FINDING COMMON GROUND: USING WATER AND HEAT OPTIMIZATION TO FACILITATE ECO-INDUSTRIAL DEVELOPMENT

by

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Abstract

The constant increase in green house gas (GHG) emissions resulting from the combustion of fossil fuels and the degradation of fresh water resources are two key characteristics of human activity that must be eliminated. These two problems result from the means by which humans utilize energy to transform materials in the manufacturing of goods and in the provision of services. Therefore, when considering how human activities could be reorganized to eliminate these GHG emissions and the degradation of fresh water resources, an analysis of how energy and water are utilized in human industrial activities is a logical first step.

In the framework of systems analysis, industrial ecology has emerged as a means of restructuring the industrial system to enable global sustainability. Industrial ecology applies ecosystem principles in studying technological organisms within industrial systems, their use of resources, their potential environmental impacts, and the ways in which their interactions with the natural world could be restructured. One approach taken in implementing industrial ecology is the development of eco industrial parks or networks where a community of businesses seeks to enhance environmental and economic performance by cooperating with each other and with the local community to efficiently manage and exchange resources.

This thesis work uses two fictional case studies to develop tools that can aid in the facilitation of eco industrial development. This methodology seeks to act as a decision support tool to provide municipal engineers, city planners, and participating companies with quantitative and qualitative information regarding the feasibility of water and heat energy cascading. The first case study combines geographical information systems (GIS) with linear programming to maximize water savings within electrical energy and capital cost constraints. The second case study demonstrates how the thermodynamic pinch analysis can be applied to chemical process simulation software and combined with GIS. This research suggests that while these tools have the potential to enhance resource use efficiency, their application is limited by the availability of data regarding water and heat energy use.

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Glossary of Terms

Term	Acronym	Definition
Composite Curves	CC	Combined temperature vs. enthalpy plots for each stream being heated and for each stream being cooled in the thermodynamic pinch analysis.
Design for Environment	DfE	A management approach that takes into account environmental considerations as a step in the product or process design or redesign.
Eco-Efficiency		The delivery of competitively-priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life-cycle to a level at least in line with the Earth's estimated carrying capacity
Eco-Industrial Network	EIN	A community of businesses located in one or various geographic regions that seek to enhance environmental and economic performance by cooperating with each other and with their surrounding communities to efficiently manage and exchange resources.
Eco-Industrial Park	EIP	A community of businesses located together on a common property that seek to enhance environmental and economic performance by cooperating with each other and with the local community to efficiently manage and exchange resources.
Ecological Footprint	EF	A framework developed by William Rees and Mathis Wackernagel to calculate the productive and assimilative ecosystem area required to sustain a level of consumption.
Environmental Management System	EMS	A means by which to manage the activities that can have an impact on the environment in a planned way in order to facilitate the identification of ways of improving environmental performance
Geographical Information System	GIS	A collection of computer hardware, software, and geographic data for capturing, managing, and displaying all forms of geographically referenced information.
Industrial Ecology (IE)	IE	The study of technological organisms, their use of resources, their potential environmental impacts, and the ways in which their interactions with the natural world could be restructured to enable global sustainability
Industrial Symbiosis	IS	The mutually beneficial exchange of resources with other firms in which society's demand for resource saving and environmental protection is considered.
Input-Output Analysis	IO Analysis	A framework developed by Wassily Leontief to correlate economic data to the associated environmental impact or resource use.
Life Cycle Analysis	LCA	An analysis of the environmental impacts incurred during resource extraction, product manufacture, product use, and product disposal or recycle.

Term	Acronym	Definition
Multi-objective Programming	MOP	Mathematical functions of a set of decision variables and parameters to represent an objective function and constraints.
Non-Governmental Organization	NGO	A not-for-profit organization formed outside of a country's governmental system to benefit members and/or the general public.
Pollution Prevention/Cleaner Production	P2	The evaluation of production processes and addressing pollution through: process modification and optimization; technology modification; good housekeeping; input substitution; on-site reuse; and off-site reuse.
Process Integration	PI	Improvements made to process systems, their constituent unit operations, and their interactions to maximize the effective use of energy, water and raw materials.
Public Private Partnership	PPP	A joint venture between the private and puplic sector.
Small to Medium Sized Enterprise	SME	Companies that typically have less than 250 people.
System		An assemblage of interconnected parts acting together as a unified whole
Thermodynamic Pinch Analysis		A technique used to identify energy saving potential for processes typically within an industrial plant or complex and subsequently aids the design of the heat exchanger network to achieve targeted saving.
United States Environmental Protection Agency	US EPA	An agency of the United States federal government appointed to protect human health and the environment.

Definition of Equation Terms

Term	Equation	Definition	Section
I_j	7	Annual volume of water consumption by industry j.	3.2.2.1
WR	7	Water reuse.	3.2.2.1
$y_{j,k}$	7	Exchange fraction representing represent the fraction of industry j's inlet water requirement provided by industry k.	3.2.2.1
n	7	Index of companies.	3.2.2.1
O_k	10	Annual volume of sewer discharge by industry k.	3.2.2.2
$x_{j,k}$	10	Fraction of company k's effluent that it provides to industry j.	3.2.2.2
E	13	Energy required to pump water per volume of water pumped.	3.2.2.5
g	13	Gravitational constant.	3.2.2.5
Δz	13	Change in elevation that water undergoes when pumped.	3.2.2.5
η	13	Pump efficiency.	3.2.2.5
f	13	Friction factor of pipe.	3.2.2.5
L	13	Length of pipe that water flows through (i.e., horizontal distance that water is pumped).	3.2.2.5
v	13	Velocity of water.	3.2.2.5
D	13	Diameter of pipe that water flows through.	3.2.2.5
ρ	13	Density of water.	3.2.2.5
EC	14	Electrical consumption required to pump water.	3.2.2.5
EEC	16	Existing electrical consumption required to pump water (i.e., without water sharing).	3.2.2.5
P	18	Percentage of existing electrical consumption to be saved in water sharing scenario (this is used as a constraint on the optimization to generate different scenarios).	3.2.2.5

Term	Equation	Definition	Section
L_{Tr}	19	Length of pipe trenching required to connect industries (this is used as a constraint on the optimization to generate different scenarios).	3.2.2.6
PC	19	Piping installation cost.	3.2.2.6
B	19	Budget.	3.2.2.6
Cp	20	The heat capacity of the fluid at constant pressure.	3.3.2.1
a, b, c and d	20	Coefficients used to calculate the heat capacity of a fluid at constant pressures (values are available from chemical engineering tables).	3.3.2.1
M	21	The fluid mass.	3.3.2.1
T	21	Temperature of the fluid.	3.3.2.1
C_{hx}	31	Cost of heat exchanger.	3.3.2.6
A_{ht}	31	Heat transfer area in heat exchanger.	3.3.2.6
H_x	32	Rate of heat exchange.	3.3.2.6
U	32	Overall heat exchange coefficient.	3.3.2.6
ΔT_{LM}	32	Log mean temperature difference.	3.3.2.6

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1.0 INTRODUCTION

1.1 Background

The scale of human activity has grown to such levels that our appropriation of raw materials and our production of compounds requiring assimilation by the planet are forever changing the very ecological conditions on Earth that make it hospitable to human life (Agardy et al., 2005; WWF, 2006; IPCC, 2007). However, because we are not immediately affected by these changes, we do not deviate from predisposed patterns of living or development. To maintain a decent quality of life for most people, the daunting task of changing people's perspectives to incorporate positive gains in ecological indicators within all aspects of human decision making processes must be addressed. This is the core element of the sustainability movement.

Planning and assessment are ways in which society is currently attempting to meet the sustainability imperative. The framework of systems analysis is a decision support tool that can be used to support these attempts. A system is a set of interacting parts that act together as a unified whole. By analyzing the inner workings of the individual parts, the relationships to the other parts, and the resulting properties of the system as a whole, systems analysis provides an overall understanding of the system from which informed decisions can be made regarding the manner in which the parts could work together to achieve desirable system properties. In the context of sustainability, one can consider a hierarchy of interconnected systems, such that the Earth's ecosphere is the system within which all human activity is embedded. In essence, human activity can be considered as a part or a subsystem of the local ecosystem where human activity is occurring; the local ecosystem in turn is a wholly embedded part of the Earth's ecosphere. If the properties of the human subsystem are inducing changes in the larger ecosystem within which it is embedded, such that the foundations of the human subsystem are being undermined, then an analysis of the parts comprising the human subsystem may help to determine how to reconfigure human activity to eliminate the negative effects associated with it.

In the context of the human subsystem, humans have developed different political, cultural, economic and social constructs that are interconnected and generally dictate peoples' actions. The idea behind the concept of sustainability is to attain an understanding of how these constructs interrelate and how they can be integrated to reinforce a positive way of living for all people while maintaining ecological systems (Gunderson and Holling, 2002). In order to preserve the ecological integrity required to maintain human well being, two key characteristics of human activity must be eliminated; the constant increase in green house gas (GHG) emissions resulting from the combustion of fossil fuels, and the depletion of fresh water resources. These two characteristics result from the means by which humans utilize energy to transform materials in the manufacturing of goods and in the provision of services. Therefore, when considering how human activities could be reorganized to eliminate these GHG emissions and degradation of fresh water resources, an analysis of how energy and water are utilized in human industrial activities is a logical first step.

Industrial Ecology (IE) has been employed as a systems approach to analyzing industrial activities. IE is defined as the study of technological organisms and their interactions with each other and the ecosystems within which they are embedded. As a guiding principle, IE views resource flows associated with individual and groups of industries as analogous to the cycling of materials and cascading of energy that occurs in natural ecosystems. In doing so, IE provides both a metaphor to natural systems with which people can relate, as well as a model of how wasted resources from one industry can be used to create mutually beneficial relationships by acting as raw material to another industry. In application to groups of industries, IE takes the form of eco-industrial parks or eco-industrial networks. An eco-industrial park is a group of co-located firms on a common property that work together with each other and the surrounding community in an attempt to exchange resources to achieve enhanced performance. An eco-industrial network is similar to an eco-industrial park, except the geographic boundaries are expanded to facilitate resource exchanges between firms in various geographic settings.

The research presented in this thesis has been conducted in partnership with Eco-Industrial Solutions[1], a Vancouver based consulting firm focused on applying industrial IE. Based on their experience with various projects, Eco-Industrial Solutions has identified a need for analytical tools that help to envision planning strategies to support eco-industrial development. This research addresses this need by providing analytical tools that build upon two pre-existing models developed by others. The first model combines geographical information systems with mathematical programming to determine the potential for water reuse among a group of industrial water users (Nobel, 1998). The second model demonstrated how chemical process simulation software could be used to model eco-industrial parks (Casavant, 2000). The research presented here reformulates the first model and addresses the need to incorporate the geographic location of existing or new infrastructure into the consideration of water reuse scenarios. It also builds upon the second model by applying the thermodynamic pinch analysis to a synthesis of this second model, and, in doing so, addresses the need for a systematic approach with which to determine heat cascading opportunities by determining an optimal use of heat among a group of industries.

1.2 Objectives and Goals

The goals of this research are to support the application of industrial ecology by developing tools to aid in determining resource sharing opportunities among industrial users and to provide a presentation of the results in a manner which, while maintaining a rigorous analytical approach, can be presented and understood by a broad range of audiences. In order to provide a common focus with which to engage almost all industries, this thesis focuses on industrial water reuse and heat cascading because water and heat energy are required in most industrial applications.

In order to meet the objectives described, this research comprises the following goals:

- To provide a literature review that allows the reader to tie industrial ecology, geographical information systems (GIS), chemical process simulation and

[1] President: Tracy Casavant. Address: Suite 501, 318 Homer St., Vancouver, BC, V6B 2V2

optimization into the framework of systems analysis as an approach to increase the efficiency of industrial resource use and potentially contribute to attaining sustainability targets;

- To develop a variation of the previously developed model of Catherine Nobel that combined GIS and linear optimization to optimize water reuse among a group of industries. This variation of the model incorporates advances in GIS analytical capacity into Nobel's framework such that the location of infrastructure can be included in the decision making process and reformulates the optimization in terms of water reuse within energy and capital cost constraints. The tools used to achieve this objective include the GIS software ArcInfo 9.1 combined with the Python programming language and the Matlab® mathematical solver. A theoretical case study is used to demonstrate the approach; and
- To synthesize and expand upon the work by Casavant that demonstrates how chemical process simulation software can be used to model an industrial ecosystem to evaluate resource sharing opportunities. This objective begins with a synthesis of the steam processes in Casavant's model using the chemical process simulator CadsimPlus. The approach is then built upon by applying the thermodynamic pinch analysis to the simulation to determine heat cascading opportunities among the industries.

1.3 Thesis Overview

This thesis is comprised of four sections following the introductory section. The second section provides a review of literature which includes:

- the context of system's analysis and sustainability assessment;
- a detailed insight into the emerging field of industrial ecology;
- an overview of geographical information systems, chemical process simulation, mathematical programming and thermodynamic pinch analysis; and
- examples of various tools used to assist in the application of industrial ecology.

Section 3 provides the formulation of the two different models that the thesis develops through the use of theoretical case studies. Section 4 presents the results of the case studies and Section 5 includes a discussion of the implications of the results and provides recommendations for future work that might build upon the work presented here. The last section, Section 6, is where the conclusions of the research are presented.

2.0 LITERATURE REVIEW

This literature review provides the reader with the necessary background information pertaining to the approach and tools used in the subsequent analytical application. In the first section the links between systems analysis and sustainability are reviewed to provide context. The second section details industrial ecology as a systems analysis approach that orients industrial activities towards contributing the societal move towards a sustainable future. The third, fourth and fifth sections familiarize the reader with the specific analytical tools, including geographical information systems and process simulation and optimization, which this research combines in various formats to support the application of industrial ecology. The sixth section summarizes the literature review and identifies how the information presented will be used throughout the remainder of the thesis.

2.1 The Context of Systems Analysis and Sustainability

The cerebral cortex is the part of the human brain that provides people with a sense of consciousness. This sense of consciousness allows us to develop mental constructs or ways of thinking to understand complex issues. One strategy to understand the world is to think in terms of organizational hierarchies or systems (Odum, 1993; Kay and Foster, 1999). A system can be described as an assemblage of interconnected parts, acting together as a unified whole. Each part may be a subsystem of the larger system (or super system) within which it is embedded. Depending on how the parts or subsystems interact, the characteristics of the system can vary. Therefore, systems tend to exhibit properties which cannot necessarily be discerned when the system is reduced down to its parts (Mitchell et al., 2004). The analysis of each of the parts to understand the interconnections and the resulting contributions to the properties of the unified whole is termed systems analysis. By analyzing systems in this way, humans gain the ability to alter the inner workings of existing systems or develop new systems such that desirable system properties are demonstrated.

When considering the world, the Earth's ecosphere can be visualized as a super system, and all human activity can be thought of as one of its subsystems. For over ninety-nine percent of human history, the human subsystem was made of low-density foragers or farmers in bands or villages consisting of no more than a few dozen persons (Tainter, 1995). During that time, it could be argued that the properties of the human subsystem had a negligible effect on the properties of the ecosphere that make life possible.

Starting in approximately the mid 1800s, the human subsystem began to grow exponentially (Meadows et al., 2004). This growth has been comprised of a positive feedback relationship where the combustion of fossil fuels and the consumption of water have enabled exponential growth in human population and industrial activity. In turn, providing enough food for an exponentially growing population and raw materials (such as metals) for an exponentially growing industrial economy has required ever increasing rates in the consumption of water and fossil fuels. In the past fifty years, global energy consumption (consisting primarily of fossil fuels) has doubled 3 times (Meadows et al., 2004) while water use continues to grow exponentially (Bos et al., 2005). Water use varies around the world in that high income countries consume the majority of their water for industrial purposes[2] while developing and mid income nations consume most of their water for agricultural purposes (Environment Canada, 2004).

In contrast to the negligible effects that the low density foragers and farmers had on the planetary system, this growth-oriented development pattern has had some consequences. Sufficient evidence now exists to indicate that the rate at which humans combust fossil fuels is large enough such that the associated atmospheric emissions of

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[2] As noted in a report on industrial water use for Environment Canada
Scharf, D., D. W. Burke, M. Villeneuve and L. Leigh (2002). Industrial Water Use, 1996. Ottawa. Public Works and Government Services Canada., "Water forms an essential requirement and input to the manufacturing process, regardless of the industrial sector. Industry would not be able to function without water to serve cooling and processing purposes and to act as a catalyst and to convey waste materials."

carbon dioxide are contributing to climate change (IPCC, 2007). On the water side, pollution of receiving waters have resulted in: fragmentation and loss of habitat; loss of biodiversity; and a reduction of the capacity of inland water ecosystems to act as a reliable source of high-quality water (Agardy et al., 2005; Bos et al., 2005). Along with pollution compromising water availability, in other regions, aquifers are being depleted due to groundwater extraction rates which are greater than aquifer recharge rates (Reisner, 1993).

These signs of ecological dysfunction, have raised urgent questions about the sustainability of the existing pattern of development. One construct that has been created to understand sustainability is the pillar approach. This framework assigns a pillar to each of the political, cultural, economic, ecological and social aspects of life, while recognizing that each are interconnected (Gibson, 2000). In relations to systems, the pillar model can be interpreted as: sustainability is a system of interacting, interdependent, and robust pillars. Although the pillar model has helped to conceptualize sustainability, it is fundamentally flawed because it propagates fragmentation between each discipline involved (Gibson, 2006) - i.e., the necessary fragmentation is an emergent property of the pillar construct. This propagation of fragmentation and the inevitable focus on tradeoffs will likely undermine the overall sustainability effort. Instead, Gibson posits an emphasis on the properties associated with sustainability in terms of criteria and requirements that must be achieved, as presented in Table 1. In doing so, Gibson acknowledges that bottom up sustainability assessments often abandon the pillar categories because the problem of unsustainability crosses the boundaries of each of the pillars.

Criteria	Requirements
Socio-ecological system integrity	Build human-ecological relations to establish and maintain the long-term integrity of socio-biophysical systems and protect the irreplaceable life support functions upon which human and ecological well-being depends.
Livelihood sufficiency and opportunity	Ensure that everyone and every community has enough for a decent life and that everyone has opportunities to seek improvements in ways that do not compromise future generations' possibilities for sufficiency and opportunity.
Intragenerational equity	Ensure that sufficiency and effective choices for all are pursued in ways that reduce dangerous gaps in sufficiency and opportunity (and health, security, social recognition, political influence, and so on) between the rich and the poor.
Intergenerational equity	Favour present options and actions that are most likely to preserve or enhance the opportunities and capabilities of future generations to live sustainably.
Resource maintenance and efficiency	Provide a larger base for ensuring sustainable livelihoods for all, while reducing threats to the long-term integrity of socio-ecological systems by reducing extractive damage, avoiding waste and cutting overall material and energy use per unit of benefit.
Socio-ecological civility and democratic governance	Build the capacity, motivation and habitual inclination of individuals, communities and other collective decision-making bodies to apply sustainability requirements through more open and better informed deliberations, greater attention to fostering reciprocal awareness and collective responsibility, and more integrated use of administrative, market, customary and personal decision-making practices.
Precaution and adaptation	Respect uncertainty, avoid even poorly understood risks of serious or irreversible damage to the foundations for sustainability, plan to learn, design for surprise, and manage for adaptation.
Immediate and long term integration	Apply all principles of sustainability at once, seeking mutually supportive benefits and multiple gains.

Table 1 - Criteria for sustainability assessment (from Gibson 2006 with permission)

In applying Gibson's criteria in site specific contexts, decision makers and people from all disciplines work together in a holistic approach toward the need to address the gap between the rich and the poor and respecting ecological constraints. While these criteria provide a broad framework across various time scales designed to meet desirable outcomes, mathematically based systems analysis models can contribute as a sub system of the framework by informing the decision making process with numerical models.

Numerical models provide people with an indicator of progress toward defined sustainability criteria.

Two model types used in systems analysis are descriptive models and prescriptive models (Revelle et al., 2004). Descriptive models provide an explanation of the interactions within the system and allow for changes in the system to be evaluated. Prescriptive models provide techniques to determine the best course of action to achieve desired results (typically as an extension of the descriptive model).

Two descriptive numerical models, which have been developed to understand the effects of human economic activities on the world, are input-output (IO) analysis (Leontief, 1970) and the ecological footprint (EF) (Wackernagel and Rees, 1996).

The IO analysis correlates economic data to the associated environmental impact or the resource use. Various studies have used IO type analyses to determine energy consumption and CO_2 emissions associated with different activities and lifestyle choices (Bin and Dowlatabadi, 2005; Carlsson-Kanyama et al., 2005; Moll et al., 2005). These studies suggest that the energy and environmental effects of a person's lifestyle choices are greatly influenced by local energy provision and transportation choices and that a large portion of these effects are indirect[3]. In an attempt to move from a descriptive to a prescriptive model, IO analysis has been combined with a linear optimization technique[4] to estimate how the consumption of goods and services could be shifted towards a more sustainable level (Nansai et al., 2007).

The EF uses trade flow data and carbon dioxide emissions estimates to calculate the area of productive biosphere that people use to live on, produce food, and assimilate the emissions associated with energy use. Ecological sustainability is then assessed by comparing the results to total ecosystem area available on the planet. Based on the most recent global and national scale EF, the ecosystem area required to support the land use,

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[3] While the study by Bin and Dowlatabadi, found that decisions regarding food were seen to have little impact on overall effects, the studies conducted by Carlsson-Kanyama et al. and Moll et al. suggest otherwise. This difference may be due to the regional nature of the studies – i.e., USA in the former and Europe in the latter.

[4] For a discussion of optimization using linear programming see Section 2.5.1

food production and energy use associated with human life in 2003 was 25% greater than what was available on Earth (WWF, 2006). Along with being applied at the global and national level, the EF has been applied at the regional or municipal level (Collins et al., 2006) and the product level in the case of mobile phones (Frey et al., 2006). From application at the municipal level, it was concluded that the main strength in the EF approach is that it provides a perspective on environmental pressures in a very easy to understand form. As such, the EF is useful tool for engaging stakeholders in evaluating policy options (Collins et al., 2006).

A more recent construct which attempts to apply sustainability criteria such as those presented by Gibson, is the framework of industrial ecology. Ecology is the science that studies interactions between living organisms and their environment (Sutton and Harmon, 1973). Taking note from the observation that, as natural ecosystems develop, they make the most effective use of available energy through a diverse array of species (Schneider and Kay, 1995), industrial ecology sees industries as technological organisms in a complex industrial food web. In doing so, the intent is to increase the efficiency of the industrial system by identifying resource exchange opportunities and organizational behaviour which promotes cooperation and, combined with sustainability criteria, aligns the flow of resources to a level respectful of the productive and assimilative capacity of natural ecosystems. In addition, by combining the natural ecosystem model with mathematical and graphical systems analysis techniques, complex ideas and scenarios can be communicated to broad audiences and perpetuate these ideas to other aspects of peoples lives. The following section elaborates on this overview of industrial ecology and provides a detailed discussion of the role it could play in facilitating a shift towards sustainability.

2.2 Industrial Ecology (IE)

2.2.1 Describing Industrial Ecology

Industrial ecology (IE) is a systems approach to the analysis of the flow of energy and materials which recognizes the connectedness of materials, products and infrastructure to ecological functions and services provided by the natural environment

(Cote, 2003). IE has been formally defined as "the study of technological organisms, their use of resources, their potential environmental impacts, and the ways in which their interactions with the natural world could be restructured to enable global sustainability" (Graedel and Allenby, 2003). The objective of "enabling global sustainability" has been elaborated further to include: preservation of the ecological viability of natural systems; ensuring an acceptable quality of life for people; and maintaining the economic viability of systems for industry, trade and commerce (Lowe, 2001).

The study of the interactions of the "technological organisms" occurs on two levels (Cote and Cohen-Rosenthal, 1998). The first level involves the study of the physical interactions including energy and material exchanges from an engineering and natural science point-of-view. The second level focuses on business relationships, inter-organizational management, and the connections between the industries and the surrounding communities. (Korhonen, 2004). These two levels acknowledge that, while natural science may provide us with indicators of ecological well being and may provide a general direction towards ecological sustainability, it is decisions made by people which determine the future we create (Cohen-Rosenthal, 2000; Korhonen, 2004), and these decisions are not always based solely on the natural sciences.

As human industries are contributing components of the larger ecosystems within which they are embedded, potential guidelines for IE projects based on the critical ecosystem principles of roundput, diversity, locality and gradual change have been identified (Korhonen, 2001a). Roundput refers to the linking of production and consumption in order to achieve the cycling of materials and cascading of energy present in natural ecosystems; diversity refers to diversity in materials, participants and in the interdependencies and interconnectedness among participants in order to maintain system resiliency; Locality refers to encouraging co-operation between local participants while respecting the productive and assimilative capacity of the local ecosystems; and Gradual Change refers to adopting an adaptive approach which builds on existing strengths within an industrial system and facilitating the gradual development of networks within the system (Korhonen, 2001a). Two additional principles include delivering functions with fewer materials (also known as dematerialization) and eliminating the use of toxic materials that upset system components (Ehrenfeld, 2000).

Successfully incorporating these principles into the human industrial system has the potential to move us towards sustainability. Ecological benefits include reduced raw material inputs, energy inputs, atmospheric emissions and waste generation while economic benefits result from reduced cost associated with avoided waste management and decreased energy use and raw materials requirements along with increased market penetration from improved environmental image (Burstrom and Korhonen, 2001). Social benefits to an IE approach include an improvement in public health resulting from reduced or eliminated emissions (Cote and Hall, 1995), the creation of more local jobs, promoting education and a general increased quality of life through community integration (Cote and Cohen-Rosenthal, 1998).

2.2.2 Evolution of the Concept of IE in the Literature

Researchers in the field of IE have demonstrated the presence of IE principles throughout history and documented the transition of IE from a vague concept to a focused research field. This section summarizes various secondary sources found within the IE literature to provide a brief overview of the evolution of the concept of industrial ecology.

Some of the principles of IE, such as cycling of materials and identification of ecological degradation and human health effects associated with industrial use of materials appeared in the literature in the mid to late 19th century (Desrochers, 2005; Marald, 2006). Similar to how IE uses the organic metaphor of ecosystems to conceptualize industrial systems, Desrochers points to the early use of an organic metaphor by the representation of these principles in a tree diagram (Desrochers, 2005). Erkman (1997) identifies that in the late 1960s, an Industry Ecology Working Group was formed in Japan to develop the idea of thinking of industrial systems in terms of ecosystems (Erkman, 1997). As noted by both Erkman (1997) and Ehrenfeld (2004), in 1983, a Belgian group prepared a report describing the industrial activities using the analogy of natural ecosystem as a means of managing resource flows within the Belgian economy (Erkman, 1997; Ehrenfeld, 2004). Although some application of these principles existed, in looking back at the emergence of large material recycling networks, Zimring (2006) notes that these occurred in the US due to economic motivation (Zimring, 2006). Although these groups raised concerns regarding current policies and practices, these concepts remained un-heard of in the mainstream until their re-emergence in 1989 (Andrews, 1999).

In 1989, an article titled "Strategies for Manufacturing"[5] suggested that the IE metaphor might have various applications in the US manufacturing sector (Frosch and Gallopoulos., 1989)). This article has sparked great interest and is the basis for the current development in IE. The success of the article is attributed to: the article's appearance in Scientific American; the author's reputation in government, engineering and business circles; the affiliation with General Motors; and it's timely release when people were seeking new strategies to improve the environmental performance of the manufacturing sector upon the release of the Brundtland Commission report (Erkman, 1997). Also during this time, the example of IE in Kalundborg, Denmark was uncovered and became the focus of many studies (Indigo, 2003).

The IE concept is showing signs of becoming institutionalized (Ehrenfeld, 2004). The concept has evolved into a field of study with: full graduate level programs in various universities and colleges around the world; consultant companies working at applying the concepts; two peer reviewed journals dedicated to the topic (Journal of Industrial Ecology, Progress in Industrial Ecology – An International journal); special editions in other academic journals dedicated to IE; and the International Society for Industrial Ecology has been formed along with different national and regional societies.

2.2.3 Strategies for Developing Industrial Ecosystems

Key implementation strategies that can help to develop a successful industrial ecosystem have been identified. These strategies include (Cote and Wallner, 2006): identifying key industrial agents that have a high development potential; implementing individually based programs which seek to reduce the ecological degradation associated

[5] The title originally proposed was "Manufacturing – The Industrial Ecosystem View" but was rejected.

with the operation of each individual industry; introducing new small and medium industrial agents that substitute the services of problematic sectors; and integrating the adapted industries and agents into a regional network. A Swedish case study on developing a local industrial ecosystem includes the following steps that reflect the strategies described above (Wolf et al., 2007):

- identification of important actors;
- analysis of internal process of main actors to avoid sub-optimization;
- mapping of relevant material and energy flows within the municipality along with identification and study of existing co-operation and competitions;
- completion of mass and heat balances to find potential for improvements followed up with a discussion of results with the existing actors and modified where required; and
- initiating a forum in collaboration with the local municipality where the actors can meet.

One of the emerging ideas from the case study was that there was an opportunity for the formation of a recycling company.

All the implementation strategies acknowledge the various scales in IE ranging from the internal interactions within a plant or firm to the interactions between co-located firms and interactions on the regional or global scale. Further, the interconnection between each of the scales, i.e., the decisions made and actions taken at one level can have direct and indirect effects in other levels, is explicitly recognized. The following sections focus on highlighting some of the barriers encountered in developing industrial ecosystems and the approaches that are available at each scale to overcome them.

2.2.4 Barriers in IE

Various barriers to the application of IE have been identified which can result in a lack of "buy in" by potential stakeholders. Some barriers to inter-company cooperation and interconnection exist at different levels such as (Fichtner et al., 2004; Fichtner et al., 2005):

- the personal level focusing on cognitive, motivational and situational barriers;

- the enterprise level in terms of communication, attitude and resources; and
- on the inter-firm level in terms of dependency, loss of control over decisions affecting resources, legal barriers, competition, assignment of costs, difference in investment cycles, and insufficient trust and communication.

Specifically, in some projects, capital cost and potential future changes to process operation leading to uncertainties in continued resource availability were the biggest barriers (Harris and Pritchard, 2004). In other projects, regulatory barriers that impede structural changes and practices required to develop IE such as building codes and zoning bylaws have also been identified (Cote and Smolenaars, 1997). In addition, loopholes within environmental law and the lack of indicators as to a level of performance required to be classed as an EIP are also seen as barriers to progress (Geng et al., 2007). In relation to a lack of indicators, the US EPA attributes a loss of management interest and funding for IE projects in 1999 to the lack of reporting on the quantitative reduction of pollution associated with the IE development (Giannini-Spohn, 2006).

Although these barriers to attaining "buy in" from all participants exist, they are not insurmountable. The following section provides a discussion of the roles played by the various actors in an IE project and some actions that can be taken to overcome some of these barriers.

2.2.5 Overcoming Barriers in IE

A fully integrated IE approach requires participation amongst a host of participants armed with methods for quantifying the effect of the project on socio-ecologic systems. IE generally involves the participation from industry, government, community, non government organizations, and third party facilitators. Different actors may join the project as it evolves. When considering industrial participants in an IE project, a differentiation is made between intra-firm and inter-firm interactions. In addition, approaches taken by both large companies and small to medium sized enterprises (SMEs), which typically have less than 250 employees, are considered.

2.2.5.1 Industries: Intra-Organisational or Plant Level Perspectives

Initiatives conducted internally within individual firms can take different forms and progressions; from the incorporation of an environmental management system to developing eco-efficiency through pollution prevention, life cycle assessment and a design for environment approach.

An environmental management system (EMS) can be used to establish association between business operations and environmental concerns within a company. An EMS provides a company with a means by which to manage the activities that can have an impact on the environment in a planned way; and facilitate the identification of ways of improving environmental performance (Starkey et al., 1998). The most common EMS model has been prepared by the International Organization for Standardisation (ISO 14001). The elements of ISO 14001 typically include (Starkey et al., 1998):

- drafting of an environmental policy;
- planning objectives and targets in relation to the environmental policy;
- implementing elements to operationalize the plan and achieve the objectives and target;
- checking to ensure that objectives and targets are being met and taking corrective action when they are not; and
- Management review of the system to ensure its ongoing effectiveness and suitability.

Additional research suggests that, in production facilities, incentive and education programs for plant operators can make a positive contribution to environmental management and could be integrated into an EMS (Boiral, 2005).

In terms of IE, a beneficial aspect of an EMS is the inclusion of ecosystem impact indicators. Indicators take the form of atmospheric emissions, water pollution, water use, energy use, solid waste production, etc. By tracking these indicators, firms can progress towards eco-efficiency. The World Business Council for Sustainable Development states that:

> "Eco-efficiency is achieved by the delivery of competitively-priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life-cycle to a level at least in line with the earth's estimated carrying capacity." (WBCSD, 2000)

In attempting to achieve eco-efficiency at the plant level, a company can take a pollution prevention approach which looks at plant operations. Pollution prevention, also called cleaner production or P2, involves evaluating the production processes and addressing pollution through: process modification and optimization; technology modification; good housekeeping; input substitution; on-site reuse; and off-site reuse (Graedel and Allenby, 2003). One way to optimize processes is through process integration. Process integration is defined as "all improvements made to process systems, their constituent unit operations, and their interactions to maximize the effective use of energy, water and raw materials"(NRC, 2003). Two of the most commonly used process integration techniques are mathematical programming and thermodynamic pinch analysis (NRC, 2007). These two techniques are outlined further in Sections 2.5.1 and 2.5.2.

As a compliment to the focus on plant operations, firms can also decide to address ecosystems impacts from a product perspective. An approach for evaluating the environmental impacts incurred throughout the product "life" (from resource extraction, to product manufacture, to product use, to product disposal or recycle) is life cycle assessment (Jensen et al., 1997). The four steps of an LCA include (Jensen et al., 1997):

- goal and scope definition;
- inventory analysis;
- impact assessment; and
- interpretation of results.

