing Number of Industries

According to Berkel et al. (2009), a typical quantitative assessment of Industrial Symbioses is the quantification of “connectedness” or “symbiotic intensity”. The former refers to the number of distinct exchanges of resources between industries, and the latter refers to the total number of industries involved in the symbiosis. In this subsection, we study the effect of increasing the symbiotic intensity on the computational time of the present model. The increase in the number of industries will be systematic, by doubling the size of the problem (thus doubling the number of industries) at each instance while tabulating the runtime in seconds. When the problem size is doubled, the number of interactions will increase dramatically, which has a significant impact on the solution time. The results are shown in Table 25 and plotted in Figure 19 below.

Table 25: Runtime results for different numbers of industries

Size of the problem	Supplier/Demand Industries	Number of Industries	Runtime (s)
1 (original problem)	I = 6, J = 11	17	0.688
2	I = 12, J = 22	34	1.259
3	I = 18, J = 33	51	1.484
4	I = 24, J = 44	68	2.032
5	I = 30, J = 55	85	3.086
7	I = 42, J = 77	119	5.379
10	I = 60, J = 110	170	10.832
20	I = 120, J = 220	340	46.901
30	I = 180, J = 330	510	161.162
40	I = 240, J = 440	680	384.476
50	I = 300, J = 550	850	640.467
60	I = 360, J = 660	1020	732.057
70	I = 420, J = 770	1190	1828.068
80	I = 480, J = 880	1360	Stopped after 90 m

In a study conducted by Berkel et al. (2009) which included IS examples of five different case studies in North America, Canada, Asia, Australia and Europe, the number of industries involved in the symbiosis ranged from 3 to 22 industries. Higher number of participating industries is possible, but highly uncommon in the literature. As can be observed from the data, the computational time does not exceed one minute for up to 340 industries participating in the symbiosis. After that, the runtime starts to increase exponentially with doubling the problem size. When the number of participating industries

was 1190, it took the software around 30 minutes to solve the model. Once the number of industries reached 1360, the model could not be solved due to the large amount of data, and a CPLEX “Out of memory” error was displayed after 90 minutes of runtime.

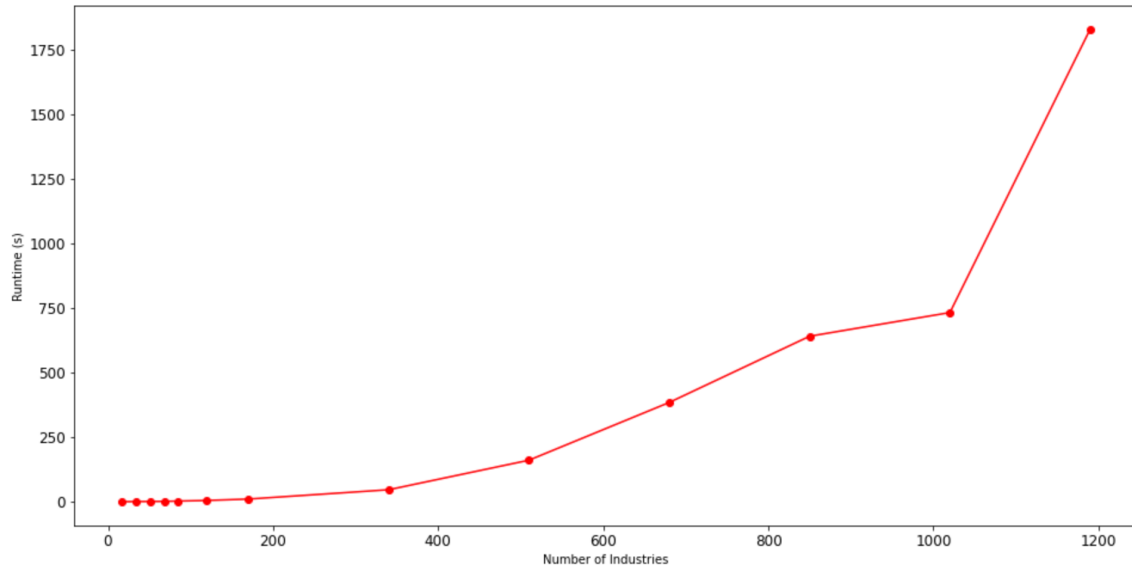


Figure 19: Runtime (s) vs. Number of Industries

Ultimately, the complexity analysis concludes that the present formulation performs exceptionally well within the reasonable range of time periods and number of industries. The runtime increases parabolically with the increase in time periods, and exponentially with the increase in number of industries.

CHAPTER 6

CONCLUSION

6.1 Summary and Remarks

To sum up, this thesis discussed a multi-objective optimization model comprising the three pillars of sustainability: economic, environmental and social objectives. In the model developed in this thesis, both energy and materials were exchanged symbiotically between industries as well as residential users. The model also takes into consideration an important yet usually overlooked phenomenon; supplier disruptions. An efficient solution methodology was developed to solve the resulting model, and the implications of the solution were discussed thoroughly. Finally, sensitivity analysis to study the effect of variations in the important parameters in the model were provided.

The original model, first developed by Afshari et al. (2020), addressed an energy symbiosis between industrial partners and residential users. The first major contribution of our thesis was modifying the model in Afshari et al. (2020) to capture the energy that is generated internally within a demand industry's facility. This was accomplished by introducing two new variables to the model, namely, π_{jt}^k and n_{jt}^k , which are defined in section (3.1). The new formulation is more representative and thorough to allow further analysis, and contains more information that enhances the decision-making process for the decision maker.