An LCA methodology has been prepared which is in accordance with ISO (ISO 14040). Upon completion of an LCA, Design for Environment (DfE) can be used. DfE is a management approach that takes into account environmental considerations as a step in the product or process design (Graedel and Allenby, 2003) or redesign. In other words, LCA identifies the environmental impacts associated with the product or processes and

DfE acts on the results. As the product life typically transcends the plant level of one firm, employing LCA or DfE requires the co-operation of different actors along the product life cycle. Attaining this co-operation shifts the focus from the intra-firm level to the inter-firm level, which is discussed in the section regarding the regional perspective.

The largest hurdle to overcoming barriers for SMEs is the lack of available resources (Starkey et al., 1998; Cote et al., 2006). As a large portion of pollution can be attributed to the activities of SMEs (Cote et al., 2006), different strategies are required to achieve systematic reductions in their associated ecological degradation. One approach at the firm level that has been developed is the software program called EcoDesign Integration Method for SMEs (EDIMS) (Pochat et al., 2007). This approach attempts to remove the barriers associated with the lack of resources within SMEs by acting as a guide with which companies can link the results of an environmental analysis of its product to the design parameters. Once the company has identified the links, the information can be used to integrate its operation and modifications to achieve specified objectives. A potential shortcoming of such a tool is that it is developed to provide advisory support for pilot projects within companies. As the time required to implement any modifications and assess their performance can be several years, the success of the EDIMS project cannot be verified until sufficient time has passed, which is typically longer then the pilot project. Nonetheless, this approach provides a preliminary approach for incorporating environmental management and consciousness in SMEs. In addition, a streamlined LCA approach (Starkey et al., 1998), although not as comprehensive as a formal LCA, reduces the amount of resources required and can make a positive contribution to environmental performance by incorporating life cycle thinking.

Additional approaches for improving the environmental performance of SMEs through inter-organization interactions are presented in following section.

2.2.5.2 Industries: Inter Organisational or Regional Perspective - Eco Industrial Parks and Eco Industrial Networks

Applying IE at the inter-organizational level is based on the system concept that the whole is greater than the some of the parts. In order to co-operate with other firms, a company can determine the potential for the exchange of resources by tracking the various raw materials, energy use, resources, products and wastes entering, stored within and leaving the company over a period of time. A record of a company's inputs, stocks and outputs may be called an ecobalance (Starkey et al., 1998)[6]. Using the information from the ecobalance, the company can then seek to participate in industrial symbiosis (IS). Industrial symbiosis is the mutually beneficial exchange of resources with other firms in which society's demand for resource saving and environmental protection is considered (Chertow, 2000). Industrial symbiosis generally considers three primary types of resource exchanges (Chertow, 2007):

- exchange of by products to substitute raw materials while reducing waste;
- sharing the use and management of utilities and infrastructure for services such as energy, water and wastewater; and
- jointly providing services for supplementary activities that are common to all firms such as fire suppression, transportation and food provision.

One form of inter-organizational co-operation is through the exchange of resources between co-located firms in an eco-industrial park (EIP). An EIP can be defined as a community of businesses located together on a common property that seeks to enhance environmental and economic performance by cooperating with each other and with the local community to efficiently manage and exchange resources (Cote and Cohen-Rosenthal, 1998; Chertow, 2000; Lowe, 2001). Similar to the concept of an EIP, an eco industrial network (EIN) expands the system boundaries and seeks to encourage industrial symbiosis within various actors within the region (Lowe, 2001).

[6] It is noted that the decision to use an EMS made at the intra-organizational level could facilitate determining an ecobalance.

EINs and EIPs can be used to encourage participation of SMEs by providing access to resources which would otherwise be unavailable. In addition, larger firms applying life cycle thinking can encourage SMEs that act as suppliers to clean up their operations by offering training and potential investment incentives (Lowe, 2001).

Some starting points for the development of EIPs and EINs are the anchor tenant model, green twinning, and industrial symbiosis kernels (Chertow, 2000; Chertow, 2007). In the anchor tenant model, the IE development is built up around the resources available from a particular industry. Some typical anchor tenants include power plants (Chertow, 2000), pulp and saw mills (Korhonen and Snakin, 2005), and local authorities or governments (Burstrom and Korhonen, 2001; von Malmborg, 2004). Green twinning involves the implementation or uncovering of one exchange, and then using that exchange to encourage and develop more. For example, the waste to energy facility built in conjunction with a nearby paper mill has spawned a water recycling system and energy cascading in the form of direct steam applications. Additional green twinning initiatives, such as district heating and the utilization of combustion gases to produce calcium carbonate is being negotiated (Speigelman, 2006).

The presence of existing relationships or networks has been described as "precursors" or "kernels" of industrial symbiosis which should be developed (Chertow, 2007). Chertow suggests that resource sharing projects involving cogeneration, landfill gas and wastewater reuse are examples of precursors that can be used catalyze the formation of new "kernels". A well know example of an EIN initiated by an industrial symbiosis kernel are the partnerships at Kalundborg, Denmark , which evolved from the need to find a surface water source to replace groundwater use (Chertow, 2000; Jacobsen, 2006).

Along with the approaches discussed above, additional "supporting pillars" to foster the development inter-organisational relationships include (Cote and Smolenaars, 1997; Geng et al., 2007):

- information management systems;
- the utilization of economic instruments;

- the review, restructuring, and implementation of regulations; and
- an appropriate educational program.

In order to build these pillars, industries require the assistance of other actors in the IE development process whose roles are discussed in the following sections.

2.2.5.3 Government Roles in IE

Government or local authority can act as an institutional anchor tenant in an industrial ecosystem. Geng et al. suggest that the government can integrate various government divisions related to IE development such that policies are implemented to limit the development of large resource depleting and polluting industries (Geng et al., 2007). Similarly, governments can pass laws encouraging business participation in IE projects (Chertow and Lombardi, 2005; Chertow, 2007). Governments can also act as information banks thus fostering both collaboration between participants and continually improving network participation (von Malmborg, 2004). In this position, the government is the main source of information and plays an active role in the knowledge transfer process.

In addition to that mentioned above, the local authority can be a physical anchor tenant because, in most areas, the local government manages or regulates the collection and disposal of wastes (Burstrom and Korhonen, 2001). In addition to identifying the potential for material exchanges and energy projects, governments can allocate effluent fees for reinvestment into local IE strategies or can implement quotas on resource use along with an accompanying penalization mechanism for non compliance (Geng et al., 2007). Other economic devices that could be employed by local governments to encourage innovation in IE development include (Cote and Smolenaars, 1997):

- increased tipping fees;
- virgin material taxes; energy taxes on non renewable energy use;
- single use packaging tax, loans, and grants; and
- business occupancy tax.

Further, tax incentives based on meeting performance targets could be used to encourage environmental improvements in industries (Fons and Young, 2006). Casavant and LeBreton have developed indicators of sustainable industrial performance (Casavant and LeBreton, 2005) which could serve as a basis for developing tax incentives.

Cost barriers to IE implementation can be addressed by the use of contracting or public private partnerships (PPP). Contracting, which has been used in the energy sector, is a method of overcoming the long payback period associated with IE projects (Fichtner et al., 2005). Contracting involves an agreement endorsed by all participants in which the contractor or a contractor consortium takes over the task of financing the project and commits to providing the service. Another approach aimed at reducing the government's exposure to financial risk is the government's support of a PPP or joint venture. In addition to reducing risk of the partners, this approach can also provide SMEs with a chance to invest in environmental management while providing for local and regional business development (von Malmborg, 2004).

2.2.5.4 Non-Governmental Organizations in IE

IE projects can be facilitated through the development or extension of non governmental organizations (NGOs) (Chertow, 2007). NGOs have demonstrated their capacity in the role of a knowledge bank for IE projects. Examples of NGO-led IE initiatives include the local eco-efficiency center at Burnside Industrial Park (EEC, 2003) and a national UK programme called the National Industrial Symbiosis Programme (NISP, 2006). Both of these efforts have included partnerships with educational institutions which can work to further perpetuate the learning to students.

NGOs have also demonstrated success in influencing industries to adopt ecologically and socially conscious practices through the use of market campaigns. This success has been achieved by lobbying group purchasing organizations, universities, corporations, and government agencies to create the demand for improved products (O'Rourke, 2005).

The building industry provides an example of how NGOs are working to transform the construction industry. The Canadian Green Building Council (CaGBC) a

Canadian NGO, and the United States Green Building Council (USGBC), administer the Leadership in Energy and Environmental Design (LEED) program. This program focuses on five design elements of the building process including: sustainable sites, energy and atmosphere, materials and resources; indoor environmental quality; and innovation & design (Canada Green Building Council, 2004). These five elements take into account the life cycle of buildings and building materials. In addition, market adoption of the program has aided in furthering the efforts of other NGOs. For example, the Forest Stewardship Council (FSC) is an NGO that promotes sustainable forestry management. Correspondence with the former director of the Eco Lumber Co-Op, a former NGO focused on creating a market for the use of Forest Stewardship Council (FSC) certified wood, indicated that the inclusion of a credit requiring the use of FSC certified wood in LEED was a very important factor in the increase in the amount of FSC wood being purchased (Brewer, 2007).

2.2.5.5 Third Party Facilitators

In attempting to build trust within an IE project, the need for communication agents has been identified (Koenig, 2005). Project experience from the Alberta By-Product Synergy Project has identified that industry has expressed a preference for a project facilitator in the form of a third party participant (Fons and Young, 2006). This role is typically filled by consultants (eg, Eco-Industrial Solutions) or researchers (Wolf et al., 2007). In the case of the government taking the role of a knowledge bank, the government may hire the third party facilitator who takes the preliminary role in IE approaches such as those presented in Section 2.2.3. The facilitator can use tools such as developing a project website, hosting workshops and design charrettes, along with advertising in local newspapers, radio and television programs (Lowe, 2001). In the case of a research oriented third party, continued student research projects provide an opportunity for tracking progression of the initiative while providing future generations with formal training in applying IE.

2.2.5.6 Community Interaction in IE

The application of IE in an area will directly affect the community of people who live and work in the area. In addition to the actors mentioned in the previous sections, additional community members include: residents, business associations, educational institutions, labour representatives and other community groups. Planners of IE projects need to acknowledge that there has to be a market for what the IE project has to offer in an area (Cote and Cohen-Rosenthal, 1998) and that public fears can jeopardize any IE initiatives (Harris and Pritchard, 2004). One strategy to overcome these hurdles is to educate and involve all members through a community engagement program. Elements of a community engagement program include (Lowe, 2001, Ch4, pp. 17):

- public workshops and conferences;
- project web sites;
- newspaper columns; and
- radio and television presentations.

These approaches can be used to gain public support for the initiative by communicating IE benefits such as the incubation of local firms; available training programs; and enhanced public services (Lowe, 2001) to community members along with allowing for their direct involvement in the decision making process.

Along with simply attaining public support, encouraging community interactions regarding the IE initiative can play a role in changing consumption habits by educating the public regarding the indirect affects associated with consumption. Many consumption concerns are converted to questions of production and technology or passed off as someone else's problem in some far away place (Conca et al., 2001). Education as part of the IE initiative can contribute to directly addressing this concern by communicating study results to consumers. In one study, an analysis of energy use associated with food production is used to inform people of the effects on energy consumption associated with different food choices (Carlsson-Kanyama et al., 2005). If energy reduction is part of a larger community sustainability plan, these study results can empower people to make informed decisions that can help them reach their goals. As an added benefit there is a potential that people who incorporate environmental thinking into some aspects their life will transfer this behaviour to other aspects of their lives (Thogersen and Olander, 2003).

2.2.6 Sustainable or Sustain a Bull: Some Criticisms of IE

The main concerns voiced regarding IE are that the concept must address overall growth in both the amount of pollution generated and in the consumption of raw materials associated with human activities. As with all complex issues, these two concerns are not mutually exclusive and not easy to address.

Criticisms have been expressed as "there is no panacea for reducing the impact of human activity on the environment, and the danger is that the rhetorical attraction of IE will provide comfort for policy makers" (Tansey, 2006). Policy makers may encourage growth in industries that apply IE concepts and ignore the goal of overall net reduction in energy and material throughput (Gibson and Peck, 2006). Also, the effectiveness of the ISO 14001 EMS in improving environmental performance has been questioned on the basis that environmental performance and its measurement in this approach are defined and set up by company management (Boiral, 2005). This concern has been raised elsewhere on the basis that firms that have the worst environmental pollution records tend to report most on the environment. Thus, projecting the image of improving environmental performance takes precedence over actually improving environmental performance (Cerin, 2004). The concern is that, by applying an IE approach which, over time, allows a company or a region to increase productivity in terms of output per unit of ecological degradation, the industrial units will grow into the savings that the IE approach created. This higher level of economic activity would in effect leave the industry or region less resilient to changes in the productive and assimilative capacities of regional and global ecosystems!

Another concern, which is influenced by both consumption and growth, is that the application of IE will increase demand for inherently unsustainable products. The most famous example of industrial symbiosis, Kalundborg Denmark, provides validation of this concern because it includes the export of sulfuric acid and petrochemicals (Tansey, 2006). Conversely, experience suggests that the broader benefits of IE may occur in the environmental innovation activities occurring in the regional context as a result of the application of IE (Mirata and Emtairah, 2005). In addition, EINs have been illustrated as learning networks by combining the learning process that has emerged through the progression of IE with a technology transfer model in order to understand the relationships, markets, processes, and interactions that occur at the regional level (Harris and Pritchard, 2004). The inclusion of selective networking (Cote and Wallner, 2006) in IE is another potential example of humans beginning to address this criticism. Selective networking suggests that people can *choose* to promote development in certain industries that contribute to the overall sustainability objectives of the area.

Another concern of the IE approach is that production and consumption occur on different spatial scales and a regional or local approach will not address this (Korhonen, 2002; Tansey, 2006). Korhonen argues that this concern can be addressed by performing both a regional approach and a life cycle approach together (Korhonen, 2002). In this way, reducing the level of ecological degradation associated with production and networking with the final consumers regarding disposal or reuse options provides a means to mitigate this concern. In addition, cleaning up the production processes will provide indirect benefits to the region where the consumption is occurring.

It is recognized that any strategy that aims to move towards sustainability, needs to reduce the level and change the patterns of consumption (Yap, 2006). In essence, this signifies a required paradigm shift. One part of the strategy " is to develop new forms of engaging the public and interested stakeholders in thinking through the consequences and characteristics of alternative development paths" (Robinson et al., 2006). Various attempts at this strategy are starting to appear (Wolf et al., 2007). Also, the metaphoric aspect in IE such as the concept of diversity, interdependency and locality have been regarded as useful in the normative aspect of a paradigm shift, while cycling materials and cascading energy provide the normal practice stage of a paradigm shift (Korhonen, 2003). The incorporation of time into the a planning process can also help to justify sacrificing short term success for secured long term success (Korhonen, 2004).

When considering a paradigm shift, Hobson argues that the fundamental view, such as the one that is present in many interpretations of eco-efficiency, must be shifted from doing more with less to "making the most of what we can potentially all share" (Hobson, 2002). Currently, in terms of ecological sustainability, the only metric which allows for this is the EF. One approach could be to use a tool such as the EF to take a baseline of a region. Once this has occurred, an EIN strategy could be employed in the region along with an LCA of the major exports and imports to the region. This LCA could be used to determine the next region to focus on by identifying environmental impacts associated with trade.

In summary, all of the concerns presented are a testament to the complexity associated with the sustainability discussion. It is generally accepted that the application of IE can lead to significant insights and efficiency gains in industrial activities. Given the current large scale industrial activity in the world, it seems rational to include a component of IE into any sustainability plan. Although IE is necessary, care and caution must be employed in its application to ensure that its basis for implementation, i.e., the shift towards sustainability, is not undermined. This means that the learning that occurs and the efficiency gains that are realized in the application of IE need to be communicated and used in continual feedback loops to the larger sustainability objectives. In this way, activities that provide feedback aimed at contributing toward achieving sustainability objectives can be positively reinforced, while activities that do not can be selected against.

2.3 Geographical Information System (GIS)

As stated in section 2.2.5.2, one of the "supporting pillars" of an industrial ecosystem is an information management system. The goal of this section is to discuss the potential use of GIS in the development and ongoing information management of an industrial ecosystem. This section provides an overview and a presentation of some applications of GIS.

A GIS is "a collection of computer hardware, software, and geographic data for capturing, managing, and displaying all forms of geographically referenced information" (ESRI, 2006). In essence, a GIS is a database with the descriptive modeling ability to illustrate in two dimensions the information contained in the database (produce maps) and provide a platform with which to conduct various spatial analyses of the database information.

A GIS map is made of one or more data frames. Each data frame consists of thematic layers, with each layer containing a collection of features that represent real world objects (ESRI, 2004). The three basic layer feature shapes included in a GIS map are: points; lines; and polygons. A point consists of a single co-ordinate pair used to represent a specific location on the Earth's surface. Depending on the scale of the map, points can be used to represent various things such as buildings, cities, trees, etc. A line consists of a sequence of co-ordinate pairs. Again, depending on the scale of the map, lines can be used to represent rivers, streets, telephone lines, etc. A polygon consists of a series of lines that are all connected, with the starting and ending co-ordinate pairs being the same. As with the other features, the map scale and the level of detail determine what real world representation the polygon will have. For example, a polygon can be used to represent a country, province, city, water body, building, etc.

Each thematic layer in a GIS map is equipped with an attribute table. The attribute table allows specific data to be linked to each feature in the layer. For example, if points are being used to represent various companies, the company names can be added to the attribute table, thus linking the point, along with its geographical co-ordinates, to the company name.

2.3.1 Applications of GIS to Industrial Ecology

The application of GIS technology has been described as being "limited only by the imagination of those who use it" (ESRI, 2006a). In terms of determining the potential for IE, a German study (Lenz and Beuttler, 2003) illustrates how a GIS was used to determine total area consumption, solar panel energy production potential, and water consumption in separate locations within a municipality. The authors of the German study concluded that the spatial reference of GIS allows regional planners enhance the process of setting priorities in action fields by relating the action fields to high priority geographical areas, making the use of GIS software necessary in regional planning.

In a different regional application, the Oldenburger Munsterland Region in Germany utilizes GIS in the form of the Regional Recycling Information System (REGRIS). REGRIS was initially developed to assist in coordinating the recycling of wood, used plastic and fluorescent tubes and as a result of its success, the system was further developed to support the recycling of granite residues and used coating powder in Eastern Austria (Hasler, 2004). Similarly, Swiss and French researchers are collaborating on the development of a GIS based program called Presteo to facilitate the implementation of industrial symbiosis around Geneva (Massard et al., 2006; Massard and Erkman, 2007).

An Indian case study demonstrates that the use of GIS as an assessment and monitoring tool for billing and collecting taxes improved the organization of the solid waste collection service and the operation of the water supply network (Saladin et al., 2002). This success of GIS in the management of municipal services suggests that GIS could also contribute to the successful organization and management of industrial symbiosis related infrastructure.

A US example demonstrates the use of GIS in the evaluation of environmental policy (Gamper-Rabindran, 2006). In the evaluation of the US EPA's voluntary industrial toxics program, a production facility's pollution related decisions were found to be correlated to voter participation rates in the community within which the facility was located. This type of correlation was made possible by combining community characteristic data with plant level location data within a GIS. This type of information can be beneficial to the implementation of IE as communities with high voter participation rates may be to more receptive to an IE project. Implementation within a receptive community could act as a leverage point to obtaining project support and further implementation within the larger region surrounding the community. Over a longer temporal scale, GIS could also be used to monitor the progression of IE along with community characteristics to determine the effect of the project on community characteristics, and vice versa.

2.4 Simulation

Simulation is a descriptive model that generates realistic events and system responses (Revelle et al., 2004). When considering the use of energy and materials in industrial applications, simulation represents a series of material and energy balances. As solving numerous material and energy balance problems for even relatively simple systems can be time consuming and cumbersome, people have created computer software programs to perform the calculations (Felder and Rousseau, 1986). These software programs can be built manually with computer applications such as Visual Basic, C++, and Python (to name only a few) or can be purchased in pre built software packages.

Some typical chemical process simulation software packages used to model factories and their processing units such as reactors, mixers, heat exchangers, boilers and burners include Matlab with its graphical interface Simulink, Aspen Plus, Hysys and CadSim Plus. In addition to solving the mass and energy balances, each software package has the ability to generate process flow diagrams which allow for a two dimensional representation of the material and energy flow through each of the system processes. These types of software packages provide a platform to virtually design process units or evaluate process modifications prior to committing resources towards experimentation associated with their implementation.

2.4.1 Applications of Simulation to Industrial Ecology

Chemical process simulation has been demonstrated to allow for the evaluation of "what if" scenarios at the plant level. In one example, process simulation is used to compare the effects associated with changing attributes of the zinc casting process (Taplin et al., 2006). The study demonstrates the ability of a simulation model to allow industries to quantitatively estimate indicators such as energy use, solid waste generation, CO_2 emissions and primary zinc consumption. In this way, modification to production processes can be planned based on simulated indicator values associated with the modification being considered.

Process simulation software has been demonstrated to be useful in the identification and simulation of potential industrial symbiosis (Casavant, 2000; Casavant and Cote, 2004). By utilizing CadSim Plus to model a few key processes within the participating companies and linking matching resource streams between companies, Casavant demonstrated how process simulation could be used to track performance of an EIN or an EIP in terms of CO_2 emissions, SO_2 emissions, waste heat, water losses, solid waste to landfill, fuel oil consumption and water usage.

Another example of the use of simulation is the organic waste research (ORWARE) model (Dalemo et al., 1997). ORWARE, developed using Matlab and Simulink, was created and used to calculate indicators such as the global warming potential, acidification potential, eutrophication potential, toxicological health effects and photo-oxidant formation along with electricity generation potential, district heating potential and fertilizer application potential associated with various municipal waste management options (Dalemo et al., 1997b; Björklund et al., 1999; Björklund et al., 2000; Eriksson et al., 2002). In doing so, ORWARE informs decision makers by facilitating the integration of ecological effects and resource potential into the selection of waste management strategies. The model has since been enhanced with sub routines to allow for the evaluation of producing hydrogen gas from municipal solid waste gasification and using the hydrogen in fuel cell vehicles (Björklund et al., 2001). Additional work has included estimates of financial costs along with the environmental impacts in the evaluation of thermal treatment technologies and the associated energy generation (Assefa et al., 2005).

2.5 Optimization

The goal of optimization is to determine the best course of actions to achieve desirable objectives. In terms of systems analysis, optimization provides analytical techniques that prescribe how the system components can interact so that the overall system exhibits specific properties. In section 2.2.5.1, mathematical programming and thermodynamic pinch analysis were identified as two of the most common optimization techniques used to identify how an industrial plant can integrate its processes to maximize the effective use of resources (p. 17). The research presented in this thesis extends mathematical programming and thermodynamic pinch analysis from the plant level to the inter-organizational level such that water and heat cascading opportunities among a group of industries operating within a specific geographic area are identified. In industrial ecology literature, this approach could be described as a means of identifying opportunities for industrial symbiosis (described in Section 2.2.5.2).

The focus of this section is to provide an introduction to mathematical programming to achieve multiple objectives and thermodynamic pinch analysis and to provide examples of how they have been applied at the inter-organizational level. These techniques will be used in the model development presented in Section 3.

2.5.1 Multi-objective Programming

Multi-objective programming (MOP) involves developing mathematical functions of a set of decision variables and parameters to represent the objective function(s) and constraint(s) (Cohon and Rothley, 2004). The objective function is the element to be optimized while constraints are the conditions which must be met. The most popular form of MOP is linear programming which constitutes linear objective functions and constraints (Revelle et al., 2004). Some typical applications of linear programming include: determining least cost distribution of goods from multiple sources to multiple destinations; selection of industrial and landfill location; and choosing which items to manufacture in order to achieve maximum profit (Revelle et al., 2004).

Two types of linear programming considered in this thesis are the weighting method and the constraint method (Revelle et al., 2004). The weighting method brings all objectives into one objective function and relative weights are assigned to each objective. The constraint method solves one objective function while converting the other objective functions into constraints. Either method takes the general form as follows (Lence, 2005):

$$\text{Maximize } Cx \text{ subject to } Ax <= b \qquad (1)$$

where:

A represents the constraint coefficient;

b represents the constraint.

x is the decision variable; and

C is the cost coefficient.

As there may be more then one decision variable, it is helpful to represent the previous parameters as sets in matrices. In matrix notation, each of these parameters can be written as follows:

$$A = \begin{pmatrix} a_{1,1} & \cdots & a_{n,1} \\ \vdots & \ddots & \vdots \\ a_{1,m} & \cdots & a_{n,m} \end{pmatrix};$$

$$b = \begin{pmatrix} b_1 \\ \vdots \\ b_m \end{pmatrix};$$

$$C = (c_1 \cdots c_n); and$$

$$x = \begin{pmatrix} x_1 \\ \vdots \\ x_n \end{pmatrix}$$

where:

n is the number of decision variables; and

m is the number of constraints:

The objective can then be rewritten as follows:

$$\max imize\sum_{i=1}^{n} c_i x_i, subject \cdot to\sum_{i=1}^{n} a_{i,m} x_i \leq b_j \qquad (2)$$

One analytic procedure that has been developed to handle linear programming problems is the simplex algorithm (Edgar and Himmelblau, 1988). This algorithm uses an iterative search technique to find the values of x that will maximize the objective function and satisfy the constraints. Various commercial computer software programs exist that can be used to apply such analytic procedures to solve linear programming problems such as Matlab, Excel Solver, GAMS and Scipy.

2.5.2 Thermodynamic Pinch Analysis

Thermodynamic pinch analysis is a technique used to identify energy saving potential for processes typically within an industrial plant or complex and subsequently aids the design of the heat exchanger network to achieve the targeted saving (Linhoff March, 1998). Since its first appearances in the literature (Linhoff and Flower, 1978; Linhoff and Hindmarsh, 1983), this optimization technique has proven it's ability to maximize heat recovery and thus minimize demand for external utilities such as steam and cooling water in the following industry sectors (NRC, 2003):

- Chemicals;
- Petrochemicals;
- Oil refining;
- Pulp & paper;
- Food & drink; and
- Steel & metallurgy.

A starting point for the analysis is the first law of thermodynamics. The first law of thermodynamics is based on the law of conservation of energy which states that energy is neither created nor destroyed (Felder and Rousseau, 1986). Considering a system composed of a fluid that is being heated or cooled, the overall energy balance can be written as follows (Felder and Rousseau, 1986):

$$\Delta H + \Delta Ek + \Delta Ep = Q + W \qquad (3)$$

Where:

ΔH is the change in enthalpy or the flow of energy required to change the temperature of the fluid;

ΔEk is the kinetic energy resulting from the motion of the system relative to some frame of reference;

ΔEp is the potential energy associated with the change in the position of the system (such as a compressed spring);

Q is the energy flowing as a result of the temperature difference between a system and its surrounding; and

W is the work energy resulting from a flow of energy such as a force or torque.

Assuming that the system is: at constant pressure; not in motion ($\Delta Ek = 0$); hasn't changed position ($\Delta Ep = 0$); and that the work associated with moving the fluid and transferring the heat is negligible ($W = 0$), equation 3 can be reduced to:

$$\Delta H = Q \qquad (4)$$

Furthermore, the change in enthalpy of the system can be written as (Trivedi, 2000):

$$\Delta H = C_pM(T_2 - T_1) \qquad (5)$$

Where:

Cp is the heat capacity of the fluid at constant pressure;

M is the fluid mass flowrate;

T_1 is the initial temperature of the fluid; and

T_2 is the final temperature of the fluid.

A plot of equation 5 with temperature on the ordinate axis and enthalpy on the abscissa yields a line with slope $1/C_pM$ as shown in the following figure:

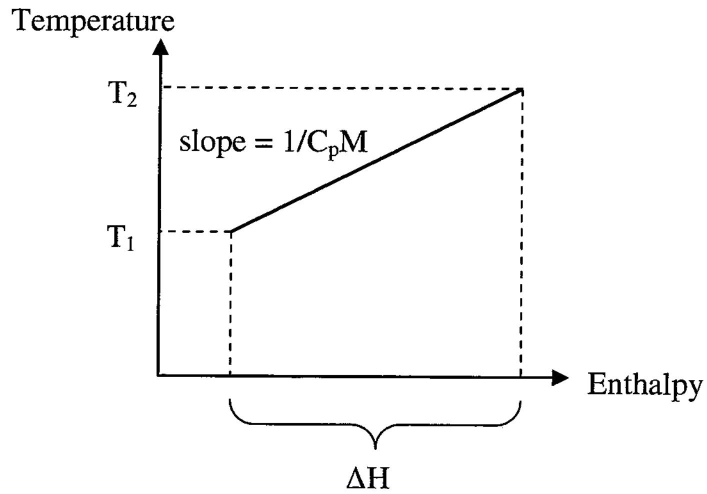


Figure 1 - Temperature Enthalpy Plot For a Cold Fluid Heated from T_1 to T_2

Figure 1 represents a temperature enthalpy plot for a fluid being heated from temperature T_1 to temperature T_2[7]. Although the pinch analysis is based on the first law of thermodynamics, the application of pinch analysis has been described as an extension of the second law of thermodynamics to the management of energy at the plant level (Dimian, 2003). In this manner, the analysis acknowledges that for every transfer of energy that occurs within the plant, there is an amount of energy that is wasted in the form of heat. The analysis also acknowledges that while there are processes within manufacturing plants that produce an abundance of heat, there are also those that require the input of heat. In order to analyse the potential for heat transfer, one of the first steps in the thermodynamic pinch analysis is the creation of composite curves for the process streams requiring heating and those requiring cooling. Composite curves are created by combining the temperature enthalpy plots for each stream being heated and for each stream being cooled. Consider the four streams of the same fluid presented in Table 2. Streams 1 and 2 require heating and streams 3 and 4 require cooling.

[7] Figure 1 does not include phase change in heating from T_1 to T_2 as the application of the thermodynamic pinch analysis presented in the heat energy model (see Section 3.3) does not include phase change. If it was included, phase change would be represented on Figure 1 as a horizontal line. The change in enthalpy of a substance undergoing a phase change at a constant temperature and pressure is known as the latent heat of the phase change (Felder and Rousseau, 1986, pp. 361).

Stream	Name	T_{start}	T_{end}	C_pM	ΔH
1	Hot_1	T_1	T_4	C_pM_1	ΔH_1
2	Hot_2	T_2	T_3	C_pM_2	ΔH_2
3	$Cold_1$	T_4	T_1	C_pM_3	ΔH_3
4	$Cold_2$	T_3	T_2	C_pM_4	ΔH_4

Table 2 - Example Data for Pinch Analysis

Figure 2 illustrates the creation of composite curves for the two streams being heated and the two streams being cooled. Note that when more then one process stream is present in a temperature interval (i.e., between T_2 and T_3 in Figure 2), the enthalpy change within the interval is added together and an average of all the slopes within the interval is assumed. As such, the composite curves presented in Figure 2 illustrate the overall heating requirements $Q_{Heating}$ and cooling requirements $Q_{Cooling}$ along the horizontal axis.

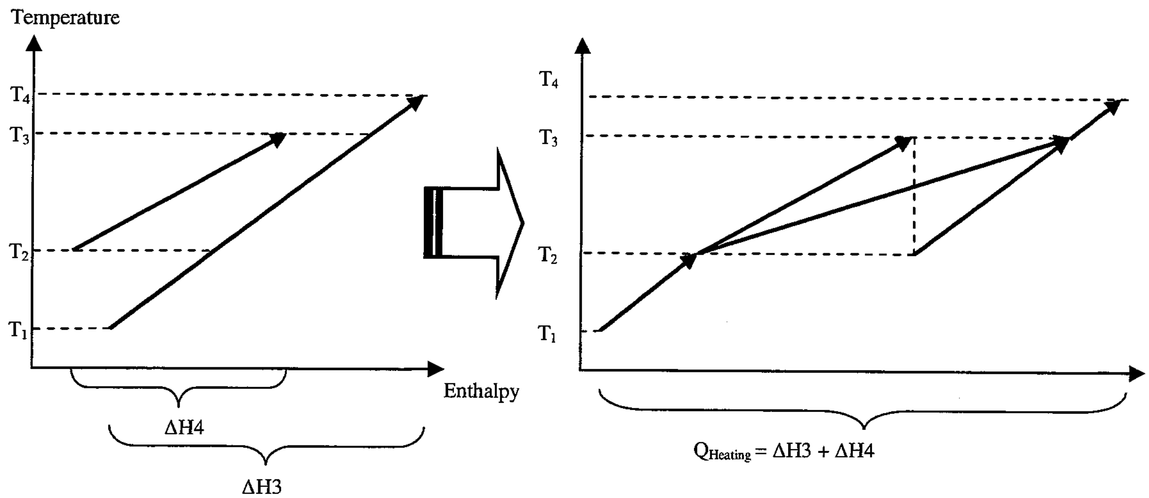


FIGURE 2A – Composite Curve for Streams Requiring Heating

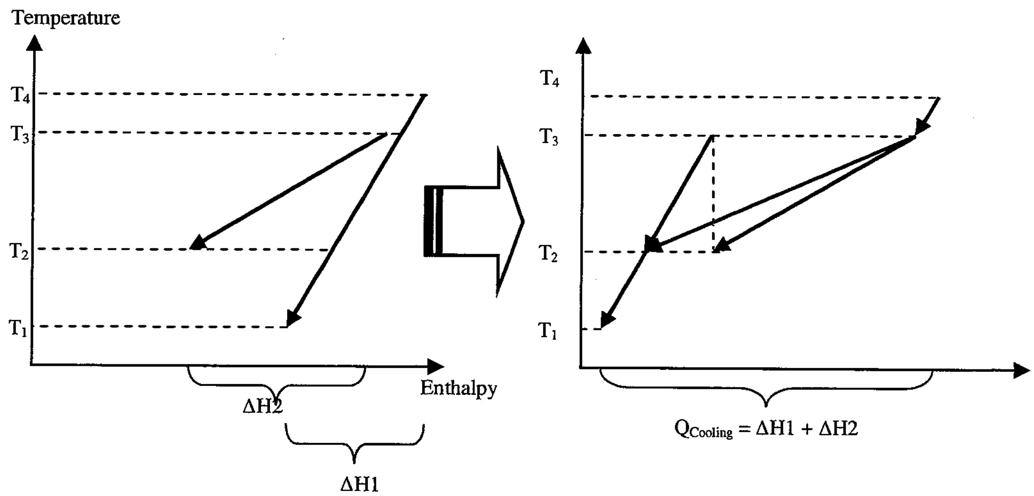


FIGURE 2B – Composite Curve for Streams Requiring Cooling

Figure 2- Heating and Cooling Composite Curves

The next step in the analysis is the selection of a minimum temperature difference between the hot and cold streams ΔT_{min}. To start, a value of ΔT_{min} is assumed and can be considered the minimum temperature gradient to ensure that heat flows from the stream requiring cooling to the stream requiring heating at all times. Linhoff March provide typical ΔT_{min} values for various process utility matches (Linhoff March, 1998). In the context of the research presented in this thesis, Linhoff March (1998) identify a typical ΔT_{min} value of 40°C for when applying the pinch analysis for heat transfer between flue gas and process streams.

Graphically, ΔT_{min} is used by shifting both the cooling composite curve down and the heating composite curve up by a factor of ½ ΔT_{min}. The curves are then shifted horizontally so that they intersect with each other and are positioned such that the cooling composite curve is on top and the heating curve is on the bottom. The point of intersection is termed the pinch point. At this point, the hot and cold streams are most constrained by ΔT_{min} (Dimian, 2003). From this graph, the heat available for transfer $Q_{Transferred}$ is read directly from the horizontal overlap of the two curves. Figure 3 illustrates the combined and shifted composite curves from Figure 2 used to identify the pinch point in which the minimum heating and cooling requirements (i.e., $Q_{Heating}$ and $Q_{Cooling}$) can be achieved through the operation of a heat exchanger network with a minimum temperature gradient of ΔT_{min} available throughout.

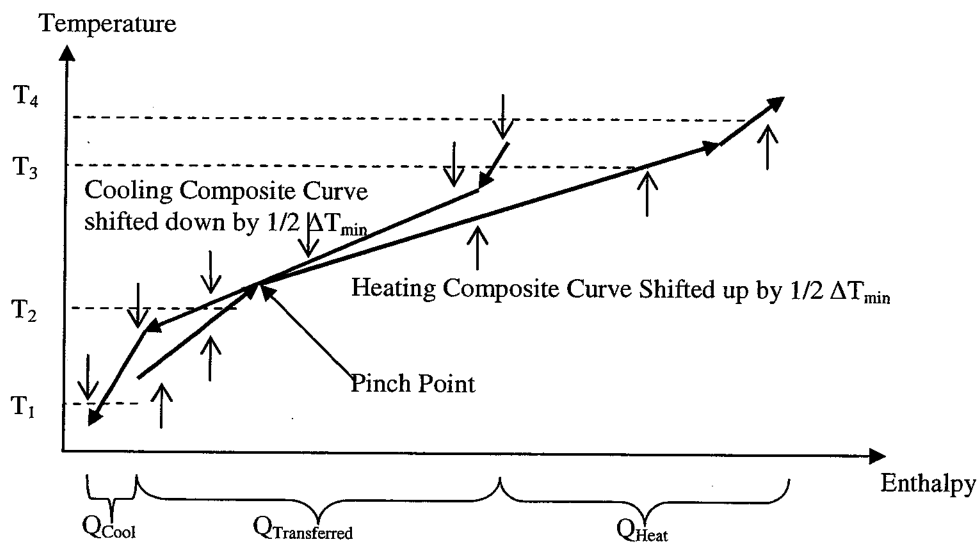


Figure 3 - Combined and Shifted Composite Curves to Identify Pinch Point and Minimum Utility Requirements

In considering multiple process streams, Linhoff and Flower developed the Problem Table Algorithm which can be used as an alternative or complement to the graphical approach to determine the minimum utility requirements (Linhoff and Flower, 1978; Linhoff and Hindmarsh, 1983; Trivedi, 2000; Dimian, 2003). As presented by Trivedi, the Problem Table Algorithm consists of the following steps:

- Select a ΔT_{min};
- Add $1/2\Delta T_{min}$ to the starting and final temperatures of the cold streams and subtract $1/2\Delta T_{min}$ from the hot streams;
- Sort temperature intervals in descending order and remove the duplicate intervals; and
- Perform an enthalpy balance for each interval as follows:

$$\Delta H_i = \left(T_{\text{int}j} - T_{\text{int}j+1}\right)\left(\sum_j^{N_{streams}} CP_{c_j} - \sum_j^{N_{streams}} CP_{h_j}\right). \qquad (6)$$

To demonstrate the problem table algorithm, Figure 4 has been created utilizing the information in Table 2 to illustrate the different temperature intervals.

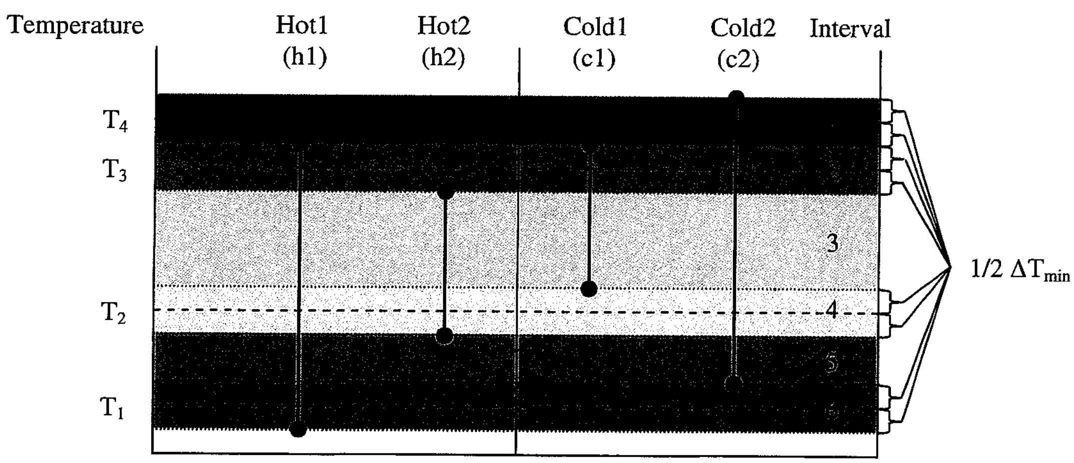


Figure 4 - Temperature Intervals

With the different temperature intervals organized as illustrated in Figure 4, the problem table can be created as represented in Table 3.

Temperature Interval	Interval Number	ΔT_{int}	$\Sigma CPcj - \Sigma CPhj$	ΔH_{int}	Heat Cascade
Hot Utility to $T_4+1/2\Delta T_{min}$	0				$Q_{heating}$
$T_4+1/2\Delta T_{min}$ to $T_4-1/2\Delta T_{min}$	1	ΔT_{min}	CPc2	$\Delta H_1 = \Delta T_{min}$ * CPc2	$Q_{heat} - \sum_{0}^{interval} \Delta H_i$
$T_4-1/2\Delta T_{min}$ to $T_3-1/2\Delta T_{min}$	2	T_4-T_3	CPc1+CPc2-CPh1	$\Delta H_2 = (T_4-T_3)$ * (CPc1+CPc2-CPh1)	$Q_{heat} - \sum_{0}^{interval} \Delta H_i$
$T_3-1/2\Delta T_{min}$ to $T_2+1/2\Delta T_{min}$	3	T_3-T_2-ΔT_{min}	CPc1+CPc2-CPh1-CPh2	$\Delta H_3 = (T_3-T_2-\Delta T_{min})$ * (CPc1+CPc2-CPh1-CPh2)	$Q_{heat} - \sum_{0}^{interval} \Delta H_i$
$T_2+1/2\Delta T_{min}$ to $T_2-1/2\Delta T_{min}$	4	ΔT_{min}	CPc2-CPh1-CPh2	$\Delta H_4 = \Delta T_{min}$ * (CPc2-CPh1-CPh2)	$Q_{heat} - \sum_{0}^{interval} \Delta H_i$
$T_2-1/2\Delta T_{min}$ to $T_1+1/2\Delta T_{min}$	5	T_2-T_1-ΔT_{min}	CPc2-CPh1	$\Delta H_5 = (T_2-T_1-\Delta T_{min})$ * (CPc2-CPh1)	$Q_{heat} - \sum_{0}^{interval} \Delta H_i$
$T_1+1/2\Delta T_{min}$ to $T_1-1/2\Delta T_{min}$	6	ΔT_{min}	-CPh1	$\Delta H_6 = \Delta T_{min}$ * (-CPh1)	$Q_{heat} - \sum_{0}^{interval} \Delta H_i$

Table 3 - Problem Table based on Temperature Intervals presented in Figure 4

The information from the problem table can then be used to draw the Grand Composite Curve (Dimian, 2003). The Grand Composite Curve (GCC) is generated by plotting the heat content of each temperature interval on the horizontal axis and the shifted temperature scale on the vertical axis. The GCC takes the form represented in Figure 5. Generally, the GCC diagram is split by the pinch point into a section above the pinch, which requires heating, and a section below the pinch, which requires cooling. The pockets in the diagram represent the heat recovery available from process to process exchange (Dimian, 2003). The GCC can be used to determine appropriate integration of heat pumps and heat engines in processes along with determining appropriate modifications such as reflux ratio, feed conditioning and side condensing/reboiling in distillation columns (Linhoff March, 1998).

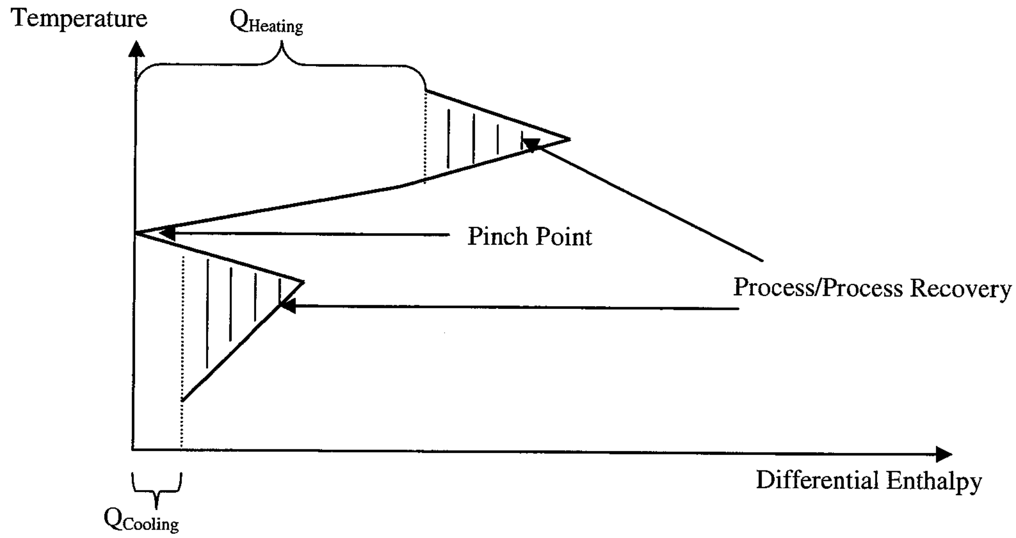


Figure 5 - Grand Composite Curve Example as adapted from Dimian

The application of pinch analysis can be carried out using either spread sheet software with graphical capabilities such as Microsoft Excel, pinch analysis specific software packages such as SuperTarget®, and several chemical process simulation software packages such as Aspen, HYSYS and CadSim Plus all include pinch analysis modules which can be integrated into simulations.

2.5.3 Applications of Optimization Tools to Industrial Ecology

Integrated simulation and optimization was used to assess the potential for incorporating CO_2 consuming processes within the infrastructure of a chemical complex (Xu et al., 2005). Utilizing the HYSYS simulation software, mixed integer non linear programming and the USEPA waste reduction algorithm (Cabezas et al., 1999), Xu et al. (2005) obtained an optimum solution that included facilities to produce acetic acid, graphite, formic acid, methylamines, propylene and synthesis gas. With these added facilities, the energy intensity per unit of economic activity was decreased, although overall energy consumption in the complex increased. As stated in the concerns with industrial ecology, an evaluation of whether the increased energy use in this area can be offset by a displacement of production of these products in other, less efficient areas would be required.

In another application, Aspen Plus was used to simulate inter-firm energy concepts such as: different natural gas fired combined cycle power plants for electricity and heat production; diverting unused energy flows from one company into another company to meet their demand for low temperature heat; the use of geothermal energy for the production of electricity and process steam; and the installation of a combined heat and power plant fired with biomass (Fichtner et al., 2004; Fichtner et al., 2005). The resulting mass and energy balances were used to calculate costs, which in turn were used in a least cost linear optimization model. The life cycle engineering software GaBi was used to compliment the approach by allowing the life stages of each system to be included in the decision making process.

Other optimization approaches have been developed where mass and energy balances are performed with a mathematical software package, rather than chemical process simulation software. For example, Geng integrated water resource management in EIPs using nonlinear programming with a Chinese mathematical solver (Geng, 2004). Geng reported finding the least cost associated with daily pumping, daily water and wastewater treatment, and amortized daily capital costs while considering the assimilative capacity of the local system as constraints. Recent communication with Geng revealed that this approach has been used in various locations throughout China in the development of EIPs (Geng, 2007).

Some approaches have combined mathematical optimization with GIS. In one study, the objectives of minimizing the cost to purchase, treat, and transport shared water and maximizing fresh water conservation amongst a group of industries were met (Nobel, 1998). This was achieved by first matching sinks and sources of water within the group of industries using water quality. The objective to minimize the cost of water sharing is mathematically represented using the pumping energy and water quality costs while the objective to maximize water conservation is represented mathematically as minimizing the amount of water attained from the water treatment plant. A weighted linear programming model is then employed with both objectives included and a user defined weighting factor is assigned to determine the relative importance of either objective. This study demonstrated how such an analysis benefits from the spatial reference and mapping capabilities of GIS within a geographic area. Recent communication with one of the principal investigators of the study indicated that they have not continued their research (Maidment, 2006). As this study determined pumping energy requirements based on straight line distances between industries, a research opportunity exists to utilize the advances in GIS analytical capacity in order to include the actual distances between industries along infrastructure trenches.

Other studies which capitalize on the use of GIS have been reported. For example, Ozyurt and Realff (2001) utilize GIS and optimization (mass and energy balances calculated with mathematical software) to assess the potential for a power plant to share low pressure steam (Ozyurt and Realff, 2001). In this case, feasibility contours which dictate the amount of steam that a company must accept relative to the distance from the power plant in order to at least satisfy an economic break even point, are used to filter out potential sinks, prior to optimizing a least cost model. A similar approach is taken to determine networking opportunities in an agricultural IE project in which peanut shells are considered for biomass exchange (Ozyurt and Realff, 2002). Correspondence with Ozyurt and Realff indicates that their general framework of using GIS combined with optimization to apply industrial ecology has not been continued, however, plans are forming to revive the work (Ozyurt and Realff, 2006).

Regarding the application of the thermodynamic pinch analysis, an abundance of literature exists demonstrating energy and cost savings at the plant level. For example, the petrochemical company LG Chemicals has estimated a $610,000 annual savings in energy cost associated with the production of ethylbenzene by applying the pinch analysis within the Aspen Plus simulation software package (Yoon et al., 2007). Similarly, different companies such as Imperial Chemical Industries, Union Carbide, and BASF have reported 30%, 50%, and 25% savings in energy cost, respectively, as a result of applying the pinch analysis (Trivedi, 2000). In terms of applying the pinch analysis at the industrial park level, site wide analysis has been used to optimize heat recovery in oil refining, petrochemical, iron and steel plants, however; site wide analysis has rarely been applied to other industrial sectors (NRC, 2003).

2.6 Summary of Literature Review

This literature review started off by describing systems analysis as a methodological approach used to conceptualize and understand what happens in the world (Section 2.1). Sustainability assessment was then introduced and both mathematically based and principles based systems analysis approaches were presented (Section 2.1). From the components put forth as criteria for sustainability, industrial ecology was selected as a basis from which to begin to address the inefficient use of resources. A detailed discussion of the literature associated with industrial ecology (Section 2.2) indicated that developing an industrial ecosystem and effectively realizing the potential efficiency gains will be subject to many barriers including a lack of understanding, trust and information. By building on existing relationships and uncovering potentials for mutually beneficial cooperation through resource exchanges, a wide variety of participants can be engaged to work together to overcome these barriers.

In order to uncover potential for mutually beneficial cooperation, tools including environmental management systems, geographical information systems, chemical process simulation, and mathematical and graphical optimization techniques have been demonstrated to contribute towards the development of eco industrial parks and networks. Review of applications in the literature reveals that the thermodynamic pinch analysis has been widely applied to realize heat savings at the plant level; however, limited applications exist where it has been used to assess the potential for heat cascading among groups of industries. Thus, an opportunity exists to apply the thermodynamic pinch analysis to a chemical process simulation of many industries in order to evaluate if heat exchange opportunities can be uncovered at the inter-industry level using a systematic approach.

In terms of water cascading models, the literature indicates that geographical information systems coupled with mathematical optimization techniques are able to uncover resource sharing opportunities. As this framework has not been pursued further to include advances in the analytical capacity of geographical information systems, an opportunity exists to enhance the approach by including the water infrastructure location to more accurately estimate the pumping energy requirements and include infrastructure costs associated with water sharing opportunities into the decision making process.

Utilizing the approaches presented in this literature review can help people envision the potential for increased resource use efficiency in the context of the larger sustainability objectives. The application of industrial ecology provides a means with which to reduce the waste associated with industry and provide people with an approach they can use to learn more about which industries fit into a sustainable economy, and which need to be rethought.

3.0 MODEL DEVELOPMENT

3.1 Introduction

Water and energy use are fundamental requirements of most industrial operations. In the preliminary stages of developing an EIN, a focus on the use of water and energy provides a leverage point with which to engage different industries which otherwise may not interact. Such a focus would benefit from knowledge regarding optimal water cascading and heat sharing opportunities. The following sections describe two models that utilize rigorous analytical approaches combined with visual representations to act as decision support tools to envision alternative planning strategies by communicating existing resource sharing opportunities for the provision of water and heating services. By demonstrating alternative planning strategies which include optimal resource sharing opportunities, these models seek to:

- provide content for discussion between different people from different industries on the topic of water and energy use in their geographic area; and
- be used as a starting point for the development of additional relationships focused on other resources of interest.

The first model focuses on determining water sharing opportunities that incorporate water quality, capital cost and pumping energy requirements into the decision process. The second model focuses on determining the potential for heat energy that is currently wasted from industrial applications to be used to meet other heating requirements within the geographic region. The following sections will detail the formulations of these two models.

3.2 Water Model Formulation

The water model presented here is a variation of the master's thesis work of Carolyn Nobel (Nobel, 1998). Based in a GIS environment, the water model has been developed to perform an analysis of an industrial water system and to determine the potential for establishing a water exchange network. The system being analysed consists of the flow of water from the municipal water source pump, through municipal distribution pipes, to each industry and from each industry, through sewer piping, to the waste water treatment plant. The water model assumes that the exchange of water between industries is dependent on a sufficient supply of water of adequate quality and will require the use of electricity to operate pumps and the installation of piping infrastructure to transport the water. The optimization of multiple objectives based on water sharing, electrical use and installation costs makes the decision regarding who should share with whom amongst a number of water users quite complex. The water model attempts to simplify the decision process by mathematically determining the maximum water sharing potential between industries, given constraints on energy use and installation cost. Furthermore, the model utilizes GIS capabilities to incorporate geographical information pertaining to the location of existing utility trenches into the decision process and to communicate the results in a map format which can be easily interpreted by a broad audience.

3.2.1 Data Requirements

The water model assumes that a GIS has been developed with the following industry information saved as attributes to a point layer representing each industry:

- Industry name;
- Annual inlet water volume (m^3);
- Annual effluent water volume (m^3);
- Inlet water quality;
- Effluent water quality; and
- Industry location data (x, y, elevation (m)).

Along with the industry data, a similar point layer that represents the water reservoir (source of raw water) and the waste water treatment plant (sink for waste water) is also required. In addition, the model also requires the inclusion of a line layer representing existing or planned utility trenches.

Table 4 has been prepared to identify who the likely sources of data might be and how easy it will be to attain the information.

Data Requirements	Potential Sources of Information	Mode of Attainment	Relative Ease of Attainment
Industry Name	• Industry • Municipality	• Ask municipality • Registry search	Generally easy to attain as data is publicly available or easily attainable through business directory search
Annual Total Water Consumption	• Industry • Water Utility	• Process water metering • Utility records (billing) • Survey or Interview	Generally difficult to attain due to either: • Need for consent from industry for utility to release information; or • Need for industry to use resources to meter water use.
Annual Effluent Water Volume	• Industry • Waste water utility • Regulatory agency	• Process water metering • Discharge permits • Utility records (billing)	Generally difficult due to either: • Need for consent from industry for utility or regulatory agency to release information; or • Need for industry to use resources to meter water use.
Required Inlet Water Quality	• Industry • Literature	• Process audit • Water reuse standards • Survey or Interview	• If literature is available regarding processes, may not be very difficult. • Water quality will generally be the most difficult to attain due to the need for industry to use resources to determine influent water quality for each process (may require hiring a process specialist if industry does not have appropriate technical staff).
Effluent Water Quality	• Industry • Literature/Standards • Regulatory agency	• Process audit • Discharge permits • Survey or Interview	• If literature is available regarding processes, may not be very difficult. • Water quality will generally be the most difficult to attain due to either: o Need for consent from industry for utility or regulatory agency to release information; or o Need for industry to use resources to determine effluent water quality from each process (may require hiring a process specialist if industry does not have appropriate technical staff).
Industry Location Data	• Industry • Municipality	• Industry provided • Municipal records • Online search	Generally easy to attain as data is typically publicly available.
Utility Location Data	• Municipality • Major Utilities	• GIS department	Generally easy to attain if municipality or local utility is involved.

Table 4 – Water Model Data Requirements and Most Likely Source of Information

As noted in Table 4, water quality data are likely to be the most difficult data to attain as this information may require an industry to divulge private information and to retain the services of a process specialist to determine required influent and effluent water quality. Attainment of water quantity data will be generally less difficult than quality as long as industries consent to the release of their data and major utilities meter water consumption and waste water generated. When various process streams are included in an industry, determining the water balances for each process may make attaining water quantity data more difficult as an industry would have to finance water monitoring. As a general estimate, when effluent quantity is not known, consultants typically assume that

20% of the influent water is lost in the plant (Casavant, 2006). Generally, names of industries and location data are easily attainable from public records or a business directory search, while local authorities can typically provide GIS maps of existing or planned infrastructure location.

Utilizing the Network Analyst tool within the GIS to analyse the industry point layer and the utility trench layer, a new line layer is generated which contains the distance between each industry along the utility trench as attributes. In addition, all three layers (industry, water and wastewater and utility trenches) are similarly analysed with the Network Analyst tool to also determine:

- The distance between each industry and the water reservoir; and
- The distance between each industry and wastewater treatment plant.

The following sections describe how the model uses this information in the decision making process.

3.2.2 Simulation and Optimization

In the water model presented here, the information described in Section 3.2.1 is used to determine the availability of water based on quantity and quality and the electrical requirements and infrastructure costs associated with different water reuse scenarios is simulated. Constrained optimization (see Section 2.5.1) is then used to analyze the simulation such that maximizing water reuse is evaluated as the objective function, and objectives related to electrical requirements and installation cost take the form of performance constraints that any water reuse scenario must adhere to. The following sub-sections provide the mathematical formulation of the constrained optimization linear programming model.

3.2.2.1 Objective Function

During a given year, industry j uses I_j m^3/year of water of quality IQ_j and discharges O_j m^3/year of water of quality OQ_j. In order to determine how much water can be shared, the exchange fraction $y_{j,k}$ is introduced to represent the fraction of industry j's inlet water requirement that can be provided by industry k. With these definitions, the linear objective function to maximize water reuse WR can be written as follows:

$$\max WR = \sum_{j=1}^{n} \sum_{k=1}^{n} (y_{j,k} * I_j) \qquad (7)$$

where:

n = Index of companies

In this formulation, $y_{j,k}$ is known as the decision variable which means that it's value will be subject to change until an optimal solution is reached. The values that $y_{j,k}$ can assume are constrained: directly based on water quality and mass balance requirements; and indirectly based on the associated electrical consumption and infrastructure installation costs. The following five sections develop the system constraints.

3.2.2.2 Mass Balance Constraints

In terms of mass balance, each industry cannot accept more water then it currently uses. This is reflected in the following two constraints:

$$y_{j,k} <= 1 \qquad (8)$$

$$\sum_{k=1}^{n} y_{j,k} <= 1 \qquad (9)$$

Just as an industry cannot accept more water then it currently uses, any feasible solution must also ensure that the fraction of company k's effluent that it gives to industry j, $x_{j,k}$, is such that the industry does not offer more water then it has to give. The constraints on $x_{j,k}$ are represented as follows:

$$x_{j,k} = (y_{j,k} * I_j) / O_k <= 1 \qquad (10), \text{ and}$$

$$\sum_{j=1}^{n} x_{j,k} <= 1 \qquad (11)$$

where:

O_k = Annual volume of water effluent from Industry k.

3.2.2.3 Water Quality Constraints

The next set of constraints is developed through initial screening of water quality to determine the maximum exchange fraction $ymax_{j,k}$. If a feasible match is obtained, (i.e., OQ_k is less then or equal to IQ_j), then $ymax_{j,k}$ is set equal to O_k / I_j (note that if O_k / I_j is greater than one, then $ymax_{j,k}$ is set equal to one). If a feasible match is not obtained, then $ymax_{j,k}$ is set equal to zero.

3.2.2.4 Non-negativity Constraint

The final direct constraint on $y_{j,k}$ is nonnegativity and is represented as follows:

$$y_{j,k} >= 0 \qquad (12)$$

In summary, the direct constraints on $y_{j,k}$ dictate that $y_{j,k}$ can assume values between zero and $ymax_{j,k}$, and within this range, O_k / I_j is the maximum value of $y_{j,k}$.

3.2.2.5 Electrical Constraint

The electrical consumption constraint has been formulated such that the user defines the electrical objectives in terms of a percentage P of the existing electricity required, EEC, to transfer water under current operating conditions (i.e., no water sharing between industries). The constraint form of the electricity objective is developed as follows:

As adapted from Nobel (Nobel, 1998), the electricity required per volume of water E, (kWh/m^3) to transfer water through a pipe can be represented as a function of the change in elevation that the water undergoes Δz and the distance it travels L as follows:

$$E\left(\frac{kWh}{m^3}\right) = \left[\frac{g\left(\frac{m}{s^2}\right)\times \Delta Z(m)}{\eta} + \frac{4\times f\times L(m)\times v^2\left(\frac{m^2}{s^2}\right)}{\eta\times D(m)\times 2}\right]\times \rho\left(\frac{kg}{m^3}\right)\times\left(\frac{1kWh}{3{,}600{,}000J}\right) \qquad (13)$$

Where:

E = energy per volume of water (kWh/m^3);

g = gravitational constant (9.81 m/s^2);

Δz = change in elevation (m);

η = pump efficiency (0.65);

f = friction factor (0.004);

L = Length of pipe that water flows through(m);

v = velocity of water (m/s);

D = diameter of pipe (m); and

ρ = density of water (1,000 kg/m^3)

Note that 1 Joule = 1 N*m = 1 kg*m^2/s^2. Refer to Appendix A for more details about with how equation 13 is used in this thesis.

Utilizing equation 13, along with the elevation and distance data from the GIS, the electricity required per volume of water transferred:

- Between the water reservoir and each industry $E_{j,w}$;
- Between each company and the wastewater treatment plant $E_{ww,j}$; and
- Between each industry $E_{j,k}$ can be calculated.

With these values, the total electrical consumption EC required to pump water can be represented as follows:

EC = Inlet Energy + Transfer Energy + Outlet Energy or

$$EC = \sum_{j=1}^{n} [E_{j,w} * (1 - \sum_{k=1}^{n} y_{j,k}) * I_j] + \sum_{j=1}^{n} \sum_{k=1}^{n} [E_{j,k} * x_{j,k} * O_k] + \sum_{j=1}^{n} [E_{ww,j} * (1 - \sum_{k=1}^{n} x_{k,j}) * O_j] \quad (14)$$

Substituting equation 10 into equation 14 and reducing yields the following:

$$EC = \sum_{j=1}^{n} [E_{j,w} * (1 - \sum_{k=1}^{n} y_{j,k}) * I_j] + \sum_{j=1}^{n} \sum_{k=1}^{n} [E_{j,k} * y_{j,k} * I_j] + \sum_{j=1}^{n} [E_{ww,j} * (O_j - \sum_{k=1}^{n} [y_{k,j} * I_k])],$$

which can be further reduced to the following:

$$EC = \sum_{j=1}^{n} [E_{j,w} * I_j + E_{ww,j} * O_j] - \sum_{j=1}^{n} \sum_{k=1}^{n} y_{j,k} * \sum_{j=1}^{n} \sum_{k=1}^{n} [E_{j,w} * I_j - E_{j,k} * I_j + E_{ww,j} * I_k] \quad (15)$$

If equation 15 is evaluated prior to any water exchange, the existing electrical requirement EEC is represented by substituting $y_{j,k} = 0$ into equation 15 as follows:

$$EEC = \sum_{j=1}^{n} [E_{j,w} * I_j + E_{ww,j} * O_j] \quad (16)$$

As such, equation 15 can be rewritten as follows:

$$EC = EEC - \sum_{j=1}^{n}\sum_{k=1}^{n} y_{j,k} * \sum_{j=1}^{n}\sum_{k=1}^{n} [E_{j,w} * I_j - E_{j,k} * I_j + E_{ww,j} * I_k] \qquad (17)$$

In terms of an electrical constraint, if the electrical consumption is constrained to be less then or equal to some percentage *P* of the existing electrical requirement EEC, then equation 11 can be reorganized to represent a constraint on $y_{j,k}$ as follows:

$$\sum_{j=1}^{n}\sum_{k=1}^{n} y_{j,k} * \sum_{j=1}^{n}\sum_{k=1}^{n} [E_{j,k} * I_j - E_{j,w} * I_j - E_{ww,j} * I_k] \quad <= \quad (1 - P / 100) * EEC \qquad (18)$$

3.2.2.6 Installation Cost Constraint

The installation cost is directly proportional to the length of pipe trenching required. As each of the water users in this model are in a fixed location, the installation cost constraint is developed such that the cost to install infrastructure may constrain the number of industries that can participate by limiting the length of piping that can be installed. The purpose of structuring this constraint in this way is so that the user can determine the maximum amount of water that can be shared within an existing budget. Mathematically, this constraint is represented as follows:

$$PC * L_{Tr} <= B \qquad (19)$$

Where:

PC = Piping installation cost, \$/m (including materials)

L_{Tr} = Length of Trenching Required, m

B = Budget \$

The format of this constraint is meant to provide flexibility by allowing the user to vary the budget and, through the use of GIS, visually identify how the variation in budget affects the length of piping that can be installed and which industries can participate. By constraining which industries can participate, the installation cost acts as an indirect constraint on $y_{j,k}$ and is not used directly in the linear optimization. Alternatively, planned infrastructure works may circumvent the cost constraint as only industries within the vicinity of the planned works may be candidates for participation.

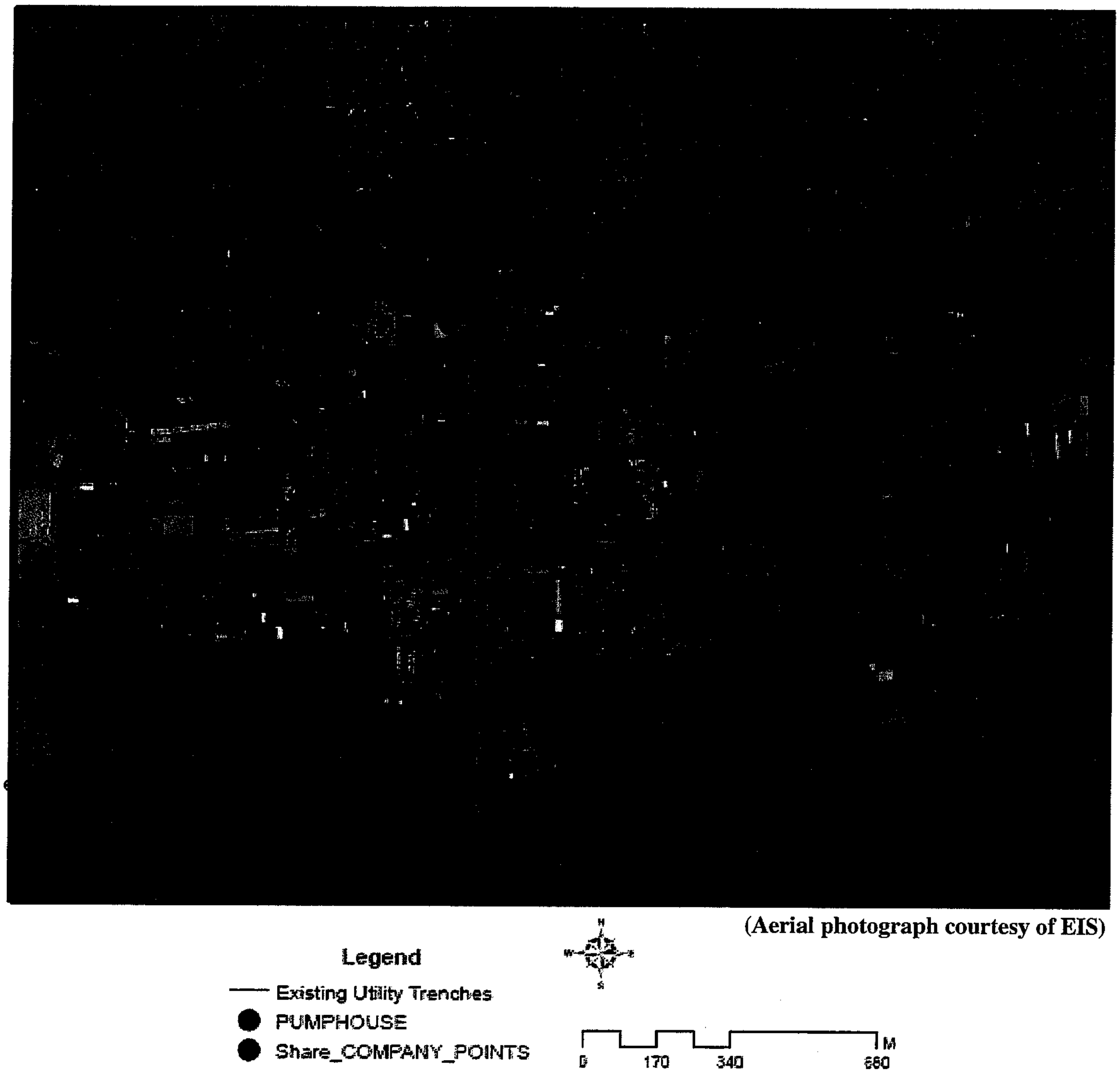
3.2.3 Case Study Data

The case study used in this thesis involves a fictional group of industries within a defined geographic area who are interested in determining water sharing potential based on their current water use. The data used was attained from a combination of project data from Eco-Industrial Solutions (EIS) (the industrial partner of this research), Carolyn Nobel's master's thesis (Nobel, 1998), a report from a water utility (report confidential but can be made available upon request), and assumptions of expected water use as described in Table 5.