The second major contribution of this thesis is formulating a comprehensive model that takes into consideration the exchange of energy as well as raw material, as opposed to only energy symbiosis by Afshari et al. (2020). The material exchange was incorporated into the model through a variation of the WMREN model addressed by Haung et al. (2020). In this thesis, the incorporated WMREN model allows demand industries to either purchase their raw material demand from an external (outside the symbiosis network) raw material market, or purchase the comprising by-products from the symbiosis network and reprocess them into the required raw material within the industry's facility.

In the literature, and more specifically, the WMREN model discussed by Haung et al. (2020), the raw material is comprised from different by-products, any of which can be used to produce the raw material. However, this does not well reflect the precise reprocessing procedure. One of the contributions of this thesis was introducing equations (6) and (7), which ensure that the demand of raw material and all by-products comprising a certain raw material, with respect to the reprocessing rate, is satisfied. This idea was further discussed in section (5.2.3).

Taking supplier disruptions into consideration was also one of the major contributions of this thesis. This idea makes the model more realistic, since exchanging energy through pipelines is subject to various types of disruptions. The disruptions were incorporated into the model by assuming that suppliers in each period suffer a loss in their fixed total supply which is based on a normal distribution. To preserve the deterministic nature of the model,

the disruptions were modeled using chance constraints, by assuming a given service level of demand satisfaction by the total supply.

When all the above ideas are considered, the resulting model was a novel formulation where both energy and material are exchanged symbiotically, while taking supplier disruptions into consideration through chance constraints. Up to our knowledge, no model in the literature exists that discusses the ideas addressed in this work.

The resulting model was solved using an efficient solution methodology, that consists of solving the model for each objective independently from the other objectives, using the results in the distance method, and finally using the optimal values obtained from the distance method as upper and lower bounds to the ϵ -constraint method. A set of solutions were obtained and discussed thoroughly in chapter 5. Results suggest that the economic and environmental objectives are positively proportional, while social value preference is inversely proportional to cost and environmental impact since it encourages building symbiotic connections between parties. Finally, the sensitivity analyses conducted for the uncertainty in supply, demand and selling prices show that an increase in supply/demand results in an increase in cost/environmental impact, and a decrease in the social values preference, and vice versa.

From a managerial standpoint, the solution placing greater emphasis on the economic objective was selected, which resulted in a total cost of \$383,805,320, an environmental impact of 428,989,300 kg CO₂ and a social value preference of 18.8. These values provide no reference of how well the symbiosis is performing economically and environmentally. Table 26 below provides the objective values when no symbiosis exists, where energy demand industries generate their full energy demand internally, and material demand industries purchase their full material demand from the external market. The table also includes a comparison between the objective values when symbiosis exists and when it does not.

Table 26: Comparison of objective values before and after the symbiosis network

	Economic	Environmental	Social
No symbiosis	573,079,530	551,412,346	0
Symbiosis	383,805,320	428,989,300	18.80
Percentage difference %	33% decrease	22.2% decrease	

As can be seen from the table, participating in the industrial symbiosis reduces the total system cost by 33%, reduces the environmental impact by 22.2% and increases the social value preference from 0 (since no industries are involved) to 18.8. Ultimately, moving from regular industrial practices to industrial symbiosis not only is economically advantageous, but helps our planet by reducing the carbon emissions into the environment.

6.2 Work Limitations and Future Directions

The present work in this thesis has the following limitations:

- The modeling technique, involving overlapping demand/supplier industries, could be enhanced through defining the industries systematically. Meaning, they may be merged in one set denoted “industries”. The data entry of the parameters, the equations and the solution performance may be enhanced as a result of this modification. The complexity analysis of the new formulation could be compared with the analysis of this thesis to assess the performance of both.
- Handling the supplier disruptions through chance constraints involves defining new variables, and finding the deterministic equivalent of the stochastic constraints resulting from the disruption random variable. Preserving the stochastic nature of the disruption and solving the model using stochastic optimization techniques may be a more accurate representation of real scenarios.
- The solution methodology used does not guarantee optimality, as is the case in the majority of multi-objective optimization problems. A new and more accurate solution methodology could be developed.
- The weight generation algorithm used to obtain an approximation of the Pareto front could be automated to generate a higher number of instances, which provides a more accurate representation of the Pareto front.
- The solution methodology was not automated to solve the three steps (independent optimization, distance method and ε -constraint method) directly. Rather, each

method was modeled separately, and the data entry from one step to the other was manually accomplished.

- The present formulation of the model was tested on an assumed case study acquired from two different sources. The formulation could be tested on a real scenario to check the applicability of the model on a real case study.

Consequently, some interesting directions emerge from this thesis that may be explored in future work. One extension is to incorporate the uncertainty of parameters, such as the demand, supply, cost and tax into the model, instead of only studying their effect in the sensitivity analysis. Stochastic optimization and robust optimization methodologies could be utilized to address the stochastic nature of the resulting model. Another possible extension is to incorporate the statistical models discussed by Kleiner et al. (2001) for pipeline failures, to model the disruption in the energy supply more accurately. Stochastic optimization may also be used to address the model, since it contains random variables for the failure prediction. Finally, developing a more efficient algorithm to handle the multiple-objective nature of the model is an interesting future direction that may be explored.

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