Data Requirements	Availability and Source
Industry Name	• Available from EIS but not used due to confidentiality concerns.
Annual Total Water Consumption	• Available from EIS and Noble thesis. • As EIS data contained annual total water consumption, estimates based on expected water use for truck and equipment washing were used (50% of annual total water consumption).
Annual Effluent Water Volume	• Assumed based on EIS experience (80% of total Water consumption).
Required Inlet Water Quality	• Assumed based on expected use combined with literature values or Nobel thesis.
Effluent Water Quality	• Assumed based on expected use and Nobel thesis
Industry Location Data	• Only x and y data was available from EIS. Nobel industry locations were incorporated into EIS base map. Elevation data was not included at this time.
Utility Location Data	• GIS line layer (x and y data only) was available from EIS for fresh water distribution piping along with location of pump house. • No GIS data for location of waste water treatment plant available, however, electrical consumption (kWh/m^3) per volume of waste water pumped to waste water treatment plant was available from utility reports.

Table 5 - Data Sources for Water Model Case Study

As indicated in Table 5, actual industry names are not used for confidentiality reasons. Industries used from EIS data were all generally small to medium sized and therefore were given numerical names preceded by the letters SME. Industries used from Nobel's thesis were also numbered and preceded by the letter N. Based on the assumed and available data, the base map illustrated in Figure 6 was constructed to provide a visual geographical representation of the case study.



(Aerial photograph courtesy of EIS)

Figure 6 - Base Map of Water Case Study

In addition to the geographical representation, the GIS industrial point layer was populated with the attributes presented in Table 6 (i.e., combined data from EIS and Nobel thesis).

A point of clarification in Table 6 is that the inlet annual water volume Qin for all the SME named companies is less than their respective outlet annual water volume Qout. The reason for this discrepancy is that the value in the Qin column for each of the SME named companies represents only fifty percent of the company's annual inlet water volume based on the assumption that fifty percent of their annual inlet water consumption was used for vehicle and equipment washing (Casavant, 2006). As such, this value was used to represent the amount of annual water consumption used for this purpose.

Name	Inlet Water Requirements				Effluent Characteristics			
	Qin (m^3/year)	TOC (mg/m^3)	TSS (mg/m^3)	TDS (mg/m^3)	Qout (m^3/year)	TOC (mg/m^3)	TSS (mg/m^3)	TDS (mg/m^3)
SME1	228*	45	45	2,500	366	5,000	5,000	5,000
SME2	742*	45	45	2,500	1,188	5,000	5,000	5,000
SME3	50*	45	45	2,500	80	5,000	5,000	5,000
N6	1,354,042	20	100	500	1,083,233	22	14	1,948
N7	1,372,004	50	100	2,500	1,097,603	375	1,619	10,220
N8	136,786	50	100	2,500	109,429	215	2,657	7,176
SME4	102*	45	45	2,500	164	5,000	5,000	5,000
SME5	111*	45	45	2,500	178	5,000	5,000	5,000
N9	200,343	20	100	500	160,274	32	29	2,388
SME6	692*	45	45	2,500	1,108	5,000	5,000	5,000
N11	501,548	50	200	1,000	401,239	1,930	29	4,204
N12	185,144	50	200	1,000	148,116	2,223	212	41,020
SME7	1,367*	45	45	2,500	2,188	5,000	5,000	5,000
N13	1,308,447	50	200	1,000	1,046,757	484	105	904
N14	389,632	50	200	1,000	311,706	431	60	1,240
N15	205,870	50	200	1,000	164,696	146	256	740
N16	75,992	50	200	1,000	60,794	1,695	795	2,324
N17	111,916	50	200	1,000	89,533	3,869	257	8,960
N18	352,327	20	50	450	281,862	46	50	536
SME18	672*	45	45	2,500	1,075	5,000	5,000	5,000
SME35	1,193*	45	45	2,500	1,909	5,000	5,000	5,000
SME36	931*	45	45	2,500	1,490	5,000	5,000	5,000
SME41	222*	45	45	2,500	356	5,000	5,000	5,000
SME51	1,092*	45	45	2,500	1,748	5,000	5,000	5,000

Table 6 - Industrial Attribute Information from EIS and Nobel
*** indicates that value represents only 50% of total annual inlet water consumption as this is the amount that is expected to be used for tasks not requiring potable water.**

In addition, available literature for water reuse provided maximum total suspended solids TSS concentrations that can be present in water used for equipment and vehicle washing (B.C. Reg. 129/99, 1999). Unfortunately, the data provided in Nobel's thesis used water quality data for Total Organic Carbon (TOC) and Total Dissolved Solids (TDS), however, the available literature for water reuse did not include these water quality parameters. As such, required inlet TOC concentrations for each SME were assumed to be 45 mg/m^3 and TDS concentrations were assumed to be 2,500 mg/m^3. The outlet quality parameters for each SME company were set higher than any required inlet concentration to ensure that this water was not available for reuse.

Another assumption incorporated into Table 6 is that the Qout values are all eighty percent of the total annual inlet. This assumption reflects industry estimates (Casavant, 2006).

As indicated in Table 6, GIS data was not available for the wastewater treatment plant servicing the location being analysed. Upon investigation, it was found that the wastewater treatment plant was located approximately 20 km from the case study area. Fortunately, an available utility report identified that energy consumption to transfer water to the wastewater treatment plant was approximately 0.327 kWh/m^3 (reference confidential but can be made available upon request). As such, this value was used for the $T_{ww,j}$ term presented in Section 3.2.2.5. In addition, as indicated in Table 5, elevation data was not available, and thus, equation 13 was calculated without it.

The final assumptions incorporated into the water model are the costs associated with infrastructure. Based on EIS data, the cost of installing infrastructure trenches and associated municipal piping was assumed to be approximately $350/m and an additional cost of $5,000 would be incurred by each participating industry to install the required piping components to handle the second water supply on their site.

Based on the information presented in this section, the following estimates have been made regarding water consumption, wastewater discharge and electricity used to pump water without water reuse among industries:

- Approximately 6,208,800 m^3 of potable water is used by the industries annually;
- Approximately 4,967,000 m^3 of wastewater is generated annually by the industries; and
- Approximately 1,828,500 kWh of electricity is used annually to pump water to each industry from the pump house and to pump wastewater to the waste treatment plant.

3.3 Heat Energy Model Formulation

Casavant demonstrated that CadSim Plus could be used to track performance of an EIN or an EIP and evaluate what if scenarios (Casavant, 2000) (see Section 2.4.1 for a discussion of the Casavant thesis). The heat energy model presented here builds on Casavant's work by applying an analytical optimization framework to a synthesis of her CadSim Plus model. Specifically, the current model demonstrates how the thermodynamic pinch analysis, introduced in Section 2.5.2, can be used along with chemical process simulation to uncover the opportunity to meet some of the heating requirements that exist in an area by recovering heat that is currently wasted from industries. The results of the thermodynamic pinch analysis are then incorporated back into the CadSim Plus model and the effects on performance indicators such as CO_2 emissions, SO_2 emissions, waste heat and fuel oil consumption can be monitored and compared to existing values. The model is further enhanced by incorporating GIS to visualize the potential infrastructure requirements and estimate construction costs.

3.3.1 Data Requirements

The heat energy model requires answers to the following specific questions regarding the heating and cooling processes associated with the industry being simulated:

- What is being heated or cooled (i.e., composition and mass)?
- How much heat must be transferred (i.e., inlet and outlet temperature and pressure)?
- What are the sources of heat (i.e., combustion fuel composition and mass)?
- What are the heating or cooling equipment efficiencies (i.e., heat loss)? and
- Where are the companies and existing infrastructure located?

Gathering this information will typically require a site visit and detailed correspondence with industrial participants who are familiar with the processes being analyzed. Table 7 outlines the potential sources for answers and modes of obtaining the required information. As described in Section 2.2.5.2, this information could be referred to as a detailed ecobalance (Starkey et al., 1998).

The following sections describe how the answers to the questions described above are used to simulate the industrial processes and to determine the opportunity to recover wasted heat energy.

Question Answered	Data Required	Potential Sources of Information	Mode of Obtaining Data
What is being heated or cooled?	• What are the processes • Composition of process streams • Mass of process streams	• Industry • Literature • Government	• Process Audit • Survey or Interview • Company records • Government data • Assumptions
How much heat must be transferred?	• inlet and outlet temperature • operating pressure	• Industry • Literature	• Process Audit • Survey or Interview • Company records • Calculations
What are the sources of heat?	• composition • mass	• Industry • Literature • Assumptions	• Process Audit • Survey or Interview • Company records • Calculations
What are the heating or cooling equipment efficiencies?	• heat loss from heating process	• Industry • Literature	• Process audit • Survey or Interview • Manufacturer rated efficiency • Assumptions
Where are the companies and existing infrastructure located?	• Company location • Utility trench location	• Industry • Local utility • Government	• Government or utility GIS department records • Business Directory

Table 7 - Sources and Attainment of Information for Heat Energy Model

3.3.2 Simulation and Optimization

The sequential steps of the heat energy model are presented in Figure 7.

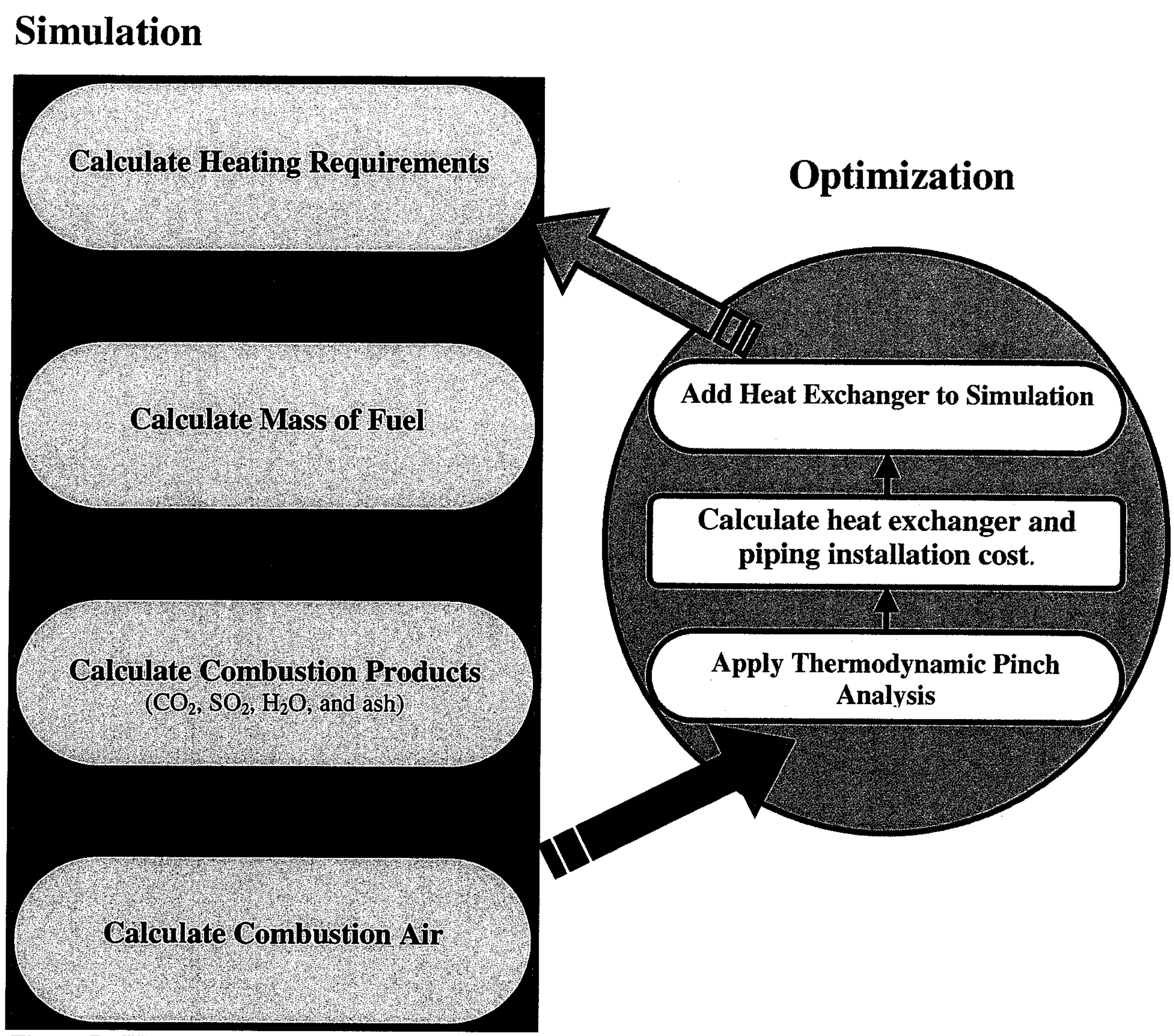


Figure 7 - Work Flow of Heat Energy Model

3.3.2.1 Calculate Heating Requirements

As indicated in Figure 7, the first step in building the CadSim Plus simulation is to determine the heating and cooling requirements. The heating and cooling requirements are determined using equation 5 ($\Delta H = C_pM(T_2\text{-}T_1)$) from Section 2.5.2. In order to calculate equation 5, the heat capacity of the fluid being heated or cooled, C_p, must first be determined. Heat capacity of a fluid at constant pressure can be calculated using the following (Felder and Rousseau, 1986):

$$C_p = a + bT + cT^2 + dT^3 \qquad (20)$$

Where

a, b, c and d are available in chemical engineering tables; and

T is the temperature of the fluid.

Note - for gases, Equation 20 is applicable at pressures low enough for the ideal gas law to apply (Felder and Rousseau, 1986).

In a multi component stream, the C_pM term from Equation 5 can be calculated as follows:

$$C_pM = \sum_{x=1}^{n} C_{px}M_x \qquad (21)$$

Where,

C_{px} is the heat capacity of a stream component;

M_x is the mass of the stream component; and

n is the number of stream components.

3.3.2.2 Calculate Mass of Fuel

The next step in the simulation is to determine how much fuel is necessary to provide the required amount of heat. In a combustion process, the mass of heating fuel required can be calculated as follows:

Fuel Mass = (Process heating requirement + Heat Loss) / Heat of $\text{Combustion}_{\text{Fuel}}$ (22)

3.3.2.3 Calculate Combustion Products

If the composition of the fuel is known, the mass of carbon dioxide, water and sulphur dioxide produced from combustion of the fuel can be calculated using the following combustion equations (Casavant, 2000):

Carbon Dioxide Production

Molar Equation $C + O_2 \rightarrow CO_2$ (23)

Mass Equation $12{*}C(\text{tonnes}) + 32{*}O_2(\text{tonnes}) \rightarrow 44{*}CO_2(\text{tonnes})$ (24)

Water Production

Molar Equation $H_2 + ½ O_2 \rightarrow H_2O$ (25)

Mass Equation $2*H_2(tonnes) + 16*O_2(tonnes) \rightarrow 18*H_2O(tonnes)$ (26)

Sulphur Dioxide Production

Molar Equation $S + O_2 \rightarrow SO_2$ (27)

Mass Equation $32*S(tonnes) + 32*O_2(tonnes) \rightarrow 64*SO_2(tonnes)$ (28)

The use of equations 23 through 28 is based on the assumption that the fuel undergoes complete combustion.

3.3.2.4 Calculate Combustion Air Requirements

Based on equations 23 through 28, the mass of O_2 required can be determined as follows:

$$O_2(tonnes) = (100\% + \%\ Excess\ O_2)*(8/3*C(tonnes) + 8*H_2(tonnes) + S(tonnes)) \quad (29)$$

Where,

% Excess O_2 is on a mass basis.

Subsequently, assuming that O_2 makes up 23.15% of air to remain consistent with Casavant, the required mass of combustion air can be calculated as follows:

$$Air(tonnes) = O_2(tonnes) / 23.15\% \quad (30)$$

3.3.2.5 Perform Pinch Analysis

Equations 5 and 15 through 22, along with mass balances on all other process streams, can be implemented in CadSim Plus to simulate each participating industry's operations. Once a simulation has been created, the thermodynamic pinch analysis, as described in Section 2.5.2, can be applied to the simulation to determine the heat savings opportunities.

3.3.2.6 Calculate Equipment and Infrastructure Costs

Costs associated with exchanging heat are estimated based on heat exchanger equipment and infrastructure requirements. Assuming that heat exchange occurs 24 hours per day for 365 days a year, counter current flow in a shell-and-tube heat exchanger, and no phase change, the cost of a heat exchanger can be a estimated as follows (Cooper and Alley, 1994):

$$C_{hx} = 53{,}742(A_{ht})^{-0.44}\exp\left(0.0672(\ln A_{ht})^2\right) \qquad (31)$$

Where:

C_{hx} = Heat Exchanger Cost (note that this is in 1992 dollars so it must be adjusted to account for inflation), and

A_{ht} = heat transfer area calculated by the following equation;

$$H_x = UA\Delta T_{LM} \quad \text{(Cooper and Alley, 1994)} \qquad (32)$$

Where:

H_x = rate of heat exchange

U = overall heat transfer coefficient

ΔT_{LM} = log mean temperature difference calculated as follows:

$$\Delta T_{LM} = \frac{(T_{1h} - T_{2h}) - (T_{1c} - T_{2c})}{\ln\left(\frac{T_{1h} - T_{2h}}{T_{1c} - T_{2c}}\right)} \quad \text{(Cooper and Alley, 1994)} \qquad (33)$$

Regarding infrastructure costs, equation 19 from Section 3.2.2.6 can be used to estimate preliminary costs associated with the installation of piping based on the length of pipe required. Upon evaluation of costs, the heat savings can then be incorporated back into the model by adding heat exchangers to the simulation to evaluate the change in performance.

3.3.3 Case Study Data

This case study is comprised of a synthesis of three of the companies from Tracy Casavant's thesis (Casavant, 2000). As part of her work, Casavant conducted an ecobalance of various companies based on the industrial ecology associated with the pulp and paper industry. For the purposes of this case study, industries from her work that had heating applications were chosen for simulation. These industries included:

- Industry A – a paperboard mill that produces paperboard from 100% recycled cardboard and utilizes a fuel oil burner to produce steam for the process;

- Industry B – a corrugated cardboard product (i.e., sheets and boxes) manufacturer that utilizes a fuel oil burner to produce steam;
- Industry D – A green house that utilizes a fuel oil burner and a wood waste burner to produce steam.

Figure 8 has been created to place these industries into a geographic context and demonstrate how GIS could be used as part of this analysis. Data attained from each of these companies by Casavant was then used to synthesize her CadSim Plus simulation. The data used and the generated process flow diagrams are presented in the following section.

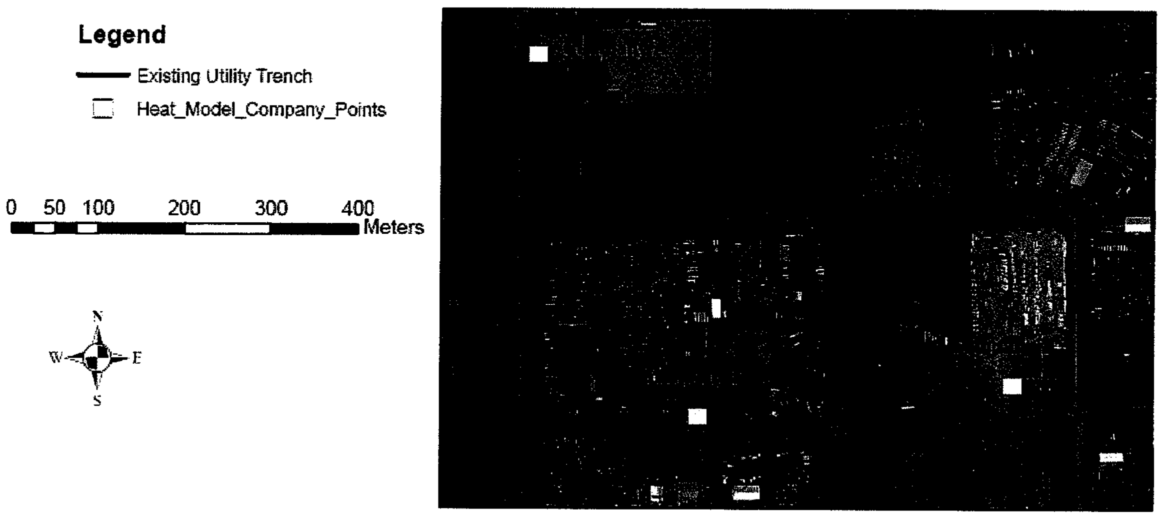


Figure 8 - Geographic Context of Heat Energy Model **(Aerial photograph courtesy of EIS)**

3.3.3.1 Case Study Simulation Data

The process flow diagram from the CadSim Plus simulation for Company A is presented in Figure 9. From Figure 9, the Boiler Stack process stream is identified as a hot stream and the Condensate Makeup process stream is identified as a cold stream. The data used to develop the process flow diagram for Company A is presented in Table 8 and Table 9.

	BOILER							COND-ENSER[2]
	FUEL-IN	AIRIN	[redacted]	ASH[1]	[redacted]	TOTAL BOILER FEED-WATER	STEAM TO PROCESS	COND-ENSATE
FLOW (t/y)	19,000	281,000	[redacted]	1,000	[redacted]	271,000	271,000	271,000
WATER (t/y)	0	4,000	[redacted]	0	[redacted]	271,000	0	271,000
FUELOIL (t/y)	19,000	0	[redacted]	1,000	[redacted]	0	0	0
STEAM (t/y)	0	0	[redacted]	0	[redacted]	0	271,000	0
N_2 (t/y)	0	213,000	[redacted]	0	[redacted]	0	0	0
O_2 (t/y)	0	64,000	[redacted]	0	[redacted]	0	0	0
SO_2 (t/y)	0	0	[redacted]	0	[redacted]	0	0	0
CO_2 (t/y)	0	0	[redacted]	0	[redacted]	0	0	0
TEMPERATURE (°C)	15	15	[redacted]	249	[redacted]	145	188	178
PRESSURE (kPa)	101	101	[redacted]	101	[redacted]	1,204	1,204	1,204

1. The ASH stream is technically not part of the BURNER unit. In order to maintain a mass balance, the ASH flow was calculated to be the FUELIN flow plus the AIRIN flow minus the FLUE GAS flow, and considered to be un-combusted FUEL OIL
2. Represents the condensing of the steam as it flows through the re-pulping and papermaking processes.

Table 8 - Company A (Paperboard Mill) Steam System Mass Flow

THERMAL PROCESS UNIT	VARIABLE	VALUE	UNITS OF MEASURE	CALC'D
BURNER (FUEL OIL)	EXCESS O_2	10	%	N
HEATER (COND TO STEAM)	DUTY	678,000	GJ/Y	Y
	HEAT_LOSS	10.8	%	Y

Table 9 - Company A Thermal Process Unit Variables

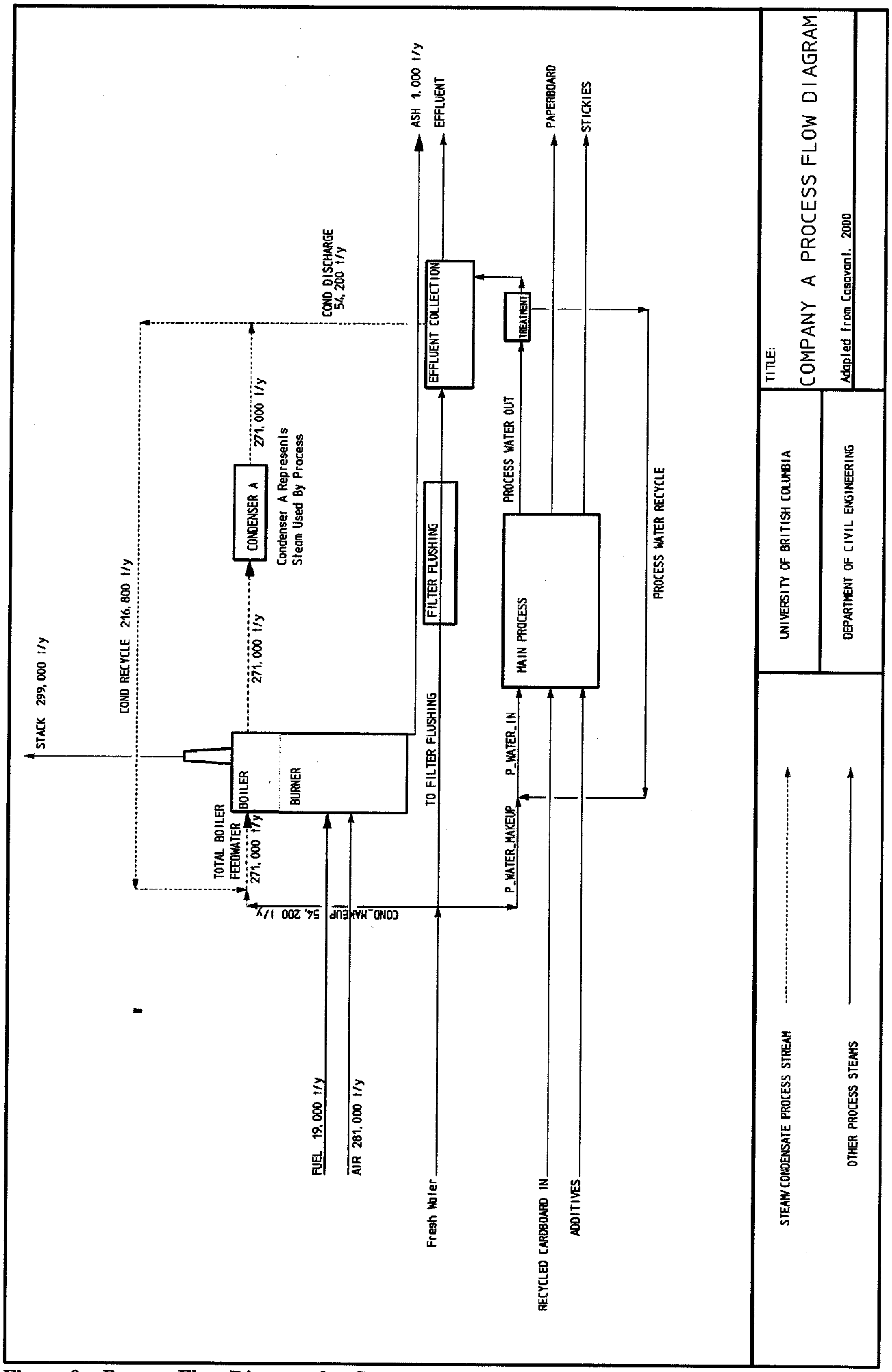


Figure 9 – Process Flow Diagram for Company A

The process flow diagram from the CadSim Plus simulation for Company B is presented in Figure 10. From Figure 10, the Fuel Oil Burner Stack process stream is identified as a hot stream and the Steam/Condensate Circulation Makeup Water process stream is identified as a cold stream. The data used to develop the process flow diagram of Company B is presented in Table 10 and Table 11.

	FUEL OIL BURNER				STEAM / CONDENSATE CIRCULATION				
	FUEL IN	AIR IN	[redacted]	ASH	[redacted]	COND. RECYCLE	WATER TO BOILER	STEAM TO PROCESS	LOST STEAM / COND
FLOW (t/y)	1,200	18,200	[redacted]	60	[redacted]	400	4,500	4,500	4,100
WATER (t/y)	0	200	[redacted]	0	[redacted]	400	4,500	0	4,100
FUELOIL (t/y)	1,200	0	[redacted]	60	[redacted]	0	0	0	0
STEAM (t/y)	0	0	[redacted]	0	[redacted]	0	0	4,500	0
N_2 (t/y)	0	13,800	[redacted]	0	[redacted]	0	0	0	0
O_2 (t/y)	0	4,200	[redacted]	0	[redacted]	0	0	0	0
SO_2 (t/y)	0	0	[redacted]	0	[redacted]	0	0	0	0
CO_2 (t/y)	0	0	[redacted]	0	[redacted]	0	0	0	0
TEMPER-ATURE (°C)	15	15	[redacted]	264	[redacted]	104	23	194	104
PRESSURE (kPa)	101	101	[redacted]	101	[redacted]	181	1,376	1,376	181

Table 10 - Company B (Corrugated Cardboard Product Manufacturer) Steam System Mass Flow

THERMAL PROCESS UNIT	VARIABLE	VALUE	UNITS OF MEASURE	CALC'D
BURNER (FUEL OIL)	EXCESS O_2	10	%	N
HEATER (STEAM)	DUTY	42,600	GJ/Y	Y
	HEAT_LOSS	71	%	N

Table 11 - Company B Thermal Process Unit Variables

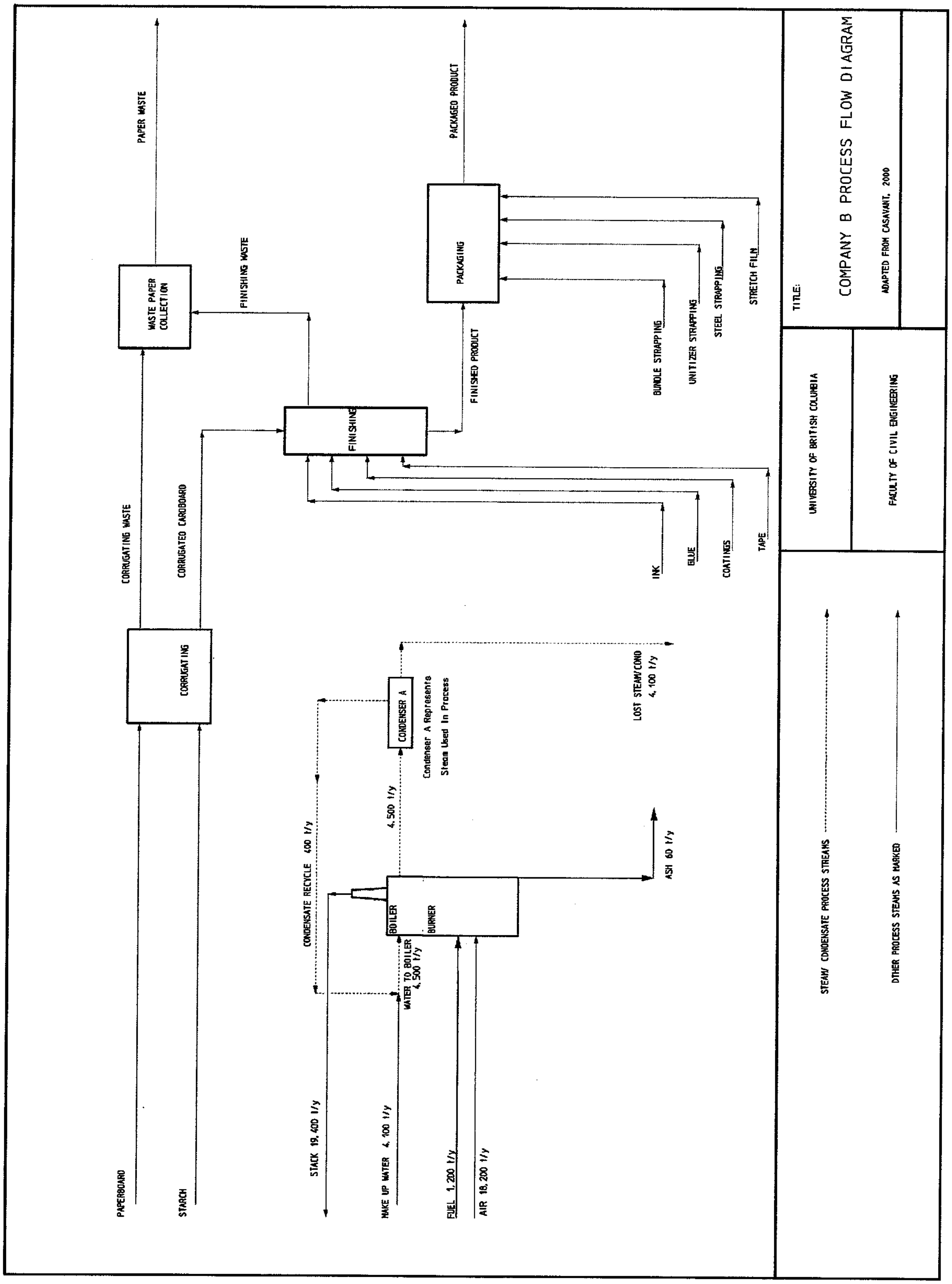


Figure 10 - Process Flow Diagram for Company B

The process flow diagram from the CadSim Plus simulation for Company D is presented in Figure 11. From Figure 11, the Fuel Oil Burner Flue Gas process stream is identified as a hot stream and the Steam/Condensate Circulation Makeup process stream is identified as a cold stream. It is noted that the Wood Chip Boiler Flue Gas process stream is not identified as a hot stream for the purposes of the pinch analysis as heat recovered from this process stream is already used to pre-heat the combustion air process stream. The data used to develop the process flow diagram of Company D is presented in Table 12, Table 13, Table 14, Table 15 and Table 16.

	FUEL OIL BURNER			
	FUELIN	**AIRIN**	[redacted]	**ASH**
FLOW (t/y)	900	13,700	[redacted]	50
WATER (t/y)	0	200	[redacted]	0
FUELOIL (t/y)	900	0	[redacted]	50
STEAM (t/y)	0	0	[redacted]	0
N_2 (t/y)	0	10,400	[redacted]	0
O_2 (t/y)	0	3,100	[redacted]	0
SO_2 (t/y)	0	0	[redacted]	0
CO_2 (t/y)	0	0	[redacted]	0
TEMPERATURE (°C)	15	15	[redacted]	217
PRESSURE (kPa)	101	101	[redacted]	101

Table 12 - Company D Fuel Oil Burner Mass Flow

UNIT	VARIABLE	VALUE	UNITS OF MEASURE	CALC'D
FUEL OIL BURNER	EXCESS O_2	10	%	N
BOILER	DUTY	32,600	GJ/Y	Y
	HEAT_LOSS	10.8	%	N

Table 13 - Company D Fuel Oil Burner/Boiler Process Unit Variables

	WOOD CHIP BOILER					
	INPUTS			OUTPUTS		
	WOOD CHIPS	AIR IN	PRE-HEATED AIR	FLUE GAS TO PRE-HEAT	FLUE GAS	ASH
FLOW (t/y)	16,900	115,900	115,900	132,600	132,600	200
WATER (t/y)	3,400	1,500	1,500	0	0	0
STEAM (t/y)	0	0	0	11,700	11,700	0
HYDROGEN (t/y)	800	0	0	0	0	0
NITROGEN (t/y)	0	87,900	87,900	87,900	87,900	0
OXYGEN (t/y)	5,100	26,500	26,500	6,300	6,300	0
CO_2 (t/y)	0	0	0	26,400	26,400	0
SO_2 (t/y)	0	0	0	27	27	0
CARBON (t/y)	7,200	0	0	0	0	0
SULPHUR (t/y)	14	0	0	0	0	0
ASH (t/y)	400	0	0	200	200	200
TEMPERATURE (°C)	15	15	53	217	105	15

Table 14 - Company D Wood Chip Boiler Mass Flow

UNIT	VARIABLE	VALUE	UNITS OF MEASURE	CALC'D
WOOD BURNER	Excess O_2	31	%	N
STEAM HEATER (WOOD CHIP BOILER)	DUTY	167,000	GJ/Y	Y
	HEAT LOSS	40	%	N
FLUE GAS TO AIR PREHEATER	DUTY	7,300	GJ/Y	Y
	HEAT LOSS	37	%	N

Table 15 - Company D Wood Chip Boiler Process Unit Variables

	STEAM / CONDENSATE CIRCULATION							
	[redacted]	COND. RECYCLE	COND. TO OIL BURNER	COND. TO WOOD BURNER	STEAM FROM OIL BURNER	STEAM FROM WOOD BURNER	STEAM TO GREEN-HOUSES	LOST STEAM / COND.
FLOW (t/y)		38,500	11,900	39,500	11,900	39,500	51,400	12,800
WATER (t/y)		38,500	11,900	39,500	0	0	0	12,800
STEAM (t/y)		0	0	0	11,900	39,500	51,400	0
TEMPER-ATURE (°C)		99	81	81	148	148	148	99
PRESSURE (kPa)		118	450	450	450	450	450	118

	PROCESS WATER			
	MAKE-UP WATER	WATER RECYCLE	WATER TO GREEN-HOUSES	LOST WATER (INC. RUNOFF)
FLOW (t/y)	29,900	44,900	74,800	29,900
WATER (t/y)	29,900	44,900	74,800	29,900
STEAM (t/y)	0	0	0	0
TEMPER-ATURE (°C)	15	15	15	15
PRESSURE (kPa)	150	150	150	101

Table 16 - Company D Water Flow

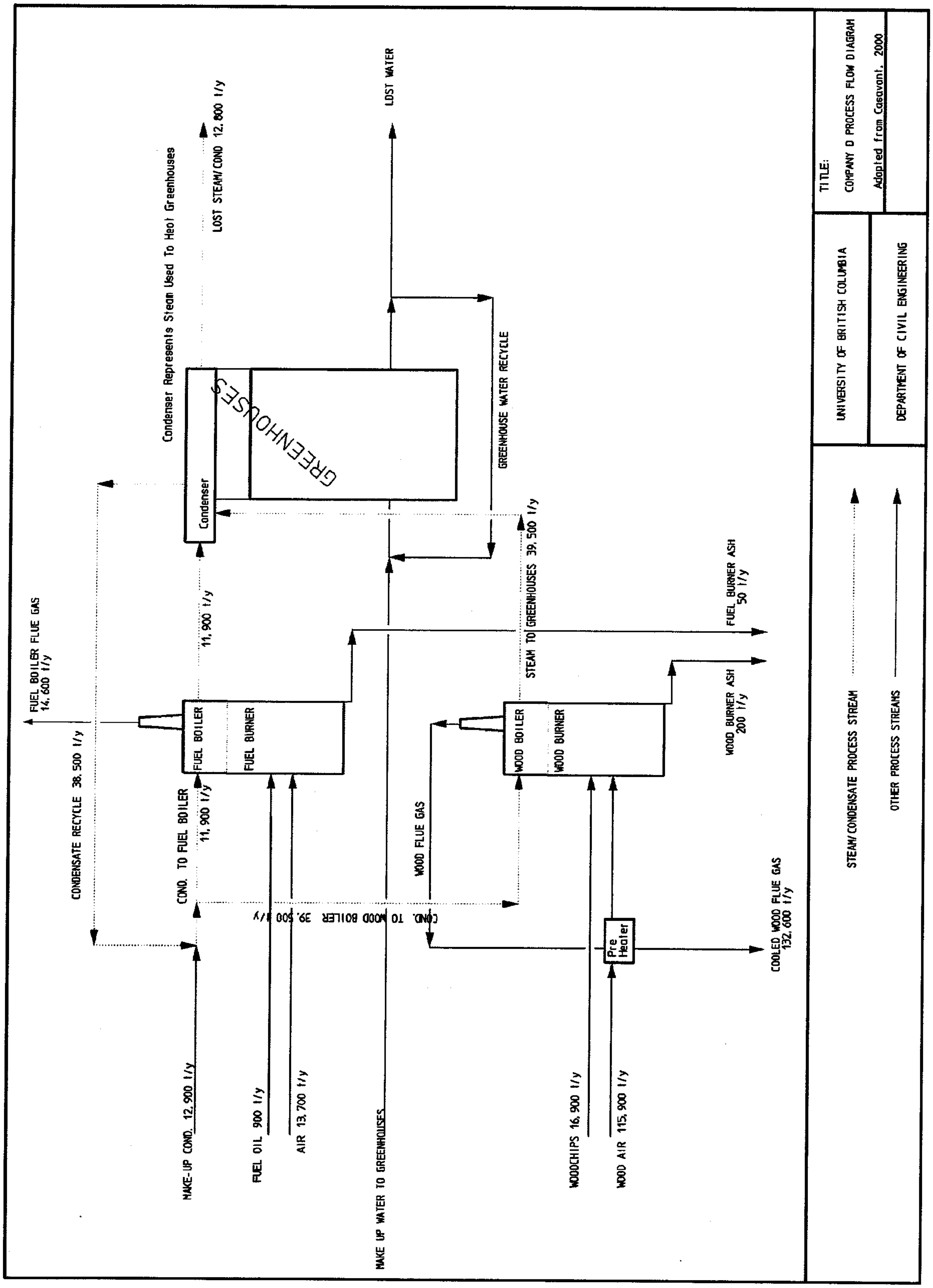


Figure 11 - Process Flow Diagram for Company D

As per Casavant's thesis, the process flow diagrams for each industry can all be included in one drawing to represent an EIN or an EIP as presented in Figure 12.

Based on the simulation results of the three companies, indicators for the existing operations are summarized in Table 17.

Indicator	**Value**
Total Fuel Oil Used	21,200 t/year
Total Ash Produced	1,300 t/year
Total CO_2 Produced	91,600 t/year
Total SO_2 Produced	500 t/year
Total Wasted Heat	214,900 GJ/year

Table 17 - Summary of Indicators from Existing Configuration

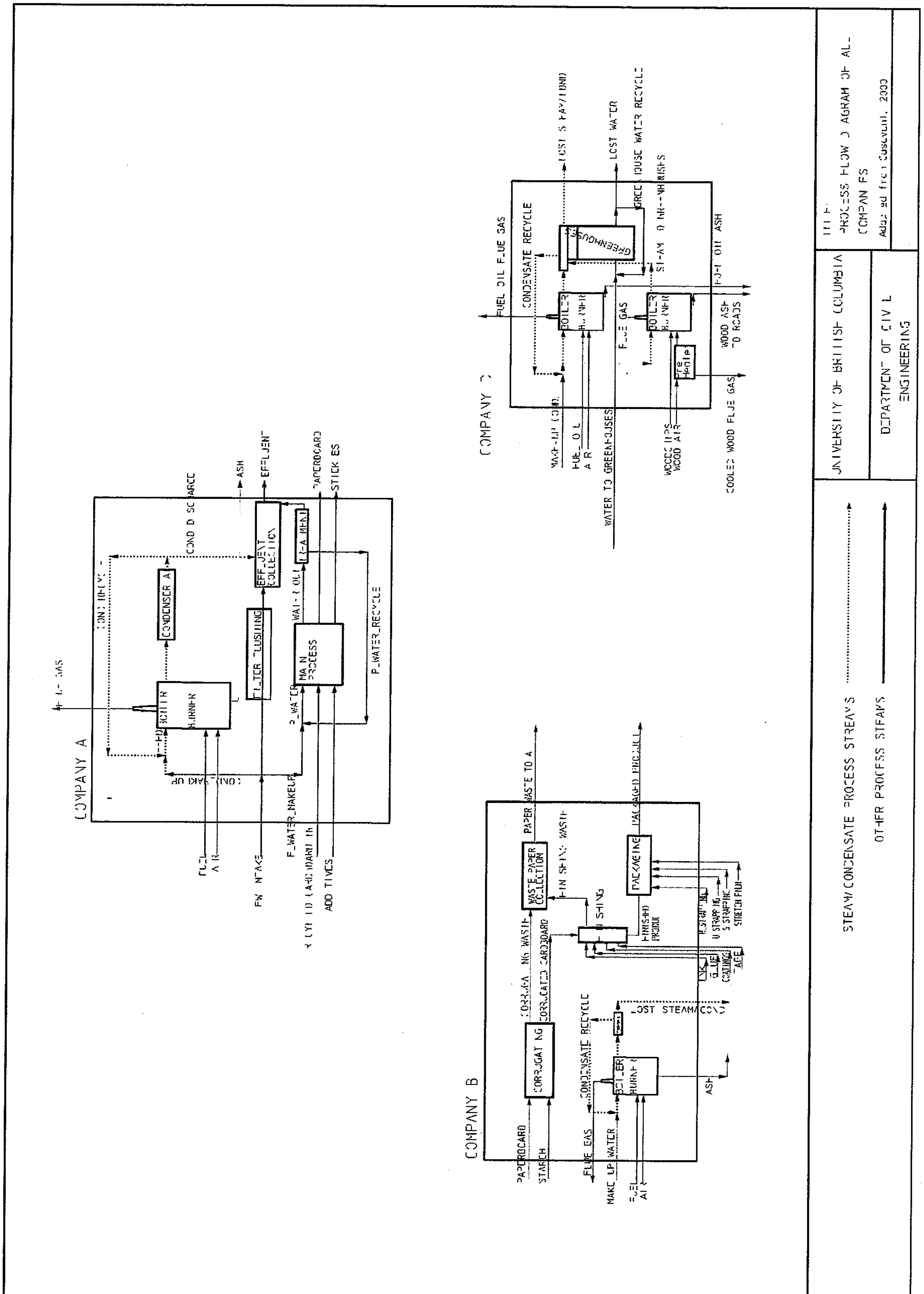


Figure 12 - EIN Process Flow Diagram (All Companies Included)

3.3.3.2 Case Study Optimization Data

The data presented in the previous section suggests that there is heat being wasted from the combustion process (i.e., 214,900 GJ/year). This section will describe the parameters used to guide the thermodynamic pinch analysis in evaluating the opportunity to recover heat otherwise wasted in stack gases, that can be used to heat boiler feed water. Recovering heat from the stack gases will decrease the amount of fuel required by the burners to produce steam.

The first step in a thermodynamic pinch analysis is to pick ΔT_{min} (as described in section 2.5.2). As the current model will evaluate heat recovery from stack gas, the value assumed for ΔT_{min} is 40°C[8]. The second step is to identify the process streams requiring heating and cooling, select the heating and cooling temperature targets; and adjusts the heating and cooling temperature targets based on ΔT_{min}. Based on the information presented in the previous section, Table 18 has been prepared to present the adjusted target temperatures.

Figure 13 illustrates the various heating and cooling process streams present in the various temperature intervals used in the analysis, and is generated with using data from Table 18.

Figure 13 demonstrates that there are 8 different temperature intervals that need to be considered in the current pinch analysis applied to the data presented. Using the temperature intervals from Figure 13 and the composition of each stream included in the pinch analysis as presented in Section 3.3.3.1, the problem table and composite curves can be generated. The problem table and composite curves are presented in the Section 4.2.

When considering the cost associated with installing piping infrastructure, a value of $350 per meter of pipe was assumed as presented in Section 3.2.3 (p. 58). In addition to piping requirements, the process stream information and the associated heating and cooling requirements are used to calculate heat exchanger costs presented in equations 31

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[8] As noted in Section 2.5.2 (p. 38), a typical ΔT_{min} value of 40°C is selected for flue gas against a process stream due to the low heat transfer coefficient for flue gas.

through 33. Key assumptions used to evaluate the cost include: a value of 1 BTU/hr for the overall heat transfer coefficient, U from equation 32 (Cooper and Alley, 1994)[9]; and a 52.85 % rate of inflation from 1992 to 2008 (Capital Professional Services, 2008) was used to adjust the cost attained from equation 31.

Process Stream	Initial Temperature (°C)	Adjusted Initial Temperature (°C)	Target Temperature (°C)	Adjusted Target Temperature (°C)	Comment
Streams requiring heating (Cold Streams)					
Company A - COND. MAKEUP	15	35	178	198	Target temperature chosen based on condensate recycle temperature
Company B - MAKE UP WATER	15	35	104	124	Target temperature chosen based on condensate recycle temperature
Company D - MAKE-UP COND.	25	45	99	119	Target temperature chosen based on condensate recycle temperature
Streams requiring cooling (Hot Streams)					
Company A - Stack	249	229	110	90	Target temperature chosen to ensure condensation of the stream does not occur.
Company B – Stack	264	244	110	90	Target temperature chosen to ensure condensation of the stream does not occur.
Company D – Fuel Oil Flue Gas	217	197	110	90	Target temperature chosen to ensure condensation of the stream does not occur.

Table 18 - Process Heating and Cooling Temperatures Adjusted for Pinch Analysis

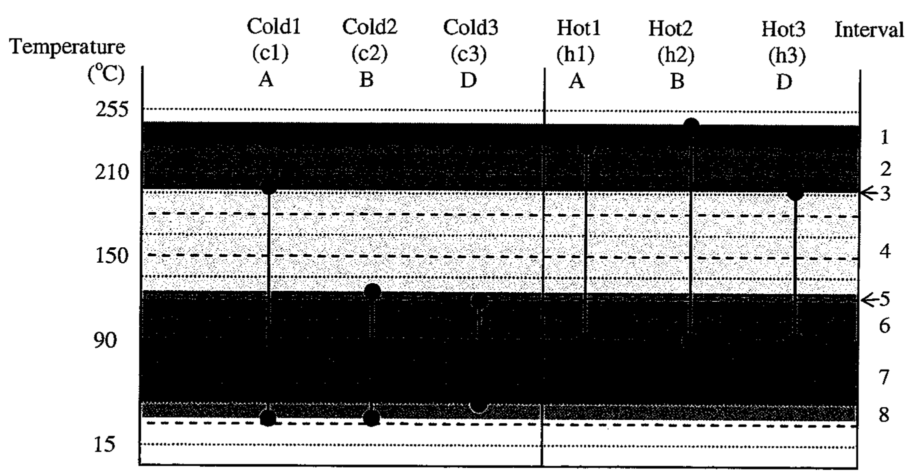

Figure 13 - Temperature Interval Diagram

[9] Page 287 of Cooper and Alley provides an overall heat transfer coefficient range from .4 to 10 (BTU/hr) for air to water heat exchangers. A value of 1 BTU/hr was assumed to remain on the conservative side of this range.

3.4 Tools Used in Models

The models presented in this work are dependent on various computer applications. The goal of this section is to describe how the computer applications are used to run each model and to outline how information is exchanged between the different applications. In doing so, this section is meant to clearly layout the software requirements and the information exchange mechanisms used to aid in any further development of the models.

3.4.1 Water Model Tools

The water model uses the Python scripting language and manual data transfer to integrate the ArcInfo GIS software program with the mathematical software program MATLAB. The software communication path for the water model is presented in Figure 14.

As presented in Figure 14, the water model starts with a GIS database created with ArcInfo 9.1 containing all of the company information. Through the use of the Python scripting language, the company information is extracted from the GIS, sorted to identify feasible water exchanges, and all the parameters of the linear programming model are generated (for sample code, refer to APPENDIX B). The user must then manually copy and paste the parameters of the linear programming model into MATLAB. The optimization results are attained from MATLAB by applying the linprog function to the parameters (to see how linprog is used in MATLAB, refer to APPENDIX C). The user must then copy and paste the MATLAB results into Microsoft Excel for tabular presentation. The resulting water exchanges are then incorporated back into ArcInfo by selecting the participating industries and generating a new layer on the map to illustrate the solution. The required infrastructure is then manually drawn onto the map in ArcInfo.

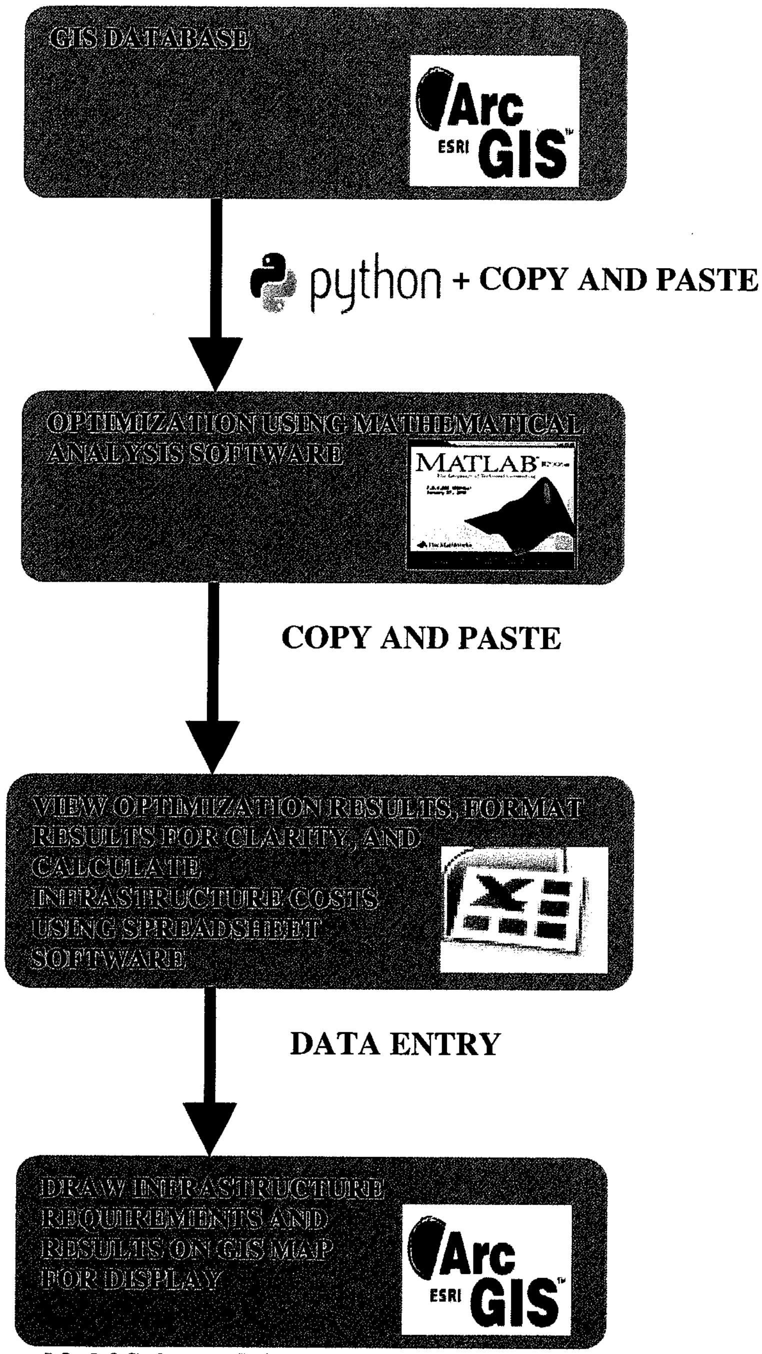

Figure 14 - Water Model Software Information Flow and Information Exchange Mechanisms

3.4.2 Heat Energy Model Tools

The heat energy model uses manual data transfer and Microsoft Excel to integrate the chemical process simulation software CadSim Plus with the ArcInfo GIS software program. The software communication path for the water model is presented in Figure 15.

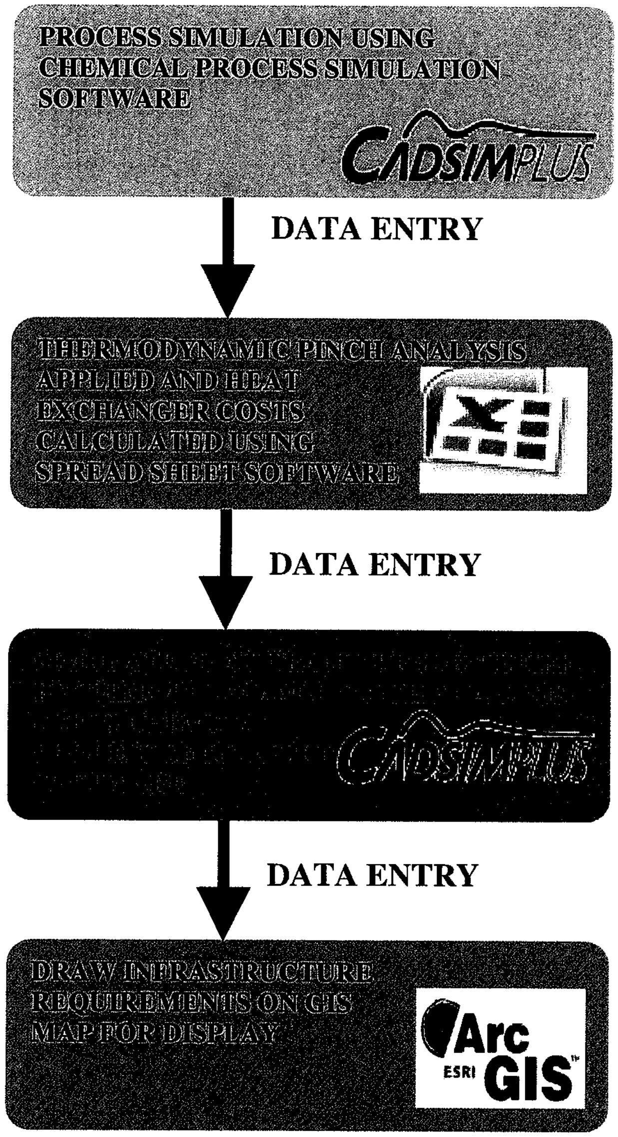

Figure 15 - Heat Energy Model Software Information Flow and Information Exchange Mechanisms

As presented in Figure 15, the heat energy model starts with a simulation created in CadSim Plus containing all the process flow information of the companies included in the analysis. Utilizing the ThermalPinch module in CadSim Plus to apply the thermodynamic pinch analysis to identified hot and cold process streams provides an estimation of the heat energy savings potential in the system. Unfortunately, the graphical interface of the ThermalPinch module was experiencing technical difficulties and was not producing correct composite curves[10]. Therefore, the process flow data was

[10] The author has since worked with Aurel Systems (the producers of CadSim Plus) to identify and correct the error in the ThermalPinch module.

manually extracted from CadSim Plus and input into Microsoft Excel to conduct the thermodynamic pinch analysis. The costs associated with the heat exchangers required to cascade the identified heat energy are also calculated using Microsoft Excel. The results of the thermodynamic pinch analysis are then incorporated back into the CadSim Plus simulation using the Heater module. The identified heat energy recovery potential of hot process streams is applied to the cold process streams by inserting a heater into the cold process streams with the duty variable of the heater set equal to the identified heat recovery. The new simulation is then run to determine the resulting effect on target indicators. The infrastructure required to support the heat energy cascading is then manually drawn onto the base map in ArcInfo to illustrate and determine the piping infrastructure costs.

4.0 MODEL RESULTS

The following sections provide the results generated by both models (see Sections 3.2.2 and 3.3.2) using the case study data presented in Sections 3.2.3 and 3.3.3.

4.1 Water Model Results

The first step in the water model is to determine the extent of feasible water exchanges based only on water quality. A screen of the case study data presented in Section 3.2.3 based on water quality identifies industries N6, N9 and N18 as sources of water for various other industries. Table 19 presents a list of all potential water exchanges based on water quality and Figure 16 illustrates the exchanges in a map format.

Potential Source of Water Based on Water Quality	Potential Sink of Water Based on Water Quality
N6	SME1, SME2, SME3, SME4, SME5, SME6,SME7, SME18, SME35, SME36, SME41, SME51, N7, N8
N9	SME1, SME2, SME3, SME4, SME5, SME6,SME7, SME18, SME35, SME36, SME41, SME51, N7, N8
N18	N7, N8, N11, N12, N13, N14, N15, N16, N17

Table 19 - Potential Water Exchanges Based on Water Quality

In order to demonstrate how the water model could be used, the case study data was utilized to generate three different scenarios. The three scenarios included:

- Scenario 1 – Maximize water reuse without using any more energy to pump water then would be used without any water reuse;
- Scenario 2 – Maximize water reuse given the constraint of minimizing energy consumption associated with pumping water; and
- Scenario 3 – Maximize water reuse with minimal cost.

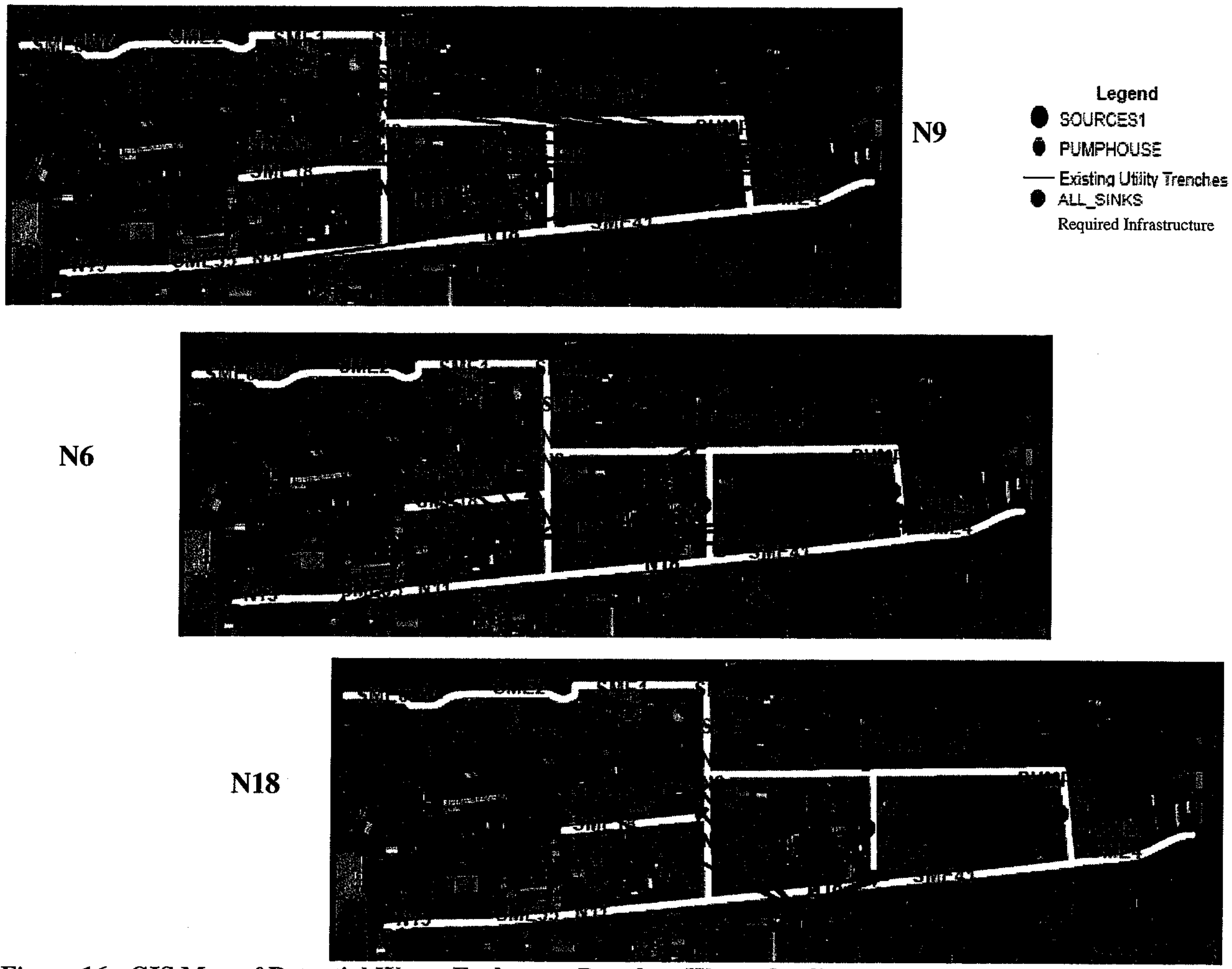

Figure 16 - GIS Map of Potential Water Exchanges Based on Water Quality **(Aerial photograph courtesy of EIS)**

4.1.1 Scenario 1 – No Additional Energy

To implement the no additional energy requirement, the water model was run with the percentage of electrical energy savings, P from equation 18, set to zero. By doing so, the linear optimization converged on a solution set of inlet water exchange fractions for each industry which maximized the amount of water reused but ensured that the electrical energy associated with pumping water stayed less than the calculated 1,828,500 kWh required for pumping water to and from each industry without any water exchanges. Table 20 presents the solution set of inlet water exchange fractions for each industry and summarizes the total mass fraction of each industry's annual water consumption that is provided by another industry[11].

[11] Note that for each SME industry, the fraction presented in the Sum Y column is only applicable to 50% of the industries annual water consumption.

SINKS	SOURCES			
	N6	N9	N18	Sum y
SME1	1	0	0	1
SME2	1	0	0	1
SME3	1	0	0	1
N6	0	0	0	0
N7	0.732	0.08	0.0057	0.8177
N8	0.53	0.35	0.0182	0.8982
SME4	0	1	0	1
SME5	0	1	0	1
N9	0	0	0	0
SME6	1	0	0	1
N11	0	0	0.0204	0.0204
N12	0	0	0.0813	0.0813
SME7	1	0	0	1
N13	0	0	0.0124	0.0124
N14	0	0	0.5045	0.5045
N15	0	0	0.0605	0.0605
N16	0	0	0.119	0.119
N17	0	0	0.1065	0.1065
N18	0	0	0	0
SME18	1	0	0	1
SME35	0	1	0	1
SME36	1	0	0	1
SME41	0	1	0	1
SME51	1	0	0	1

Table 20 - Solution Set of the Decision Variables ($y_{j,k}$) for Scenario 1

Note that $y_{j,k}$ represents the inlet mass fractions of water attained from each source. The column titled Sum y adds each $y_{j,k}$ term for each company to provide an overall estimate of the total fraction of water obtained from water sharing.

Based on the results presented in Table 20, Figure 17 has been prepared to illustrate the water exchanges and the required infrastructure in a map format. In this scenario, the following indicators have been calculated:

- Approximately 1,523,000 m^3/yr of water is exchanged among industries. This translates to a 25% reduction in potable water consumption and a 31% reduction in generated wastewater;
- Total electrical energy used to pump water is approximately 1,550,100 kWh which represents a savings of approximately 15%. Note that this occurred even though the constraint was set at no required energy savings;
- All 24 companies have been included in the water sharing; and

- The total length of trenching required is approximately 6,070 m which translates to a total infrastructure cost of approximately $2,250,000 (including $5,000 for each participating industry).

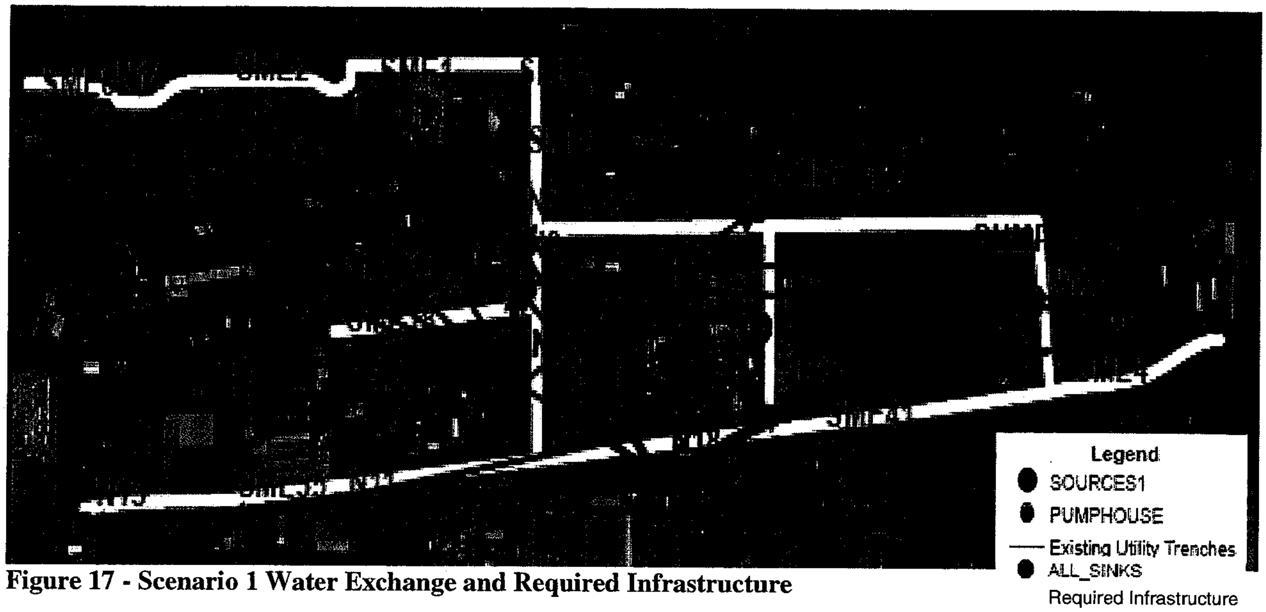

Figure 17 - Scenario 1 Water Exchange and Required Infrastructure

(Aerial photograph courtesy of EIS)

4.1.2 Scenario 2 – Minimize Electrical Energy Consumption

In order to determine what the minimum electrical consumption could be, the required percentage of electrical energy savings, P from equation 18, was continually increased until a feasible solution was no longer attainable from the linear programming model. By doing so, the linear optimization converged on the solution set presented in Table 21[12].

[12] Note that for each SME industry, the fraction presented in the Sum Y column is only applicable to 50% of the industries annual water consumption.

SINKS	SOURCES			
	N6	N9	N18	Sum Y
N7	0.7895	0.0155	0	0.805
N8	0	1	0	1
SME4	0	1	0	1
SME5	0	1	0	1
N15	0	0	1	1
N17	0	0	0.679	0.679
SME41	0	1	0	1

Table 21 – Solution Set of the Decision Variables ($y_{j,k}$) for Scenario 2
Note that $y_{j,k}$ represents the inlet mass fractions of water attained from each source. The column titled Sum y adds each $y_{j,k}$ term for each company to provide an overall estimate of the total fraction of water obtained from water sharing.

Based on the results presented in Table 21, Figure 18 has been prepared to illustrate the water exchanges and the required infrastructure in a map format.

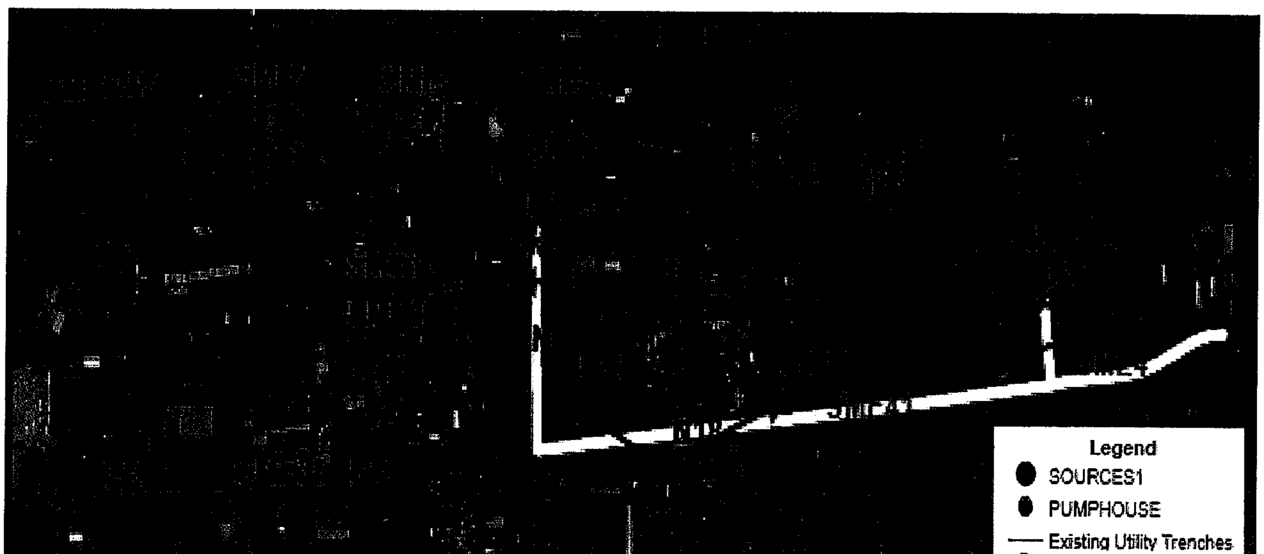

Figure 18 – Scenario 2 Water Exchange and Required Infrastructure

(Aerial photograph courtesy of EIS)

In this scenario, the following indicators have been calculated:

- Approximately 1,523,000 m^3/yr of water is exchanged among industries. This translates to a 25% reduction in potable water consumption and a 31% reduction in generated wastewater;
- Total electrical energy used to pump water is approximately 1,464,300 kWh which represents a savings of approximately 20%. Note that this was the maximum energy savings target that yielded a feasible solution;

- Only 10 companies have been included in the water sharing; and
- The total length of trenching required is approximately 2,030 m which translates to a total infrastructure cost of approximately $760,500 (including $5,000 for each participating industry).

4.1.3 Scenario 3 - Least Cost to Do Something

In applying Scenarios 1 and 2, it became evident N6 was a large source of water for reuse. By inspecting the water quality criteria of the other industries along with the GIS maps, an opportunity to reuse all of the water from N6 by neighbouring industries N7 and N8 is evident. In this scenario, the length of piping was fixed to service only these three industries. By doing so, the linear optimization converged on the solution set presented in Table 21.

SINKS	SOURCE
	N6
N7	0.6895
N8	1

Table 22 - Solution Set of the Decision Variable ($y_{j,k}$) for Scenario 3
Note that $y_{j,k}$ represents the inlet mass fractions of water attained from N6.

Based on the results presented in Table 22, Figure 19 has been prepared to illustrate the water exchanges and the required infrastructure associated with this scenario in a map format.

In this scenario, the following indicators have been calculated:

- Approximately 1,082,800 m^3/yr of water is exchanged among industries. This translates to a 17% reduction in potable water consumption and a 22% reduction in generated wastewater;
- Total electrical energy used to pump water is approximately 1,515,600 kWh which represents a savings of approximately 17%;
- Only 3 companies have been included in the water sharing; and
- The total length of trenching required is approximately 230 m which translates to a total infrastructure cost of approximately $95,500 (including $5,000 for each participating industry).

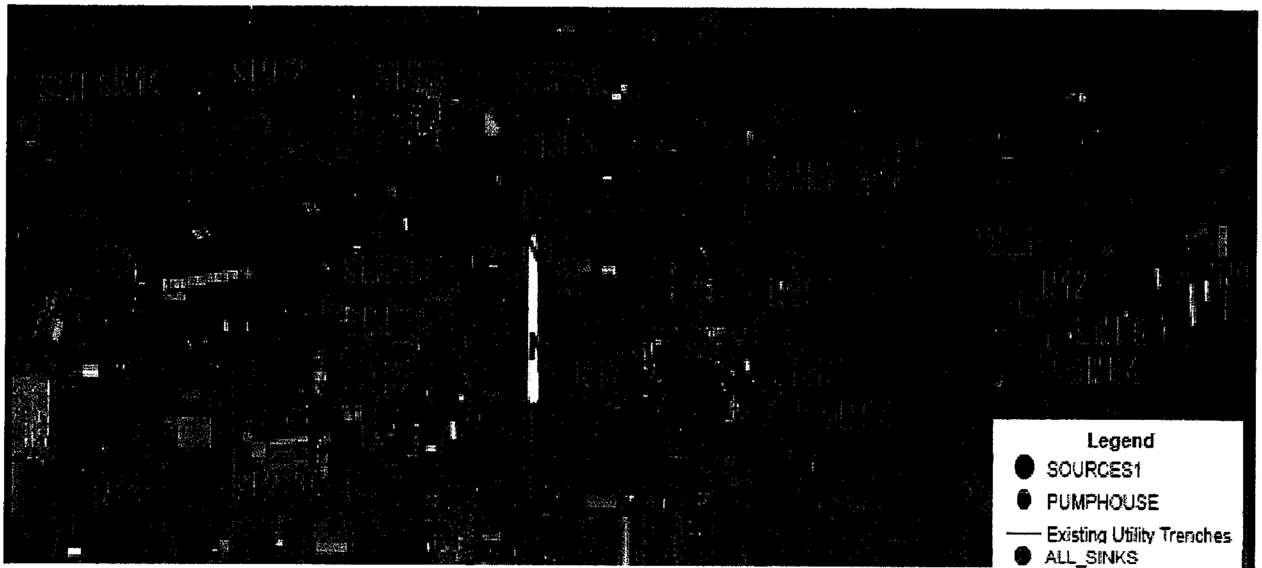

Figure 19 - Scenario 3 Water Exchange and Required Infrastructure

(Aerial photograph courtesy of EIS)

4.2 Heat Energy Model Results

The thermodynamic pinch analysis was applied using the process stream composition data presented in Section 3.3.3.1 and the optimization data presented in Section 3.3.3.2. The composite curves, shifted composite curves, and the grand composite curve, generated as part of the analysis, are presented in Figure 20.

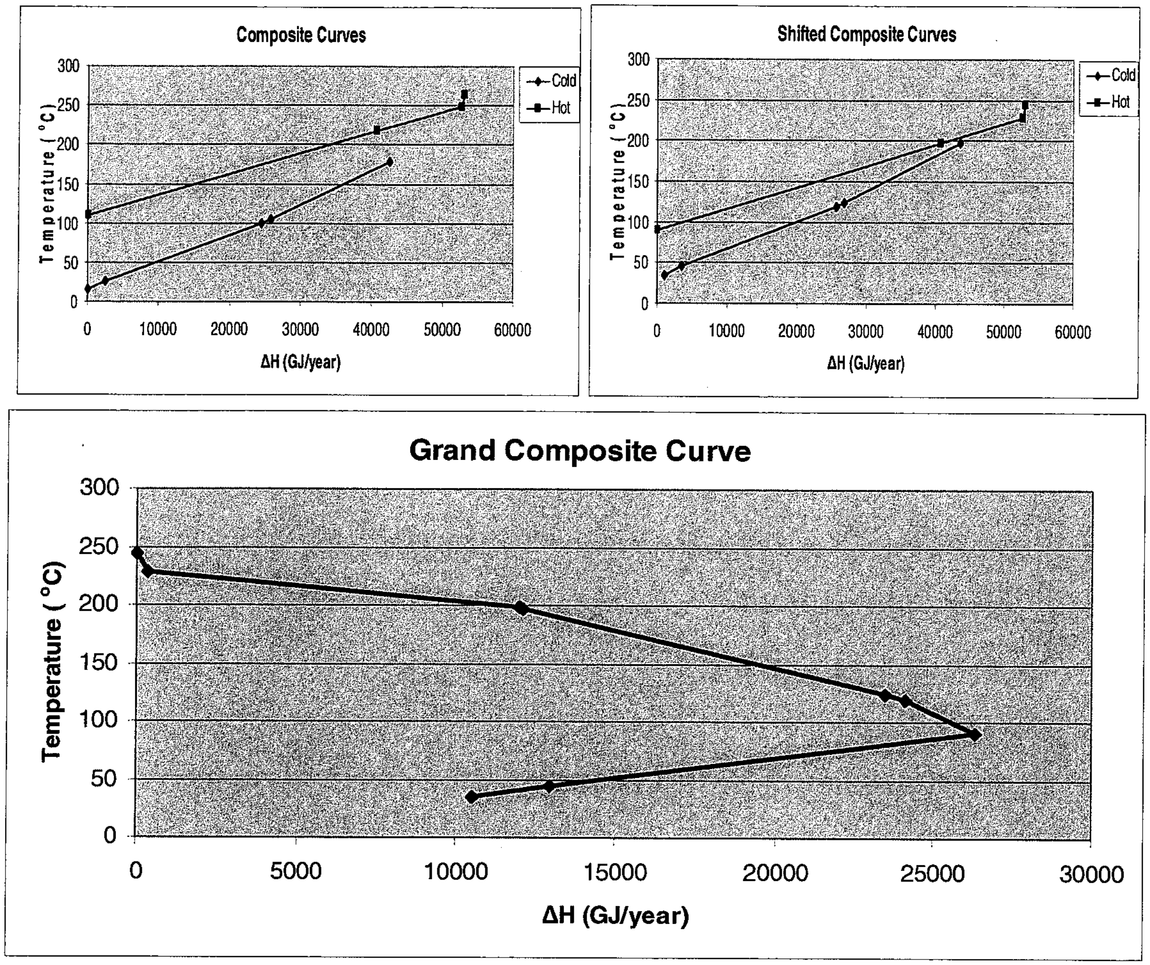

Figure 20 - Composite Curves based on Case Study Data

The composite curves suggest that approximately 80 % (42,500 GJ out of 53,000 GJ per year) of the heat liberated annually from cooling the stacks to 110 °C could be used to heat each condensate makeup water process stream. Similarly, the problem table presented in Table 23 indicates that an additional 10,500 GJ per year of heat is still available once all included heating requirements have been met (i.e., each condensate makeup stream is heated to the same temperature as the condensate recycle stream).

Temperature Interval	Interval Number	ΔT_{int}	Process Streams Present in Interval	ΔH_{int}	Heat Available to Cascade
(°C)		(°C)		(GJ/year)	(GJ/year)
244 to 229	1	15	B_{hot}	-300	300
229 to 198	2	31	A_{hot}, B_{hot}	-11,600	11,900
198 to 197	3	1	A_{cold}, A_{hot}, B_{hot}	-100	12,100
197 to 124	4	73	A_{cold}, A_{hot}, B_{hot}, C_{hot}	-11,400	23,500
124 to 119	5	5	A_{cold}, A_{hot}, B_{hot}, B_{cold}, C_{hot}	-700	24,100
119 to 90	6	29	A_{cold}, A_{hot}, B_{hot}, B_{cold}, C_{hot}, C_{cold}	-2,200	26,300
90 to 45	7	45	A_{cold}, B_{cold}, C_{cold}	13,400	12,900
45 to 35	8	10	A_{cold}, B_{cold}	2,400	10,500

Table 23 - Problem Table Based on Case Study Data

Based on the heat recovery results of the pinch analysis, heat exchangers are applied to the CadSim Plus model to incorporate the heat recovery into the model. The options for heat exchanger configuration along with the associated installation costs are presented in Table 24. From Table 24, Option 2 (which includes heat recovery from Company A and Company B) appears to be the relatively cheapest option. The process flow diagram of Option 2 is presented in Figure 21.

Option	Heat Source	Heat Sink	Heat Exchanged (GJ/year)	Heat Exchanger and Infrastructure Cost (2008 $)
1	Company A Company B Company D Company A	Company A Company B Company D Company D	37,000 1,500 1,700 2,300	1,590,000
2	Company A Company B Company A	Company A Company B Company D	37,000 1,500 4,000	1,560,000
3	Company A Company A Company A	Company A Company B Company D	37,000 1,500 4,000	1,630,000

Table 24 - Options for Heat Exchanger Configuration and Associated Costs

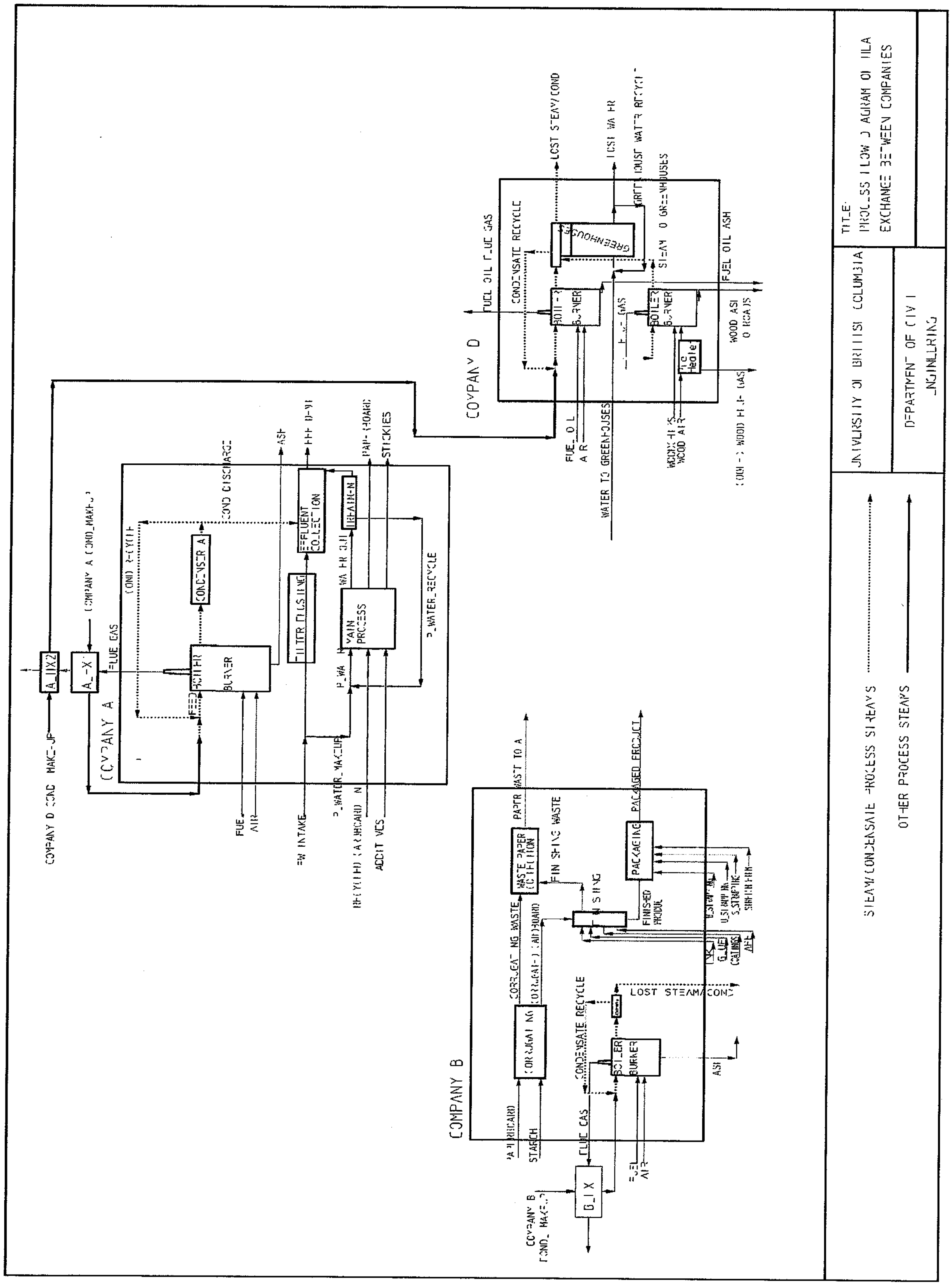

Figure 21 - Process Flow Diagram of Heat Exchange Scenario 2

In a geographic context, the piping infrastructure layout required to transfer the hot water from Company A to Company D is presented in Figure 22.

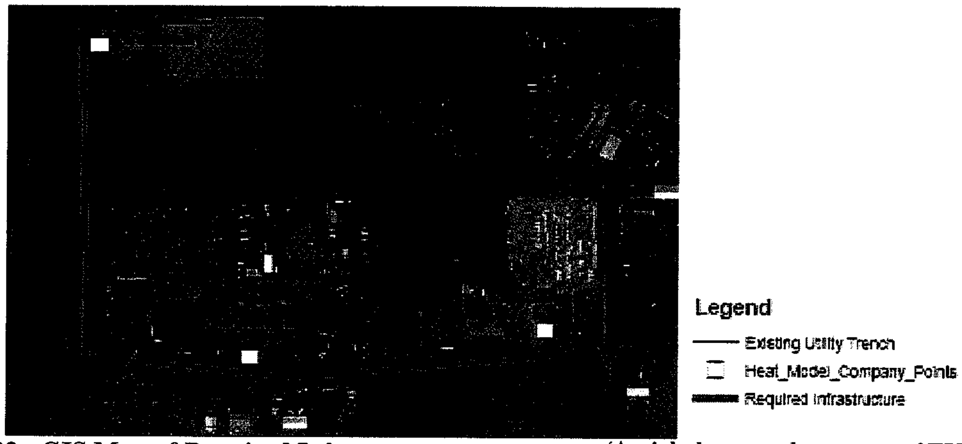

Figure 22 - GIS Map of Required Infrastructure **(Aerial photograph courtesy of EIS)**

The exchange of heat presented in this case study will require the installation of approximately 1,000 m of piping between Company A and Company D. Table 25 presents a summary of the calculated indicators when the heat recovery is incorporated in the CadSim Plus simulation.

Indicator	Value Calculated after Heat Exchange
Total Fuel Oil Used	20,100 t/year
Total Ash Produced	1,200 t/year
Total CO_2 Produced	87,700 t/year
Total SO_2 Produced	500 t/year
Total Wasted Heat	162,100 GJ/year

Table 25 - Summary of Indicators after Heat Exchange Incorporated into Simulation

The results in Table 25 indicate an approximate 5% reduction in annual fuel oil requirements, associated emissions, and ash produced; along with a 24% reduction in wasted heat.

4.3 Summary of Results

Table 26 summarizes the results obtained from the application of the water model and the heat energy model to the case study data. In addition, Table 26 includes the constraints used to allow for different scenarios to be evaluated.

	Scenario	Constraint	Result
Water Model	1	•No additional electrical energy used to pump water in reference to baseline	•24 companies involved •25 % savings in potable water consumption •31 % savings in generated wastewater •15 % savings in electrical energy used for pumping water •Installation cost of $2,250,000
	2	•Minimize Electrical Energy Use	•10 companies involved •25 % savings in potable water consumption •31 % savings in generated wastewater •20 % savings in electrical energy used for pumping water •Installation cost of $760,500
	3	•Least Cost to Do Something	•3 companies involved •17 % savings in potable water consumption •22 % savings in generated wastewater •17 % savings in electrical energy used for pumping water •Installation cost of $95,500
Heat Energy Model	2	•Temperature of Stack Gas >= 110°C •Condensate Make Up Stream Heated to Temperature of Condensate Recycle	•5% reduction in annual fuel oil requirements •5% reduction in annual CO_2 emissions •5% reduction in annual SO_2 emissions •5% reduction in annual Ash produced •24 % reduction in wasted heat •Installation cost of $1,560,000.

Table 26 - Summary of Water Model and Heat Energy Model Results

The results demonstrate that both models can provide decision makers with information regarding:

- resource saving opportunities;
- pollution reduction estimates;
- costs associated with infrastructure required to realize savings; and
- which companies can be engaged.

5.0 DISCUSSION

The work presented in this thesis uses case study data to demonstrate practical approaches to increase resource use efficiency among industrial participants of a resource exchange system. Specifically, the optimization techniques used in the two models presented here act as a preliminary screen to facilitate the development of eco industrial networks. The water model built on the thesis work of Carolyn Nobel (1998) by incorporating the location of utility trenches to more accurately estimate electrical energy associated with pumping water and the installation costs of infrastructure required to cascade water between industries. The heat energy model built on the thesis work of Tracy Casavant (2000) by applying the thermodynamic pinch analysis to a synthesis of a few industries from her EIN model to uncover heat exchange opportunities between industries and to calculate heat exchanger costs. Additionally, the heat energy model uses GIS software to calculate infrastructure costs and display infrastructure requirements. This section provides a discussion of the practical implications of the case study results; limitations of the approach; and additional research recommendations.

5.1 Practical Implications of Results

The case study results demonstrate that knowledge of how participants use resources can help make more efficient use of water and heat energy by applying optimization techniques to determine the potential for resource exchange between different participants. The purpose of this section is to discuss what people who apply the models presented in this work can expect to get out of the approach. Depending on which perspective is taken, the motivation for applying the models will vary. On one hand, a local authority may wish to determine how resource use could be optimized due to limitations on resource availability and waste assimilation capacity within the region. On the other hand, an industry or group of industries may be seeking a competitive advantage in the marketplace by reducing costs associated with waste disposal and resource consumption. In both cases, the promotion of environmentally responsible practices is likely to benefit the proponent through increased marketability. The main benefit of the models is that they can both be used to inform either perspective.

Generally, the models directly provide users with:

- Identification of sources and sinks of water and heat energy;
- Evaluation of different water and heat energy cascading scenarios to determine: potential reduction in resource consumption, potential reduction in waste generation, relative energy savings, and relative infrastructure costs required to realize the savings; and
- Illustration of the resource exchanges and required infrastructure in a map format.

Table 27 provides an overview of how the model outputs could be used from the perspective of either a local authority or private industry.

Perspective	Model Output and Use		
	Identify sources and sinks of water and heat energy	**Evaluate different water and heat energy cascading scenarios**	**Illustrate the resource exchanges and required infrastructure**
Local Authority	• Identify major resource consumers and producers. • Start the discussion between resource users to encourage cooperation. • Raise awareness and promote education regarding resource use within industries.	• Demonstrate how different actors could contribute to meeting regional objectives. • Potential to capitalize on planned infrastructure projects. • Demonstrate savings potential to encourage participation. • Maximize resource use efficiency within allotted budget. • Assess requirements to operate micro utility. • Determine utility rates for participants.	• Engage a broad audience. • Easily relate the scope and scale of municipal work in a geographical context.
Private Industry	• Identify potential customers or suppliers.	• Determine capital investment costs. • Prepare financial model.	• Engage partners and broad audience. • Compliment business case with visual representation.

Table 27 - Water Model Uses from Different Perspectives

The following sections will use the case study results to demonstrate the practical uses of the models from both perspectives.

5.1.1 Using the Source and Sink Information

Determining the sources and sinks of water and heat energy will allow for the identification of: major water consumers, waste water producers, major heat energy consumers and producers, and how many industries could be engaged.

In the context of the water model case study data, industries N6, N7 and N13 consume approximately 65 % of the potable water used by the study participants. In the context of the heat energy model case study data, Company A requires approximately 74 % of all the heat energy used in the case study for it's heating needs. If the local authority intended to promote water use or heat energy use efficiency strategies at the intra-organizational level, these industries could provide a starting point for further investigation. Similarly, from the private industry perspective, internal water and heat energy use optimization within these industries may present an opportunity to reduce water costs, fuel costs and disposal fees.

In terms of promoting industrial symbiosis, screening of the water model case study data identifies industries N6, N9, and N18 as sources of water for other industries. Similarly, screening of the heat energy model case study data identifies that there is sufficient heat being lost up the stack of Company A to preheat the boiler make-up streams of Company A, Company B and Company D to the same temperature as their condensate recycle process streams. To promote cooperation, the local authority could work to facilitate communication among industries by holding meetings in which each industry is represented. This approach could serve to connect individuals from different companies by presenting the water quality distribution, the heat energy distribution, and informing participants about who can share with whom. The information sharing meetings could be used to build relationships between industries and raise awareness about the regional water and energy issues and the strategies that could be implemented to deal with them.

Private industries could use this information to identify potential customers or suppliers of water or heat energy. For example, in the water model case study data, common sinks for N6, N9 and N18, are N7 and N8. The local authority could facilitate discussions between these industries as mentioned above, or alternatively, the industries could further evaluate the opportunities themselves. In order to aid in evaluating opportunities, the linear programming model and the thermodynamic pinch analysis are used to provide the next level of detail to participants by identifying water and heat energy cascading opportunities that will meet the defined objectives.

5.1.2 Considering the Water Model Results

The case study used three different scenarios to represent how the water model could be used to produce results that maximize the amount of water shared among industries under different constraints. Scenario 1 constrains the solution by not allowing any more electricity to pump water than is currently used; Scenario 2 constrains the solution by maximizing electricity savings associated with pumping water; and Scenario 3 constrains the solution by limiting the amount of participants by constraining the amount of money that can be spent on installing infrastructure.

Scenario 1 presents a solution that finds a sink for all the water that qualifies for exchange, which includes water from N6, N9 and N18. This solution uncovers the potential to reduce raw water consumption by approximately 25% while decreasing the amount of waste water generated by approximately 31%. By placing a constraint on electrical energy used by the water distribution and wastewater collection system such that the overall system uses relatively less electricity to service each industry than is used under the existing configuration without water exchange, the model converges on a solution that decreases the electrical energy consumption associated with pumping water by 15% and includes all 24 industries. If a goal of the local authority is to include all industries in an effort to raise awareness among both large and small water consumers, this solution could be used as a basis for engaging all the industries and advising how each industry could contribute. The estimated infrastructure installation cost of approximately $2,250,000 provides the local authority with a budget estimate that can be plugged into larger financial models for evaluation.

In scenario 2, electrical energy savings is maximized at 20%. The main differences in the results of scenario 2 from scenario 1 are that only 10 industries are included in the exchange and the infrastructure costs are reduced by approximately two thirds to approximately $760,500. This reduction in cost comes primarily from the reduction in infrastructure required. In order to exchange the same amount of water as scenario 1 and also attain an additional 5% in electrical energy savings, the water model converged on a solution that favoured water exchanges between industries in closer proximity than scenario 1.

In scenario 3, the close proximity of major water consumer N6 to sinks N8 and N7 presents the potential to reduce overall raw water consumption by 17%, waste water discharged by 22%, and electrical consumption by 17% for a capital investment of only $95,500. While this scenario only includes 3 industries, it is important for a few reasons. Firstly, the opportunity to reduce water consumption, wastewater generation, and electrical consumption for a relatively small cost may be seen as a starting point for development. The relatively low cost may be seen as a low financial risk opportunity to encourage cooperation. If this sharing scenario is realized, future projects could add more industries in a phased approach. Secondly, this scenario is important because it first defined the amount of infrastructure and then optimized based on the proximity of the industries. In this way, the model can be used to capitalize on planned infrastructure upgrade projects. If an infrastructure project is planned, this model could be applied in a similar fashion as scenario 3 to uncover water sharing opportunities among all industries in close proximity to the planned infrastructure project. In this regard, if the utility trenches are opened up and the underground piping is going to be exposed as part of the planned work anyway, the installation of the required water exchange infrastructure would only be an incremental step in the planned infrastructure project.

In any of the three scenarios, the business model would likely need to leverage the expected operational savings against the capital costs. From the perspective of the local authority, the expected annual reduction in electricity costs and the expected annual reduction in water and sewage treatment costs associated with the reduction in raw water consumption and wastewater generated would need to be compared to the annual costs required to maintain the water exchange system and installation costs amortized annually for the expected life of the system. In addition, in the case where existing water withdrawal rates and pollution generation rates cannot be sustained, the capital costs would need to be considered against either lost industrial capacity or avoided costs associated with increasing water system capacity, if increasing system capacity is possible. From the perspective of private industries initiating the development, the cost savings could be presented as avoided sewerage fees for water sources and discounted supply costs for sinks of cascaded water. In existing pricing scenarios where sewerage fees are already incorporated in water fees, instead of avoided sewer fees, sources of water could receive all or a portion of the discounted water fees paid by the industries acting as sinks. One consideration could be that N6, N9, and N18 become partners in a micro utility that supplies water to eligible sinks at a discounted rate. Similar to the local authority perspective, the projected annual revenue generated from the sale of water from the source companies could be used to develop the financial justification for the capital investment required to install the necessary infrastructure.

5.1.3 Considering the Heat Energy Model Results

The results from applying the heat energy model generally have similar practical implications as the results from the application of the water model in that they have the ability to identify resource sharing opportunities for decision makers and provide estimates of the costs required to install the necessary infrastructure. In this sense, the use of an optimization technique to identify an approximate 5% reduction in annual fuel oil requirements, associated emissions, and ash produced, along with a 24% reduction in wasted heat, demonstrates how the thermal pinch analysis can be used to facilitate industrial symbiosis. By highlighting the potential for alternative heat cascading scenarios along with associated indicators such as emissions and infrastructure costs, this model provides both central authorities and private industries with an estimate of how much can be saved and what it will cost to install.

Similar to the water model, the business case for installing the heat cascading infrastructure from the perspective of either the central authority or private industry would likely need to leverage the expected annual operational savings against the annual costs required to maintain the heat exchanger network and installation costs amortized annually for the expected life of the system. Operational savings for heat sinks would take the form of avoided fees associated with emissions to the atmosphere, reduced ash production, and reduced fuel costs. In terms of heat sources, operational savings would take the form of revenue generated from the sale of previously wasted heat. From the perspective of the central authority (or major utility), the incentive to facilitate heat cascading may stem from regional aspirations to reduce greenhouse gas emissions. If this is the case, the central authority may choose to pay for and operate the heat exchange equipment under the umbrella of other existing utilities provided.

In terms of the case study data presented in Table 24, it is important to point out that the estimated installation costs of each of the heat energy options were all within approximately 4% of each other. As these estimated costs are so close, for preliminary budget purposes, the installation costs for each option can be considered equal. This differs from the water model in that the installation costs of the three scenarios of the water model all varied by an order of magnitude. This difference can be attributed to the fact that the majority of the installation cost associated with the water model depended on the length of piping, however, the majority of the cost associated with the heat energy model depends on the cost of the heat exchangers. As the cost of heat exchangers is largely dependant on the required heat exchanger area, since the amount of heat being exchanged in each of the options considered does not change, neither does the total heat exchanger area. The cost of piping infrastructure would be expected to have a more significant effect on the installation cost if the distances between companies increased.

5.1.4 Seeing is Believing – Benefits of Maps

While the models used to generate the results are complex, the results must be communicated in a simple fashion to engage a broad audience. Therefore, for a central authority, presenting the results in a map format provides a communication medium that is crucial to engaging non-technical stakeholders. The maps generated from the case study results easily provide audiences with a visual representation of: where companies are located, who is sharing water with whom, and where the required infrastructure will be located. With this information, participants in the water exchanges and other members of the region can easily comprehend the geographic scope of the project.

In addition, central authorities may find GIS compatible resource use optimization models useful from a municipal infrastructure management perspective. The National Research Council (NRC) has reviewed various available asset management systems (Halfawy et al., 2006) and has suggested that the next generation of asset management tools will be GIS-based (Vanier et al., 2004). Since most municipalities in Canada have, or are developing, GIS capabilities, model results could be integrated as layers into existing municipal infrastructure GIS maps and communicated to large audiences very easily. This integration could also help asset managers easily cross reference the location of infrastructure required to support resource exchanges with existing infrastructure maintenance program locations in order to coordinate construction efforts.

In terms of the private industry perspective, the benefits of GIS are the same in that the engagement of broad audiences through visual illustrations can add value to any business proposal and help to gain project acceptance from the local community. By informing large audiences, the maps could also provide the added benefit of being used as advertisement for both the municipal efforts and the participating industries.

5.2 Limitations of the Approaches

The main limitation of the approach presented in this thesis is the availability of data. For example, the original intent of this thesis was to apply the water model to project data collected by Eco-Industrial Solutions (EIS) to assist in their work efforts to develop EIN strategies. Unfortunately, data availability was limited, and therefore, fictional case studies comprising portions of "real" data had to be used to demonstrate the methodology. The limitation of data emphasizes the lack of detailed process knowledge regarding resource use in industries. In Table 4, water quality and quantity associated with different specific processes were identified as the most difficult data to gather due to the investment of resources required to get the data. For this thesis, water consumption data was made available by the local water utility, however, a lack of data regarding the amount and quality of water required for specific tasks within each participating industry necessitated estimates to be made based on the expected water usage. This lack of resource use data represents the relatively immature state of eco industrial development in Canada. The work conducted by Eco-Industrial Solutions represents some of the most progressive efforts to develop eco-industrial networks in the country, however, the groundwork is still being laid in terms of gathering the required level of information and understanding the resource flows within and between industries.

Until progress is made in measuring and sharing specific data regarding water use and energy use at the process scale of industries, the models presented in this thesis can not be used in real world applications. That being said, the demonstration of what tools are available to policy makers and the general public may generate interest and aid in the effort to create the political will to obtain the required information.

5.3 Further Development Potential

The models presented in this thesis describe how data could be used and identify which data needs to be collected in order to apply the models. In conjunction with trying to get the data, more effort could be spent on making the models more sophisticated. Ideas regarding what could be done on both of these topics are presented in the following sections.

5.3.1 Trying to Get the Data

With the ever increasing evidence of global warming, people are becoming more aware of the implications associated with the misuse of our natural resources. As people become more aware, they begin to value resource use efficiency more. This is manifested in political agendas and coordinated efforts to maximize resource use efficiency. Examples of this raised awareness and consequent changes include the province of British Columbia's recently implemented carbon tax and the federal incentive programs such as the Federation of Canadian Municipalities Gas Tax incentive program or the ecoEnergy action plan. This shift bodes well for eco-industrial development. The current dearth of data for exchange modeling could be addressed by collection programs among industrial partners. Some necessary first steps in this endeavor could include:

- Developing costs, expertise and the scope of work required to conduct audits of resource use within industries;
- Determining the metering and data collection equipment required along with associated costs to install, measure, collect, manage and analyze the data;

- Assessing utility rates and discharge fees to determine how they could change to promote desired behaviour; and
- Evaluating applicable incentive programs to determine specifically what funds are available.

Once a working methodology is in place to collect detailed industry information, it could become a component of a larger proposal to implement an eco-industrial networking strategy which could include the following components:

- Get organized: develop an information management system. In terms of the work presented in this thesis, utilizing a GIS to manage and illustrate data is favoured;
- Know your local resource capacity: determine local ecosystem production and assimilative capacity (water, land and CO_2). In addition, learn what expertise and initiatives already exist within the area of application and build upon them;
- Attain industry information: use Table 4 and Table 7 as guidance to determine what industries are present and what data is readily available;
- Process audits: coordinate the implementation of sub-metering and data collection, along with education of participants. The International Measurement and Verification Protocols provide methodologies for how to implement and conduct sub-metering of processes (Efficiency Valuation Organization, 2007);
- System optimization: once an industrial audit and sub-metering program has been implemented, the detailed process data can be used to optimize the industrial system. In this sense, internal process optimization can be evaluated together with an eco-industrial networking approach (such as the one presented in this thesis) to determine an optimized overall system performance; and
- Respect locality: system optimization can use water, land and overall ecosystem assimilative capacity of CO_2 to determine what level of industrial

activity can be sustained (i.e., they can become constraints on the optimization).

In terms of where to start, an opportunity exists to engage municipalities that have already participated in projects regarding municipal infrastructure. Eleven Canadian municipalities have demonstrated cooperation with the NRC by providing data regarding sewer conditions (Newton and Vanier, 2006). As part of the Municipal Infrastructure Investment Planning (MIIP) project, the NRC used data from the eleven municipalities to demonstrate how their tools could be used for predicting the deterioration of sewers and for prioritizing maintenance projects. Similarly, the province of Alberta is supporting the GIS based Municipal Infrastructure Management System (MIMS) initiative to assist small to medium sized municipalities in managing their infrastructure (MIMS, 2006). Selecting a group of the municipalities that have participated in the referenced projects to act as case studies for applying the above mentioned eco-industrial networking strategy has the opportunity to: capitalize on the information collected regarding the location of infrastructure; take advantage of the existing collaboration with the participating municipalities; and compliment identified maintenance projects with the potential to develop infrastructure that could facilitate industrial symbiosis.

5.3.2 Enhancing the Water Model

Effort put forth to collect more detailed process information from industries could be complimented with further work to enhance the model utility. For example, the models could be made more sophisticated by incorporating elements such as: resource demand and production time profiles; resource storage capacity; ecological productive and assimilative capacity; and waste treatment or conversion options. In addition, since the majority of communication between the software packages used in the model was achieved through manual data transfer, further work to improve the interface between the different software packages to automate data transfer would be beneficial. In improving the interface, other optimization techniques more amenable to dynamic scenarios could be used to drive the communication between the different software packages.

In terms of communication, the water model currently relies on manual data transfer between the software packages. In order to incorporate all of the different enhancements mentioned above, more work is required to improve communication between the modeling software packages. Ideally, a computer application that acts as an optimization tool would be developed to drive the communication between modeled components. The development of this optimization tool would be made easier with the help of computer scientists and mathematicians to incorporate their expertise in the field of communication between computer software packages that provide detailed analysis of each parameter and provide assistance in developing and coding the algorithm to evaluate different scenarios.

The function of the optimizer would be to: provide the model with exchange scenarios; receive information from each component of the model regarding indicators from the exchange; evaluate the indicators based on optimization objectives; and converge on exchange solutions that meet the objectives. One optimization algorithm that could suit this purpose is a genetic algorithm. Genetic algorithms are optimization techniques based on the principles of natural selection and genetics (Holland, 1995; Sastry et al., 2005). Decision variables are coded and a "population" of solution sets is generated. Solution sets are evaluated using fitness functions and those that perform the best are carried forward to the next "generation" of solution populations. They are allowed to "reproduce" with other solution sets in a process called crossover and are additionally subject to random mutations. The purpose of random mutations is to attempt to prevent the genetic algorithm from converging on local optimum rather than a global optimum. This process produces generations of populations that continually improve in terms of performance against the fitness functions and is repeated until solution sets that meet specified exit criteria are achieved.

In terms of supply and demand of water, the water model uses annual estimates. The annual estimates allow for a linear optimization model to be used. While an annual time increment can be used to sufficiently determine preliminary water exchange potential, it does not account for variations in supply and demand occurring at smaller time increments. Some of these variations include hourly and daily fluctuations in demand and effluent production associated with the types of processes in use and the hours of operation along with seasonal variations in water use. In essence, while an annual estimate may indicate that two industries may be potential candidates for exchange, hourly, daily and seasonal fluctuations in operations may prohibit exchange due to water not being available when it is needed. As such, one way to enhance the model would be to incorporate time sensitive water use profiles into the optimization. In this way, demand profiles would need to be evaluated against production profiles in order to determine feasible exchanges.

In terms of energy used to pump water, the water model assumes a constant pipe size and flow rate. By utilizing a water distribution modeling software package such as WaterCAD or WaterGEMS, more accurate estimates of pumping energy requirements could be attained. This type of software could also facilitate the use of non-linear water demand and production profiles. In addition, work has been done to combine these types of tools to real time process data (Joshi et al., 2007). An added benefit of WaterGEMS is that it is also set up to integrate with ArcGIS software.

Another model enhancement could be the inclusion of water storage capacity. Storage capacity could refer to both storage of effluent and storage of rain water. In this way, the model could treat storage infrastructure as a separate industry in the optimization. Software programs such as the Water Balance Model, developed to support decision making regarding rain water management, could be used to estimate how much rainwater could be collected (WBM, 2008). Other software programs such as Visual MODFLOW could also be used to incorporate subsurface flow and aquifer storage capacity (Visual-MODFLOW-Pro, 2004).

Although, a waste water treatment plant could either be incorporated into the water model as an additional industry, or in the case where one industry installs additional treatment equipment, as reduced contaminant concentrations in effluent, the water model does not explicitly incorporate treatment options. In assessing energy use and installation cost associated with the water exchange, the inclusion of wastewater treatment equipment could provide for a more representative model. In this way, different treatment options could be evaluated based on effluent characteristics and the additional water reuse, along with installation cost and operating energy requirements associated with treatment. Also, the potential to identify industries with similar effluents allows for the consideration of treatment options amenable to their specific characteristics which could allow for the potential to make the best use of the waste stream (i.e., nutrient recovery and methane generation). Some examples of commercially available wastewater treatment plant design software packages that could be used include GPS-X, SimuWorks, and BioWin. In addition, Nemerow provides a great resource of effluent characteristics of various industries (Nemerow, 1978). His work, combined with wastewater treatment plant simulations, could provide a starting point with which to identify candidate industries whose waste streams could be combined to make the best use of the effluent at the treatment plant level. This information could then be used as a basis with which to identify and approach similar industries for detailed study.

The incorporation of ecosystem productive and assimilative capacity limitations would also help to enhance the model. Currently, these could be added as constraints on the raw water supply and the discharge capacity of the wastewater treatment plant. An alternative approach would be to use an ecosystem modeling tool to evaluate the effect of wastewater treatment plant discharge and surface water runoff on aquatic ecosystems. An example of a modeling tool that could be considered for this task is the free software Ecopath with Ecosim (UBC-Fisheries, 2008). This software is used to model aquatic ecosystem behaviour and food chain analysis, but could be evaluated to determine if the effects of nutrient loading and water temperatures associated with discharge and runoff on aquatic ecosystems can be modeled.

In structuring further development of the model, it may be worthwhile to establish a collaborative, interdisciplinary research project. Table 28 has been prepared to identify what pools of resources could be tapped to aid in this effort.

One approach would be to use the information in Table 28 as a starting point to determine who could be approached to contribute in terms of: departments from Universities; ministries, branches or departments from governments; and private sector and NGO expertise. In this sense, inclusion of universities allows for access to research capabilities and training opportunities for the students that will be entering the workforce; inclusion of governments allows for access to the decision makers in terms of setting, evaluating and potentially even changing laws that act as barriers to adaptive strategies; and the inclusion of NGOs and the private sector allows access and input from those who apply their expertise (including the use of software programs) in projects everyday. Such a project would not only improve the model, but would also act as a means of allowing experts in each field to work together and learn how specific decisions that they make in their own professional niches affect other common objectives. A project of this nature would compliment integrated water management approaches such as the Water Sustainability Action Plan for British Columbia's Green Infrastructure Partnership development of decision support tools (BCWWA and BCMWLAP, 2004)(note that the Water Balance Model previously mentioned is currently being used by the Green Infrastructure Partnership) .

Element	Skill set	Likely to have Required Skill set
Water demand and production profiles	• Process Control • Process Engineering	• Chemical Engineers • Mechanical Engineers
Water Storage Capacity and Detailed Municipal pumping simulation	• Municipal Hydraulics • Surface and Subsurface Hydrology	• Civil/Municipal Engineers • Geological Engineers • Landscape Architects
Liquid Waste Management	• Organic and Inorganic wastewater treatment (along with dealing with the sludge that is generated)	• Chemical Engineers • Environmental Engineers • Civil/Municipal Engineers
Ecological Productive and Assimilative Capacity	• Ecosystem assessment	• Ecologists • Biologists • Landscape Architects • Fisheries scientists • Oceanographers
Software Communication	• Software and hardware interface development	• Computer Scientists
Detailed GIS	• Geography • Infrastructure • Land Use	• All previously mentioned disciplines • Planners • Geographers
Non-Linear or Evolutionary Algorithm Development	• Mathematical	• All previously mentioned disciplines • Mathematician

Table 28 - Identification of Skill Sets and Disciplines that Could Aid in Model Development

5.3.3 Enhancing the Heat Energy Model

One enhancement that could be made to the heat energy model is to include the affect on plume dispersion resulting from cooling the stack gas. In the industries considered, the target temperature of the stacks was set to 110°C in order to not condense the water in the stack gas. In general terms, the cooling of the stack gas would decrease the volume of the process stream and would be expected to reduce the plume dispersion. This reduction in dispersion would need to be considered in terms of local air quality.

In addition, the heat energy model that could be enhanced is to incorporate the capture of latent heat from the stacks by cooling the stack gas even further. Technology is available that has demonstrated the ability to condense the water out of the process stream and recuperate the heat without causing performance loss within the boilers (Zhelev and Semkov, 2004).

Another enhancement that could be made to the model is to utilize the GIS to extend the model to include homes in the analysis. For homes, estimates of residential hot water demand could be included and would represent a sink (i.e., a cold stream in the pinch analysis) for additional heat energy that could be captured. If a district heating system was being considered, the waste heat from the stacks could be considered as an energy source to heat the water and ensure that each house is provided with hot water at a temperature of 60°C.

Finally, processes that close the carbon loop could be investigated. For example, technologies for removing CO_2 from stack gas such as monoethanolamine (MEA) absorption and membrane processes exist (Alie, 2004; Bailey and Feron, 2005). In terms of closing the loop on the CO_2, captured CO_2 can be converted to synthesis gas and used as a feedstock to make products such as methanol (Xu et al., 2005; Al-Museabbeh and Al-Shammari, 2006). In this scenario, the heat energy model could be applied, but the additional process units used to condense the stream and convert the CO_2 to methanol could be included in the analysis and compared to conventional means of producing methanol.

5.4 A Nod to Risk

When conducting a macroscopic optimization of any resource use, the concern has been raised regarding industries becoming locked into old technologies (Wolf et al., 2007). The basis for this concern is that if the overall industrial system is optimized based on the inefficient operation of a participating industry, then there would be no incentive for the industry to optimize its own internal operations. In addition, other industries that become dependent on the resources attained from the inefficient industry could be negatively affected by a lack of resource availability should the inefficient industry choose to optimize its internal operations.

Two approaches are presented to address these concerns. The first approach would be to apply the model in a manner that takes into account the internal optimization potential of each industry. The second approach borrows from the concept of connectance in food web analysis as a guiding principle to develop redundancy in water supply so that the overall risk of becoming locked in to old technologies can be reduced.

The first approach would be to incorporate an estimate of internal optimization potential into each analysis. For example, if an industry has undergone extensive internal optimization efforts, a high degree of confidence may be associated with its resource sharing potential. However, if an inefficient operation is identified, estimates can be made regarding the internal optimization potential. For example, if an audit of an industry determines that there is a potential to become 20% more efficient in water use, then this 20 % could be factored into calculations regarding how much water would be required for and available from this industry.

Another approach to minimizing this risk is to include redundancy and diversity of resource supply. Typically, as ecosystems evolve from developmental stages to mature stages: food chains progress from linear to web-like forms; internal symbiosis develops; the amount of information increases; nutrients conservation improves; and the overall stability of the ecosystem improves (Odum, 1969). In food web analysis, the feeding habits of different species are analysed to determine the flow path of energy through the ecosystem. Connectance is the ratio of the number of connections to the number of possible connections among different types of species in the food web. Connectance is calculated as follows (Briand, 1983; Hardy and Graedel, 2002; Graedel and Allenby, 2003):

$$\text{Connectance } (C) = 2 * L / (S*(S-1))$$

Where: L = number of links or connections; and

S = number of different species

Studies suggest that biological ecosystems have an average connectance of approximately 0.42 (Briand and Cohen, 1987). As mature ecosystems tend towards higher rates of nutrient cycling and stability, one would expect that systems with similar connectance levels would indicate similar performance in terms of nutrient cycling and stability or resistance to perturbations. In applying food web analysis to different industrial ecosystems to determine the connectance of industries in terms of raw materials, industrial ecosystems appear to have similar connectance values to biological ecosystems (Hardy and Graedel, 2002). Graedel and Allenby indicate these results are surprising as it is expected that since biological ecosystems are more mature in their evolutionary states than industrial ecosystems, the connectance of the biological ecosystems are expected to be higher (Graedel and Allenby, 2003). The studies conclude that although the broad "feeding habits" of industries may allow for sharing of resources, since connectance considers only the number of connections and not the quantities of resources involved in the connections, then "there may be little value in terms of connectance in designing EIPs with many more than half a dozen industrial organisms". Essentially, this conclusion indicates that when there are many industries involved, although many firms may be connected to some degree by material exchanges, industries use so many different materials that connectance does not really offer any sort of guiding principles as it only measures whether industries are linked in any way.

Conversely, it can be suggested that the application of connectance from the perspective of a single resource may provide different results. Considering that food chain analysis tracks the flow of energy (although in many different forms) through the ecosystem, perhaps a focus on the connectance of a single resource such as energy or water in an industrial ecosystem may prove useful in assessing the stability of their respective systems (i.e., the maturity of either the water system or the energy system).

Consider the water model case study data, the water system consists of 24 industries, 1 water treatment plant, and 1 waste water treatment plant. In the original case where no water is exchanged, each industry is connected to the water treatment plant and the waste water treatment plant. In this case, $S = 26$ and $L = 48$. As such, connectance within the water system is calculated to be 0.15. In terms of ecosystems, this low connectance would reflect a seemingly immature ecosystem. Now, if we consider the results associated with Scenario 1 where all industries are included in the optimization, then L becomes 73 and the connectance increases to 0.22. Although the results do not indicate that the connectance of the water system has reached that of a mature biological ecosystem, it has helped move it in that direction. In terms of risk associated with lock in, connectance of biological ecosystems could provide targets to strive for. For example, in the case study data, to achieve a connectance of approximately 0.42, there would have to be 137 linkages. This could provide a target for identifying where in the system any additional treatment options may be added. This would increase stability in terms of external fluctuations in water supply and ecosystem receiving capacity in that the recycling rate would decrease the amount of water required and wastewater generated. In addition, it would also increase the number of water producers within the system so that consumers would have a diverse group of water providers to choose from in the event that one producer is removed from the system for one reason or another.

In addition to the risk of lock in, in water exchange scenarios, a few other potential risks that are worthwhile noting and would require additional investigation include:

- Quality of supply. In the event that an industry is a producer of water, it must provide water with the agreed upon quality. In this case, a risk arises in that if industrial processes are dependant on water of a certain quality, and contamination changes the water quality, then the industry receiving the water may suffer losses. Mechanisms would need to be in place to guarantee the quality of water; and
- Lack of adequate infrastructure. Conventional municipal sewers are sized and constructed based on estimated volumes of water and sewage contents. In the event that water is reused in the system without additional treatment, the result would be an increase in the concentration of sewage contents and a decrease in the total volume moving through the sewers. A risk arises in that the concentration may have adverse affects on the corrosion of pipes and sewage

transportation problems may increase due to the removal of water from the sewage.

6.0 CONCLUSIONS

The use of water and energy are fundamental prerequisites to industrial operations. In attempting to make the best use of our resources, a focus on water and energy provides a common approach that can be transferred to all regions to engage industrial participants that otherwise, might not connect with each other. From the work presented in this thesis, it can be concluded that:

- More measurement, verification and data collection is required at the intra-organizational level to better understand how water and heat are used within industrial processes;
- Data collected at the intra-organizational level needs to be made available at the inter-organizational level to co-ordinate strategies for resource savings opportunities; and
- The models presented demonstrate a practical approach to uncovering resource sharing opportunities to increase the efficiency of water and heat energy use among industrial participants.

Based on the conclusions above, the following recommendations are made:

- Immediate research should be conducted to determine costs, expertise, available resources, and the scope of work necessary to implement data collection programs among industrial participants; and
- The models could be made more sophisticated by incorporating resource storage capacity, ecological productive and assimilative capacity, and waste treatment options. In addition, since the models currently use annual resource production and demand, actual resource production and demand time profiles would provide more accurate estimates of resource exchange potential.

Current patterns of water and energy use result in more wasted resources then required for the services being provided. This research presents approaches and identifies additional work required to help people make informed decisions about resource use to avoid wasting as much as we currently do. Although the real world application of models such as those presented in this thesis by themselves do not constitute a sustainable approach to resource use, hopefully they will contribute to the development of a piece of one – the piece that seeks to re-shape our existing patterns of water and energy use to account for the fact that our current use patterns cannot be sustained.

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APPENDIX A – Pumping Energy

Appendix A provides details about how the electrical energy associated with pumping water is calculated in this research. As used by Nobel (Nobel, 1998), the work required by a pump used to transport water can be calculated as follows:

$$\eta W_p = \frac{\Delta P}{\rho} + g\Delta z + \left(\frac{\alpha_b v_b^2}{2} - \frac{\alpha_a v_a^2}{2} \right) + 4f \frac{L}{D} \frac{v^2}{2}$$

As per Nobel, the following assumptions are applied:

1. Standard pressure at the inlet and outlet of the pipe, $\frac{\Delta P}{\rho} \Rightarrow 0$
2. Turbulent flow, $f \approx 0.004$
3. Constant pipe diameter, $\frac{\alpha_b v_b^2}{2} - \frac{\alpha_a v_a^2}{2} \Rightarrow 0$
4. Pump efficiency $\eta = 0.65$
5. The acceleration of gravity, g = $9.8 \frac{m}{s^2}$

The diameter, D, of the piping for water transfer between industries was assumed to be 0.15 m (6 inches). The diameter, D, for the water main from the pumphouse was assumed to be 0.25 m (10 inches).

Similar to Nobel, a velocity, v, of 8m/s was chosen for transfer pumping, however, a velocity of 0.6 m/s was used for the velocity of the water being pumped from the pumphouse.

Substituting assumptions 1 and 3 into the work equation allows the work equation to be reduced as follows:

$$W_p\left(\frac{J}{kg}\right) = \frac{g\left(\frac{m}{s^2}\right) \times \Delta Z(m) + \frac{4 \times f \times L(m) \times v^2\left(\frac{m^2}{s^2}\right)}{D(m) \times 2}}{\eta}$$

Note that $1\,J = 1\,N \cdot m = 1\,\frac{kg \cdot m}{s^2} \cdot m$; and therefore, $1\frac{J}{kg} = 1\frac{m^2}{s^2}$.

As such, the work equation can be converted to an electrical energy per volume of water (E) by multiplying the work equation by the density of water, ρ (1000 kg/m^3), and converting Joules to kilowatt-hours (kWh) (i.e., 1 kWh = 3,600, 000 J).

$$\mathrm{E}\left(\frac{kWh}{m^3}\right)=\frac{g\left(\frac{m}{s^2}\right)\times \Delta Z(m)+\dfrac{4\times f\times L(m)\times v^2\left(\frac{m^2}{s^2}\right)}{D(m)\times 2}}{\eta}\times \rho\left(\frac{kg}{m^3}\right)\times\left(\frac{1kWh}{3{,}600{,}000J}\right)$$

Including the assumptions for pumping water between industries, the electrical energy required per volume of water can be reduced as follows:

$$\mathrm{E}\left(\frac{kWh}{m^3}\right)=0.00419\times \Delta Z(m)+0.00146\times L(m)$$

Including the assumptions for pumping water from the pumphouse to the industries, the electrical energy required per volume of water can be reduced as follows:

$$\mathrm{E}\left(\frac{kWh}{m^3}\right)=0.00419\times \Delta Z(m)+0.0000048\times L(m)$$

APPENDIX B – Python Code

Appendix B presents the following:

- A python script titled "PRINT ARRAY". This script is used to search the GIS database file that contains all of the company information and the utility location data. In searching the database file, this script determines:
    - maximum inlet fractions between companies;
    - maximum overall inlet fractions for each company;
    - maximum outlet fractions between companies;
    - maximum overall outlet fractions for each company;
    - energy multipliers from the pumphouse to each company (kWh/m^3);
    - energy multipliers between each company (kWh/m^3);
    - inlet water volume requirements for each company; and
    - outlet water volume generated for each company.

  This information allows the exchange of water to be simulated, forms the constraints for the optimization, and is stored in independent arrays, which are printed as indpendant text files;

- Print outs of the arrays created in "PRINT ARRAY"; and

- A python script titled "PRINT MATLAB". This script formats all of the outputs from PRINT ARRAY for use in the Linprog function (linear programming solver) in Matlab.

```
####File name = PRINT ARRAY
#### This file creates and prints the following arrays:
#### company data from the GIS;
#### maximum inlet fractions between companies;
#### maximum overall inlet fractions for each company;
#### maximum outlet fractions between companies;
#### maximum overall outlet fractions for each company;
#### energy multipliers from the pumphouse to each company (kWh/m3);
#### energy multipliers between each company (kWh/m3);
#### inlet water volume requirements for each company; and
#### outlet water volume generated for each company.


import sys, string, os, win32com.client, pythoncom, math, numpy, scipy
from scipy import *
from scipy.io import write_array

##############################################################################
```

```
####This Section accesses the GIS database, defines the workspace, calls the toolbox
####from ArcGIS and reads in the GIS database file.

pgp = win32com.client.Dispatch("esriGeoprocessing.GpDispatch.1")
pgp.Workspace = "C:\\arcgis\\Eco_Water"
pgp.AddToolbox("C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Data Management
Tools.tbx")
COMPANY__dbf = "C:\\arcgis\\ThesisMap\\MAP\\NobelSME\\ReducedCompInfo.dbf"

##############################################################################
####Make a list which contains all the GIS info.
####Count and store the number of companies in the variable called "Count"
Count = pgp.GetCount(COMPANY__dbf)
####Create a search through the database.
rows = pgp.SearchCursor(COMPANY__dbf)
####Initialize the search.
row = rows.Next()
####Create a list that can be populated with the company information.
company_array = { }
####Populate the list with industry information.
while row:
 name = row.getvalue("NAME")
 company_array[name] = [row.getvalue("NAME"), row.getvalue("CompIN"),
row.getvalue("INTOC"),
                row.getvalue("INTSS"), row.getvalue("INTDS"),
row.getvalue("CompOUT"),
                row.getvalue("OUTTOC"), row.getvalue("OUTTSS"),
row.getvalue("OUTTDS")]
 row = rows.Next()
####Assign a number to correspond with each piece of data and the column that it is in
####the list
NAMEID = 0
h2oin = 1
TocIn = 2
TssIn = 3
TdsIn = 4
h2oout = 5
TocOut = 6
TssOut = 7
TdsOut = 8

###############################################################################
#### Make 2 lists, 1 that has the info for the Pumphouse and one for the rest. #########
#### Since there is one pumphouse in the data named "PUMP", we separate this data
#### from the Industries
Number_of_Properties = 9
```

```
w, h = Number_of_Properties, 1
Pumphouseinfo = [[None]*w for i in range(h)]
COMPANYinfo = {}
matchname = company_array.keys()
Number_of_Pumphouses = 0
for name in matchname:
   column = 0
   if name == "PUMP":
      while column < Number_of_Properties:
         Pumphouseinfo[0][column] = company_array[name][column]
         column += 1
      Number_of_Pumphouses += 1
   else:
      COMPANYinfo[name] = [company_array[name][0], company_array[name][1],
company_array[name][2],
                     company_array[name][3], company_array[name][4],
company_array[name][5],
                     company_array[name][6], company_array[name][7],
company_array[name][8]]
Number_of_Companies = Count - Number_of_Pumphouses
PUMPinfo = numpy.array(Pumphouseinfo)
##############################################################################
####Make 2 lists.  1 list that contains all the distances between the companies and
####another that contains the distances between the pumphouse and the companies
Distance__dbf =
"C:\\arcgis\\ThesisMap\\MAP\\NobelSME\\NobelSMEReducedDist.dbf"
w, h = Number_of_Companies, Number_of_Companies
distancearray = [[0]*w for i in range(h)]
w, h = Number_of_Companies, Number_of_Pumphouses
WTPDistance = [[None]*w for i in range(h)]
row2s = pgp.SearchCursor(Distance__dbf)
row2 = row2s.Next()
while row2:
   if row2.getvalue("OriginID") == 20:
      if row2.getvalue("Destinatio") <= 19:
         distcolumn = row2.getvalue("Destinatio") - 1
         WTPDistance[0][distcolumn] = row2.getvalue("Total_Leng")
      elif row2.getvalue("Destinatio") >= 21:
         distcolumn = row2.getvalue("Destinatio") - 2
         WTPDistance[0][distcolumn] = row2.getvalue("Total_Leng")
   elif row2.getvalue("OriginID") <= 19:
      if row2.getvalue("Destinatio") <= 19:
         distrow = row2.getvalue("OriginID") - 1
         distcolumn = row2.getvalue("Destinatio") - 1
         distancearray[distrow][distcolumn] = row2.getvalue("Total_Leng")
      elif row2.getvalue("Destinatio") >= 21:
```

```
        distrow = row2.getvalue("OriginID") - 2
        distcolumn = row2.getvalue("Destinatio") - 2
        distancearray[distrow][distcolumn] = row2.getvalue("Total_Leng")
  else:
     distrow = row2.getvalue("OriginID") - 2
     distcolumn = row2.getvalue("Destinatio") - 2
     distancearray[distrow][distcolumn] = row2.getvalue("Total_Leng")
  row2 = row2s.Next()

##########################################################################
####Make a list that contains all the Pumping kWh/m3 between companies(energylist)
w, h = Number_of_Companies, Number_of_Companies
energylist = [[None]*w for i in range(h)]
row = 0
matchname = COMPANYinfo.keys()
for name in matchname:
 column = 0
 while column < Number_of_Companies:
####Note that we don't have elevation data so that portion is left out of the energy calc
#### Also, this multiplier is based on a 6" pipe or 150 mm and provides energy in units
#### of kWh  - see APPENDIX A
  energylist[column][row] = 0.00146 * distancearray[row][column]
  column += 1
 row += 1
####Convert the list into an array
Intercompany_transfer_energy_multiplier = numpy.array(energylist)
##########################################################################
####Make a list that contains all the Initial Inlet Pumping kWh/m3 for
####companies(Inletenergylist - it is one column).  SEE APPENDIX A for Calculations
w, h = Number_of_Companies, 1
Inletenergylist = [[None]*w for i in range(h)]
column = 0
row = 0
while row < Number_of_Companies:
 Inletenergylist[0][row] = 0.0000048*WTPDistance[0][row]
 row += 1
Inlet_energy_multiplier = numpy.array(Inletenergylist)
##########################################################################
####OUTLET ENERGY MULTIPLIER kWh/m3- as supplied from page 11 of 17 from -
####http://www.acrwc.ab.ca/Download/Report05.pdf
OutletEnergyMultiplier = 0.327
##########################################################################
####Make a list that contains all the Initial Inlet Total Pumping Energy for
####companies(InletTotalEnergy)
InletTotalEnergy = { }
row = 0
```

```
while row < Number_of_Pumphouses:
 column = 0
 matchname = COMPANYinfo.keys()
 for name in matchname:
  InletTotalEnergy[row, column] = COMPANYinfo[name][h2oin] *
Inletenergylist[0][column]
  column += 1
 row += 1
################################################################################
####Make a list that contains all the Initial Outlet Pumping Total Energy for
companies(OutletTotalEnergy)
OutletTotalEnergy = { }
row = 0
column = 0
matchname = COMPANYinfo.keys()
for name in matchname:
   OutletTotalEnergy[row, column] = COMPANYinfo[name][h2oout] *
OutletEnergyMultiplier
   column += 1

################################################################################
####Make a list that contains all the Initial Pumping Energy for each of the
####companies(InitialEnergy)
InitialEnergy = { }
column = 0
row = 0
while column < Number_of_Companies:
  InitialEnergy[column] = InletTotalEnergy[row, column] + OutletTotalEnergy[row,
column]
  column += 1

################################################################################
####Calculate the Total Initial Pumping Energy for all companies(Total_inital_energy)
row = 0
column = 0
Total_inital_energy = 0
while column < Number_of_Companies:
   Total_inital_energy += InitialEnergy[column]
   column += 1
################################################################################
#### make an array - QINBIG that has all the inlet water volumes. (i.e, number of
#### companies X number of companies). (Each row contains the inlet water volume,
#### number of companies times)
#### Also, make another array (QINSMALL) that is a 1 X number_of_companies array
#### that holds the inlet water amount in a smaller list
row = 0
```

```
w, h = Number_of_Companies, Number_of_Companies
QINBIGs = [[None]*w for i in range(h)]
while row < Number_of_Companies:
   column = 0
   matchname = COMPANYinfo.keys()
   for name in matchname:
      QINBIGs[column][row] = COMPANYinfo[name][h2oin]
      column += 1
   row += 1
w, h = 1, Number_of_Companies
QINSMALLs = [[None]*w for i in range(h)]
column = 0
matchname = COMPANYinfo.keys()
for name in matchname:
   QINSMALLs[column][0] = COMPANYinfo[name][h2oin]
   column += 1
QINBIG = numpy.array(QINBIGs)
QINSMALL = numpy.array(QINSMALLs)

############################################################################
####make an array - QOUTBIG that has all the outlet water volumes. (i.e, number of
####companies X number of companies) (each row contains the outlet water volume,
####number of companies times)
#### Also, make another array (QOUTSMALL)that is a 1 X number of companies array
#### that holds the outlet water amount in a smaller list.
row = 0
w, h = Number_of_Companies, Number_of_Companies
QOUTBIGs = [[None]*w for i in range(h)]
while row < Number_of_Companies:
   column = 0
   matchname = COMPANYinfo.keys()
   for name in matchname:
      QOUTBIGs[column][row] = COMPANYinfo[name][h2oout]
      column += 1
   row += 1
w, h = 1, Number_of_Companies
QOUTSMALLs = [[None]*w for i in range(h)]
column = 0
matchname = COMPANYinfo.keys()
for name in matchname:
   QOUTSMALLs[column][0] = COMPANYinfo[name][h2oout]
   column += 1
QOUTBIG = numpy.array(QOUTBIGs)
QOUTSMALL = numpy.array(QOUTSMALLs)

############################################################################
```

```
#### Assume there are n companies.  Make an nXn list with each row and column
####representing a company where the rows include the amount available to take in BY
####the column company(matcharray).
#### matcharray will be used to determine the maximum fraction of companies output
#### that can be used by other companies.
#### Make another nXn list that contains rows which include the amount available to be
####given TO the row BY the column(matchINarray)
####matchINarray will be used to determine the maximum fraction of a company's input
####that can be substituted by other companies output.
#### i.e matchINarray will provide the upper bound in the optimization.  matcharray will
#### be used as a constraint on the outlet fraction available for use  by other companies.
h2oin = 1
TocIn = 2
TssIn = 3
TdsIn = 4
h2oout = 5
TocOut = 6
TssOut = 7
TdsOut = 8

#### Initialize the march arrays so they can be populated
matcharray = { }
matchINarray = { }
row = 0
matchname =  COMPANYinfo.keys()
for name in matchname:
 column = 0
 matchname2 = COMPANYinfo.keys()
 for name2 in matchname2:
  if COMPANYinfo[name][TocOut] <= COMPANYinfo[name2][TocIn]:
    if COMPANYinfo[name][TssOut] <= COMPANYinfo[name2][TssIn]:
      if COMPANYinfo[name][TdsOut] <= COMPANYinfo[name2][TdsIn]:
        matcharray[row, column] = COMPANYinfo[name2][h2oin]
        matchINarray[column, row] = COMPANYinfo[name][h2oout]
      else:
        matcharray[row, column] = 0
        matchINarray[column, row] = 0
    else:
      matcharray[row, column] = 0
      matchINarray[column, row] = 0
  else:
    matcharray[row, column] = 0
    matchINarray[column, row] = 0

  column += 1
 row += 1
```

```
################################################################################
####Maximum Fractions that can be Shared###############################
#### Make a list that contains all the outlet fractions(out_frac_array) and a list that
####contains inlet fractions(in_frac_array). These are the maximum sharing constraints
#### between individual industries (i.e. nXn).
#### Build another array that stores the maximum inlet (max_in_fractions_array) and
#### outlet fraction (max_out_fractions_array) that is available to share. These are the
#### overall inlet and outlet Constraints (i.e., nX1).

#### initialize the 4 arrays
w, h = Number_of_Companies, Number_of_Companies
in_frac_array = [[None]*w for i in range(h)]
w, h = Number_of_Companies, Number_of_Companies
out_frac_array = [[None]*w for i in range(h)]
w, h = Number_of_Companies, 1
max_in_fractions_array = [[None]*w for i in range(h)]
w, h = Number_of_Companies, 1
max_out_fractions_array = [[None]*w for i in range(h)]
w, h = Number_of_Companies, 1
TotalMaxin1 = [[None]*w for i in range(h)]
maxinfrac = 0
maxoutfrac = 1

##### GET THE OUT FRACTION
row = 0
matchname = COMPANYinfo.keys()
for name in matchname:
 column = 0
 outlet_frac = 0
 matchout = 0
 inlet_frac = 0
 matchin = 0
 while column < Number_of_Companies:
  matchout = matcharray[row, column]
  if float(matchout)/COMPANYinfo[name][h2oout] >= 1.0000:
    out_frac_array[column][row] = 1.0000
  else:   out_frac_array[column][row] = float(matchout)/COMPANYinfo[name][h2oout]

#### This next line keeps track of the total outlet fraction
  outlet_frac += matchout

#### GET THE IN FRACTION
  matchin = matchINarray[row, column]
  if float(matchin)/COMPANYinfo[name][h2oin] >= 1.0000:
    in_frac_array[row][column] = 1.0000
```

```
  else:   in_frac_array[row][column] = float(matchin)/COMPANYinfo[name][h2oin]

#### This next line keeps track of the total inlet fraction
  inlet_frac += matchin
  column += 1

#### This section of code constrains the total outlet and inlet fraction to be less than 1.
 newinlet = float(inlet_frac)
 newoutlet = float(outlet_frac)
 maxin = newinlet/COMPANYinfo[name][h2oin]
 maxout = newoutlet/COMPANYinfo[name][h2oout]
 if maxout >= 1.0:
     max_out_fractions_array[0][row] = 1.0
 elif maxout < 0.009:
     max_out_fractions_array[0][row] = 0.0
 else:  max_out_fractions_array[0][row] = maxout

 if maxin >= 1.0:
    max_in_fractions_array[0][row] = 1.0
    TotalMaxin1[0][row] = maxin
 elif maxin < 0.009:
    max_in_fractions_array[0][row] = 0.0
    TotalMaxin1[0][row] = 1
 else:
    max_in_fractions_array[0][row] = maxin
    TotalMaxin1[0][row] = maxin
 row += 1

####Convert all the lists to arrays
INfractions = numpy.array(in_frac_array)
OUTfractions = numpy.array(out_frac_array)
maxINfractions = numpy.array(max_in_fractions_array)
maxOUTfractions = numpy.array(max_out_fractions_array)

#########################################################################
#### Print all arrays to data files so that they can be evaluated prior to optimization

write_array('C:\\arcgis\\Eco_Water\\dataFiles\\NobelSME\\ReducedSet\CompanyInfo.dat
', printcompanyinfos)
write_array('C:\\arcgis\\Eco_Water\\dataFiles\\NobelSME\\ReducedSet\Infractions.dat',
INfractions)
write_array('C:\\arcgis\\Eco_Water\\dataFiles\\NobelSME\\ReducedSet\QINBIG.dat',
QINBIG)
write_array('C:\\arcgis\\Eco_Water\\dataFiles\\NobelSME\\ReducedSet\QINSMALL.dat',
QINSMALL)
```

```
write_array('C:\\arcgis\\Eco_Water\\dataFiles\\NobelSME\\ReducedSet\QOUTBIG.dat', QOUTBIG)
write_array('C:\\arcgis\\Eco_Water\\dataFiles\\NobelSME\\ReducedSet\QOUTSMALL.dat', QOUTSMALL)
write_array('C:\\arcgis\\Eco_Water\\dataFiles\\NobelSME\\ReducedSet\OUTfractions.dat', OUTfractions)
write_array('C:\\arcgis\\Eco_Water\\dataFiles\\NobelSME\\ReducedSet\maxINfractions.dat', maxINfractions)
write_array('C:\\arcgis\\Eco_Water\\dataFiles\\NobelSME\\ReducedSet\maxOUTfractions.dat', maxOUTfractions)
write_array('C:\\arcgis\\Eco_Water\\dataFiles\\NobelSME\\ReducedSet\TransferEnergy.dat', Intercompany_transfer_energy_multiplier)
write_array('C:\\arcgis\\Eco_Water\\dataFiles\\NobelSME\\ReducedSet\InletEnergy.dat', Inlet_energy_multiplier)
```
$$END PRINT ARRAY

OUTPUTS FROM PRINT ARRAY

CompanyInfo.dat

Name	Inlet Water Requirements				Effluent Characteristics			
	Qin (m^3/year)	TOC (mg/m^3)	TSS (mg/m^3)	TDS (mg/m^3)	Qout (m^3/year)	TOC (mg/m^3)	TSS (mg/m^3)	TDS (mg/m^3)
SME1	228	45	45	2500	366	5000	5000	5000
SME2	742	45	45	2500	1188	5000	5000	5000
SME3	50	45	45	2500	80	5000	5000	5000
N6	1354042	20	100	500	1083233	22	14	1948
N7	1372004	50	100	2500	1097603	375	1619	10220
N8	136786	50	100	2500	109429	215	2657	7176
SME4	102	45	45	2500	164	5000	5000	5000
SME5	111	45	45	2500	178	5000	5000	5000
N9	200343	20	100	500	160274	32	29	2388
SME6	692	45	45	2500	1108	5000	5000	5000
N11	501548	50	200	1000	401239	1930	29	4204
N12	185144	50	200	1000	148116	2223	212	41020
SME7	1367	45	45	2500	2188	5000	5000	5000
N13	1308447	50	200	1000	1046757	484	105	904
N14	389632	50	200	1000	311706	431	60	1240
N15	205870	50	200	1000	164696	146	256	740
N16	75992	50	200	1000	60794	1695	795	2324
N17	111916	50	200	1000	89533	3869	257	8960
N18	352327	20	50	450	281862	46	50	536
SME18	672	45	45	2500	1075	5000	5000	5000
SME35	1193	45	45	2500	1909	5000	5000	5000
SME36	931	45	45	2500	1490	5000	5000	5000
SME41	222	45	45	2500	356	5000	5000	5000
SME51	1092	45	45	2500	1748	5000	5000	5000

Infractions.dat (fraction of Qin (y) that can be obtained from another industry)

				N6					N9										N18					
SME1	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SME2	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SME3	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N7	0	0	0	0.790	0	0	0	0	0.117	0	0	0	0	0	0	0	0	0	0.205	0	0	0	0	0
N8	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
SME4	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SME5	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SME6	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.562	0	0	0	0	0
N12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
SME7	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.215	0	0	0	0	0
N14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.723	0	0	0	0	0
N15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
N16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
N17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
N18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SME18	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SME35	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SME36	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SME41	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SME51	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

QINBIG.dat (a 24x24 matrix that contains the Qin in m^3 for each industry in each row)

228	742	50	1354042	1372004	136786	102	111	200343	692	501548	185144	1367	1308447	389632	205870	75992	111916	352327	672	1193	931	222	1092
228	742	50	1354042	1372004	136786	102	111	200343	692	501548	185144	1367	1308447	389632	205870	75992	111916	352327	672	1193	931	222	1092
228	742	50	1354042	1372004	136786	102	111	200343	692	501548	185144	1367	1308447	389632	205870	75992	111916	352327	672	1193	931	222	1092
228	742	50	1354042	1372004	136786	102	111	200343	692	501548	185144	1367	1308447	389632	205870	75992	111916	352327	672	1193	931	222	1092
228	742	50	1354042	1372004	136786	102	111	200343	692	501548	185144	1367	1308447	389632	205870	75992	111916	352327	672	1193	931	222	1092
228	742	50	1354042	1372004	136786	102	111	200343	692	501548	185144	1367	1308447	389632	205870	75992	111916	352327	672	1193	931	222	1092
228	742	50	1354042	1372004	136786	102	111	200343	692	501548	185144	1367	1308447	389632	205870	75992	111916	352327	672	1193	931	222	1092
228	742	50	1354042	1372004	136786	102	111	200343	692	501548	185144	1367	1308447	389632	205870	75992	111916	352327	672	1193	931	222	1092
228	742	50	1354042	1372004	136786	102	111	200343	692	501548	185144	1367	1308447	389632	205870	75992	111916	352327	672	1193	931	222	1092
228	742	50	1354042	1372004	136786	102	111	200343	692	501548	185144	1367	1308447	389632	205870	75992	111916	352327	672	1193	931	222	1092
228	742	50	1354042	1372004	136786	102	111	200343	692	501548	185144	1367	1308447	389632	205870	75992	111916	352327	672	1193	931	222	1092
228	742	50	1354042	1372004	136786	102	111	200343	692	501548	185144	1367	1308447	389632	205870	75992	111916	352327	672	1193	931	222	1092
228	742	50	1354042	1372004	136786	102	111	200343	692	501548	185144	1367	1308447	389632	205870	75992	111916	352327	672	1193	931	222	1092
228	742	50	1354042	1372004	136786	102	111	200343	692	501548	185144	1367	1308447	389632	205870	75992	111916	352327	672	1193	931	222	1092
228	742	50	1354042	1372004	136786	102	111	200343	692	501548	185144	1367	1308447	389632	205870	75992	111916	352327	672	1193	931	222	1092
228	742	50	1354042	1372004	136786	102	111	200343	692	501548	185144	1367	1308447	389632	205870	75992	111916	352327	672	1193	931	222	1092
228	742	50	1354042	1372004	136786	102	111	200343	692	501548	185144	1367	1308447	389632	205870	75992	111916	352327	672	1193	931	222	1092
228	742	50	1354042	1372004	136786	102	111	200343	692	501548	185144	1367	1308447	389632	205870	75992	111916	352327	672	1193	931	222	1092
228	742	50	1354042	1372004	136786	102	111	200343	692	501548	185144	1367	1308447	389632	205870	75992	111916	352327	672	1193	931	222	1092
228	742	50	1354042	1372004	136786	102	111	200343	692	501548	185144	1367	1308447	389632	205870	75992	111916	352327	672	1193	931	222	1092
228	742	50	1354042	1372004	136786	102	111	200343	692	501548	185144	1367	1308447	389632	205870	75992	111916	352327	672	1193	931	222	1092
228	742	50	1354042	1372004	136786	102	111	200343	692	501548	185144	1367	1308447	389632	205870	75992	111916	352327	672	1193	931	222	1092
228	742	50	1354042	1372004	136786	102	111	200343	692	501548	185144	1367	1308447	389632	205870	75992	111916	352327	672	1193	931	222	1092
228	742	50	1354042	1372004	136786	102	111	200343	692	501548	185144	1367	1308447	389632	205870	75992	111916	352327	672	1193	931	222	1092

QOUTBIG (a 24x24 matrix that contains the Qout in m^3 for each industry in each row)

366	1188	80	1083233	1097603	109429	164	178	160274	1108	401239	148116	2188	1046757	311706	164696	60794	89533	281862	1075	1909	1490	356	1748
366	1188	80	1083233	1097603	109429	164	178	160274	1108	401239	148116	2188	1046757	311706	164696	60794	89533	281862	1075	1909	1490	356	1748
366	1188	80	1083233	1097603	109429	164	178	160274	1108	401239	148116	2188	1046757	311706	164696	60794	89533	281862	1075	1909	1490	356	1748
366	1188	80	1083233	1097603	109429	164	178	160274	1108	401239	148116	2188	1046757	311706	164696	60794	89533	281862	1075	1909	1490	356	1748
366	1188	80	1083233	1097603	109429	164	178	160274	1108	401239	148116	2188	1046757	311706	164696	60794	89533	281862	1075	1909	1490	356	1748
366	1188	80	1083233	1097603	109429	164	178	160274	1108	401239	148116	2188	1046757	311706	164696	60794	89533	281862	1075	1909	1490	356	1748
366	1188	80	1083233	1097603	109429	164	178	160274	1108	401239	148116	2188	1046757	311706	164696	60794	89533	281862	1075	1909	1490	356	1748
366	1188	80	1083233	1097603	109429	164	178	160274	1108	401239	148116	2188	1046757	311706	164696	60794	89533	281862	1075	1909	1490	356	1748
366	1188	80	1083233	1097603	109429	164	178	160274	1108	401239	148116	2188	1046757	311706	164696	60794	89533	281862	1075	1909	1490	356	1748
366	1188	80	1083233	1097603	109429	164	178	160274	1108	401239	148116	2188	1046757	311706	164696	60794	89533	281862	1075	1909	1490	356	1748
366	1188	80	1083233	1097603	109429	164	178	160274	1108	401239	148116	2188	1046757	311706	164696	60794	89533	281862	1075	1909	1490	356	1748
366	1188	80	1083233	1097603	109429	164	178	160274	1108	401239	148116	2188	1046757	311706	164696	60794	89533	281862	1075	1909	1490	356	1748
366	1188	80	1083233	1097603	109429	164	178	160274	1108	401239	148116	2188	1046757	311706	164696	60794	89533	281862	1075	1909	1490	356	1748
366	1188	80	1083233	1097603	109429	164	178	160274	1108	401239	148116	2188	1046757	311706	164696	60794	89533	281862	1075	1909	1490	356	1748
366	1188	80	1083233	1097603	109429	164	178	160274	1108	401239	148116	2188	1046757	311706	164696	60794	89533	281862	1075	1909	1490	356	1748
366	1188	80	1083233	1097603	109429	164	178	160274	1108	401239	148116	2188	1046757	311706	164696	60794	89533	281862	1075	1909	1490	356	1748
366	1188	80	1083233	1097603	109429	164	178	160274	1108	401239	148116	2188	1046757	311706	164696	60794	89533	281862	1075	1909	1490	356	1748
366	1188	80	1083233	1097603	109429	164	178	160274	1108	401239	148116	2188	1046757	311706	164696	60794	89533	281862	1075	1909	1490	356	1748
366	1188	80	1083233	1097603	109429	164	178	160274	1108	401239	148116	2188	1046757	311706	164696	60794	89533	281862	1075	1909	1490	356	1748
366	1188	80	1083233	1097603	109429	164	178	160274	1108	401239	148116	2188	1046757	311706	164696	60794	89533	281862	1075	1909	1490	356	1748
366	1188	80	1083233	1097603	109429	164	178	160274	1108	401239	148116	2188	1046757	311706	164696	60794	89533	281862	1075	1909	1490	356	1748
366	1188	80	1083233	1097603	109429	164	178	160274	1108	401239	148116	2188	1046757	311706	164696	60794	89533	281862	1075	1909	1490	356	1748
366	1188	80	1083233	1097603	109429	164	178	160274	1108	401239	148116	2188	1046757	311706	164696	60794	89533	281862	1075	1909	1490	356	1748
366	1188	80	1083233	1097603	109429	164	178	160274	1108	401239	148116	2188	1046757	311706	164696	60794	89533	281862	1075	1909	1490	356	1748

OUTfractions.dat (fraction of Qout (x) that can be shared with another industry)

0	0	0	0.00021	0	0	0	0	0.00142	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0.00068	0	0	0	0	0.00463	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0.00005	0	0	0	0	0.00031	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
0	0	0	0.12628	0	0	0	0	0.85345	0	0	0	0	0	0	0	0	0	0.48529	0	0	0	0	0
0	0	0	0.00009	0	0	0	0	0.00064	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0.00010	0	0	0	0	0.00069	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0.00064	0	0	0	0	0.00432	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.65686	0	0	0	0	0
0	0	0	0.00126	0	0	0	0	0.00853	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.73039	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.26961	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.39706	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0.00062	0	0	0	0	0.00419	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0.00110	0	0	0	0	0.00744	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0.00086	0	0	0	0	0.00581	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0.00020	0	0	0	0	0.00139	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0.00101	0	0	0	0	0.00681	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

maxINfractions.dat (Maximum fraction of Qin (Σy – also called ymax) that can be obtained from another industry)

1	1	1	0	1	1	1	1	0	1	0.56198	1	1	0.21542	0.72341	1	1	1	0	1	1	1	1	1

maxOUTfractions.dat (Maximum fraction of Qout (Σx – also called xmax) that can be shared with another industry)

0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0

TransferEnergy.dat (kWh/m^3 – between each industry industries)

0.000	0.076	0.165	0.256	0.192	0.233	0.538	0.57	0.663	0.194	0.408	0.519	0.335	0.557	0.146	0.425	0.370	0.265	0.360	0.342	0.473	0.340	0.442	0.136
0.076	0.000	0.242	0.332	0.268	0.309	0.614	0.65	0.740	0.117	0.484	0.596	0.411	0.633	0.069	0.501	0.447	0.342	0.436	0.419	0.550	0.417	0.518	0.212
0.165	0.242	0.000	0.091	0.026	0.068	0.372	0.41	0.498	0.359	0.242	0.354	0.169	0.391	0.311	0.259	0.205	0.100	0.194	0.177	0.308	0.175	0.276	0.030
0.256	0.332	0.091	0.000	0.064	0.047	0.360	0.35	0.441	0.450	0.152	0.379	0.214	0.301	0.402	0.181	0.215	0.009	0.104	0.156	0.217	0.155	0.198	0.120
0.192	0.268	0.026	0.064	0.000	0.041	0.353	0.39	0.479	0.385	0.216	0.335	0.150	0.365	0.337	0.240	0.186	0.074	0.168	0.150	0.281	0.149	0.257	0.056
0.233	0.309	0.068	0.047	0.041	0.000	0.394	0.4	0.488	0.427	0.199	0.376	0.191	0.324	0.379	0.228	0.227	0.056	0.151	0.109	0.240	0.108	0.245	0.097
0.538	0.614	0.372	0.360	0.353	0.394	0.000	0.03	0.125	0.731	0.449	0.018	0.219	0.598	0.684	0.180	0.234	0.351	0.257	0.504	0.514	0.502	0.163	0.402
0.572	0.649	0.407	0.350	0.388	0.397	0.034	0	0.091	0.766	0.439	0.053	0.253	0.588	0.718	0.170	0.224	0.341	0.247	0.507	0.505	0.505	0.153	0.437
0.663	0.740	0.498	0.441	0.479	0.488	0.125	0.09	0.000	0.857	0.530	0.144	0.344	0.679	0.809	0.261	0.315	0.432	0.338	0.598	0.596	0.596	0.244	0.528
0.194	0.117	0.359	0.450	0.385	0.427	0.731	0.77	0.857	0.000	0.601	0.713	0.528	0.548	0.048	0.618	0.564	0.459	0.553	0.536	0.632	0.534	0.635	0.329
0.408	0.484	0.242	0.152	0.216	0.199	0.449	0.44	0.530	0.601	0.000	0.467	0.355	0.149	0.553	0.269	0.304	0.142	0.192	0.182	0.065	0.184	0.286	0.272
0.519	0.596	0.354	0.379	0.335	0.376	0.018	0.05	0.144	0.713	0.467	0.000	0.200	0.617	0.665	0.198	0.236	0.369	0.275	0.485	0.533	0.484	0.181	0.384
0.335	0.411	0.169	0.214	0.150	0.191	0.219	0.25	0.344	0.528	0.355	0.200	0.000	0.504	0.480	0.106	0.051	0.224	0.163	0.300	0.421	0.299	0.123	0.199
0.557	0.633	0.391	0.301	0.365	0.324	0.598	0.59	0.679	0.548	0.149	0.617	0.504	0.000	0.596	0.418	0.453	0.292	0.341	0.215	0.084	0.216	0.435	0.421
0.146	0.069	0.311	0.402	0.337	0.379	0.684	0.72	0.809	0.048	0.553	0.665	0.480	0.596	0.000	0.570	0.516	0.411	0.505	0.488	0.619	0.486	0.587	0.281
0.425	0.501	0.259	0.181	0.240	0.228	0.180	0.17	0.261	0.618	0.269	0.198	0.106	0.418	0.570	0.000	0.054	0.171	0.077	0.337	0.335	0.335	0.017	0.289
0.370	0.447	0.205	0.215	0.186	0.227	0.234	0.22	0.315	0.564	0.304	0.236	0.051	0.453	0.516	0.054	0.000	0.206	0.112	0.336	0.369	0.334	0.071	0.235
0.265	0.342	0.100	0.009	0.074	0.056	0.351	0.34	0.432	0.459	0.142	0.369	0.224	0.292	0.411	0.171	0.206	0.000	0.094	0.166	0.208	0.164	0.188	0.130
0.360	0.436	0.194	0.104	0.168	0.151	0.257	0.25	0.338	0.553	0.192	0.275	0.163	0.341	0.505	0.077	0.112	0.094	0.000	0.260	0.258	0.258	0.094	0.224
0.342	0.419	0.177	0.156	0.150	0.109	0.504	0.51	0.598	0.536	0.182	0.485	0.300	0.215	0.488	0.337	0.336	0.166	0.260	0.000	0.131	0.002	0.354	0.206
0.473	0.550	0.308	0.217	0.281	0.240	0.514	0.51	0.596	0.632	0.065	0.533	0.421	0.084	0.619	0.335	0.369	0.208	0.258	0.131	0.000	0.133	0.352	0.337
0.340	0.417	0.175	0.155	0.149	0.108	0.502	0.51	0.596	0.534	0.184	0.484	0.299	0.216	0.486	0.335	0.334	0.164	0.258	0.002	0.133	0.000	0.352	0.205
0.442	0.518	0.276	0.198	0.257	0.245	0.163	0.15	0.244	0.635	0.286	0.181	0.123	0.435	0.587	0.017	0.071	0.188	0.094	0.354	0.352	0.352	0.000	0.306
0.136	0.212	0.030	0.120	0.056	0.097	0.402	0.44	0.528	0.329	0.272	0.384	0.199	0.421	0.281	0.289	0.235	0.130	0.224	0.206	0.337	0.205	0.306	0.000

InletEnergy.dat' (kWh/m^3 – from pumphouse to industries)

0.038
0.044
0.025
0.029
0.024
0.027
0.012
0.014
0.021
0.053
0.039
0.01
0.014
0.051
0.049
0.02
0.016
0.029
0.025
0.035
0.044
0.035
0.022
0.027

```
####File name = PRINT MATLAB
#### This File prints the following in Matlab format:
#### vector ub (upper bounds);
#### vector lb (lower bounds);
#### vector b (constraints);
#### vector (-)f (this contains all the inlet water requirements (objective scalers that are
#### multiplied by negative 1 as linprog finds the minimum of the function f*x – See
#### Appendix C); and
#### matrix A which gets multiplied by x such that A*x <=b – i.e., conditions that the
####constraints are applied to (maximum outlet fractions, maximum overall inlet
####fractions, maximum overall outlet fractions, and energy constraints).

#################################################################
import sys, string, os, win32com.client, pythoncom, math, numpy, scipy, fpformat
from scipy import *
from scipy.io import write_array
from scipy.io import read_array

####Read in all the arrays that were printed with the last code
Number_of_Companies = 24

INfractions1 =
read_array('C:\\arcgis\\Eco_Water\\dataFiles\\NobelSME\\ReducedSet\Infractions.dat')
QINBIG1 =
read_array('C:\\arcgis\\Eco_Water\\dataFiles\\NobelSME\\ReducedSet\QINBIG.dat')
QINSMALL1 =
read_array('C:\\arcgis\\Eco_Water\\dataFiles\\NobelSME\\ReducedSet\QINSMALL.dat')
QOUTBIG1 =
read_array('C:\\arcgis\\Eco_Water\\dataFiles\\NobelSME\\ReducedSet\QOUTBIG.dat')
QOUTSMALL1 =
read_array('C:\\arcgis\\Eco_Water\\dataFiles\\NobelSME\\ReducedSet\QOUTSMALL.da
t')
OUTfractions1 =
read_array('C:\\arcgis\\Eco_Water\\dataFiles\\NobelSME\\ReducedSet\OUTfractions.dat'
)
maxINfractions1 =
read_array('C:\\arcgis\\Eco_Water\\dataFiles\\NobelSME\\ReducedSet\maxINfractions.d
at')
maxOUTfractions1 =
read_array('C:\\arcgis\\Eco_Water\\dataFiles\\NobelSME\\ReducedSet\maxOUTfractions
.dat')
Intercompany_transfer_energy_multiplier =
read_array('C:\\arcgis\\Eco_Water\\dataFiles\\NobelSME\\ReducedSet\TransferEnergy.d
at')
```

```
Inlet_energy_multiplier1 =
read_array('C:\\arcgis\\Eco_Water\\dataFiles\\NobelSME\\ReducedSet\InletEnergy_with
Outlet.dat')
InletEnergy = numpy.ravel(Inlet_energy_multiplier1)

################################################################################
####Optional but can specify a required %energy reduction in the new scenario
PercentReduce = 21
##OUTLET ENERGY MULTIPLIER kWh/m3- as supplied from page 11 of 17 from -
##http://www.acrwc.ab.ca/Download/Report05.pdf
OutletEnergyMultiplier = 0.327

################################################################################
#### Reshape the arrays that were read in

InitialGuessarray = numpy.reshape(InitialGuessarray1, (Number_of_Companies,
Number_of_Companies))
QOUTBIG2 = numpy.reshape(QOUTBIG1, (Number_of_Companies,
Number_of_Companies))
QINBIG2 = numpy.reshape(QINBIG1, (Number_of_Companies,
Number_of_Companies))
QINBIG = numpy.array(QINBIG2)
INfractions3 = numpy.reshape(INfractions1, (Number_of_Companies,
Number_of_Companies))
row = 0
h, w = Number_of_Companies, Number_of_Companies
Infractions = [[0.0]*w for i in range(h)]
while row < Number_of_Companies:
   column = 0
   while column < Number_of_Companies:
      Infractions[row][column] = INfractions3[row][column]
      column += 1
   row += 1
INfractions = numpy.array(Infractions)
Yoriginal2 = numpy.copy(INfractions)
Yoriginal = numpy.ravel(Yoriginal2)

OUTfractions3 = numpy.reshape(OUTfractions1, (Number_of_Companies,
Number_of_Companies))
row = 0
h, w = Number_of_Companies, Number_of_Companies
Outfractions = [[0.0]*w for i in range(h)]
while row < Number_of_Companies:
   column = 0
   while column < Number_of_Companies:
      Outfractions[row][column] = OUTfractions3[row][column]
```

```
        column += 1
    row += 1
OUTfractions = numpy.array(Outfractions)
outfracs2 = numpy.copy(OUTfractions)
outfracs = numpy.ravel(outfracs2)

row = 0
h, w = Number_of_Companies, Number_of_Companies
QOUTBIGS = [[None]*w for i in range(h)]
while row < Number_of_Companies:
    column = 0
    while column < Number_of_Companies:
        QOUTBIGS[column][row] = QOUTBIG2[row][column]
        column += 1
    row += 1
QOUTBIG = numpy.array(QOUTBIGS)
QOUTBIGRavelled = numpy.ravel(QOUTBIG)
Qin_QOUT_Ratio1 = QINBIG / QOUTBIG
QIN_QOUT_Ratio = numpy.ravel(Qin_QOUT_Ratio1)
QINBIGCOPY = QINBIG
QINBIGCONSTRAINT = numpy.ravel(QINBIGCOPY)

#####################################################
##ADDED as QINBIG needs to be flipped – [In1, In1; In2, In2; etc] (note that ; means
##new row) needs to be flipped to [In1, In2; In1, In2; etc] to calculate
##QIN_QOUT_RatioFLIP coming up
h, w = Number_of_Companies, Number_of_Companies
QINBIGFLIP = [[None]*w for i in range(h)]
row = 0
while row < Number_of_Companies:
    column = 0
    while column < Number_of_Companies:
        QINBIGFLIP[column][row] = QINBIG[row][column]
        column += 1
    row += 1
QINBIGFLIP1 = numpy.array(QINBIGFLIP)
QINBIGCONSTRAINT2 = numpy.ravel(QINBIGFLIP)

#################################################
### added because Qin_QOUT_RatioFLIP contains all the Ij  / Ok
### See equation
h, w = Number_of_Companies, Number_of_Companies
QOUTBIGFLIP = [[None]*w for i in range(h)]
row = 0
while row < Number_of_Companies:
    column = 0
```

```
    while column < Number_of_Companies:
        QOUTBIGFLIP[column][row] = QOUTBIG[row][column]
        column += 1
    row += 1
QOUTBIGFLIP1 = numpy.array(QOUTBIGFLIP)
Qin_QOUT_RatioFLIPPER = QINBIGFLIP1 / QOUTBIG2
Qin_QOUT_RatioFLIP = numpy.ravel(Qin_QOUT_RatioFLIPPER)

################################################################################
####################################
#### NOW WE NEED TO CONVERT EVERYTHING TO Matlab format
################################################################################
NumberYcons = Number_of_Companies * Number_of_Companies
NumberXcons = Number_of_Companies * Number_of_Companies
NumberTotalYcons = Number_of_Companies
NumberTotalXcons = Number_of_Companies
NumberYnonneg = Number_of_Companies*Number_of_Companies
constraints_length = NumberYcons + NumberXcons + NumberTotalYcons +
NumberTotalXcons + 1 + NumberYnonneg
number = 0

################################################################################
####################################
## first print out the objective scalers (i.e. - QINBIG)
matf = 0
f = "f = [-" + str(QINBIGCONSTRAINT2[matf]) + "; "
while matf < NumberYcons - 2:
    matf += 1
    f += "-" + str(QINBIGCONSTRAINT2[matf]) + "; "
matf += 1
f += "-" + str(QINBIGCONSTRAINT2[matf]) + "]"
print f

################################################################################
#### Now print the lower and upper bounds
#### Lower bound = 0
print "lb = zeros(" + str(NumberYcons) + ",1);"

################################################################################
#### Upper bound – i.e., upperbound = inlet fractions from the last code which has been
#### named Yoriginal in this code
matub = 0
ub = "ub = [" + str(Yoriginal[matub]) + "; "
while matub < NumberYcons - 2:
    matub += 1
    ub += str(Yoriginal[matub]) + "; "
```

```
matub += 1
ub += str(Yoriginal[matub]) + "]"
print ub
##############################################################################
###### NOW MAKE THE 'A' Matrix
######First - add the x constraints - i.e., the ratio of in to out (xj,k = yj,k *( Ij / Ok)
######(EQUATION 10)
###### Qin_QOUT_RatioFLIP contains all the Ij / Ok
###### This builds a list that is 576*576 units long.  Imagine an 576 by 576 matrix.
A1a = [0] * NumberYcons * NumberYcons
counter = 0
while counter < NumberYcons:
   A1a[counter * NumberYcons + counter] = Qin_QOUT_RatioFLIP[counter]
   counter += 1

######second - add the summed y constraints - i.e., a list that is 24* 576 units long to
###### (EQUATION 9)
######represent a 24 by 576 matrix
A2a = [0] * NumberYcons * Number_of_Companies
counter = 0
counter2 = 0
while counter2 <= NumberYcons - 1:
   counter3 = 0
   while counter3 < Number_of_Companies:
      A2a[counter * NumberYcons + counter2] = 1
      counter2 += 1
      counter3 += 1
   counter += 1

######third - add the summed x constraints - i.e., a list that is 24* 576 units long to
######(EQUATION 11)
######represent a 24 by 576 matrix
A3a = [0] * NumberYcons * Number_of_Companies
counter = 0
counter2 = 0
while counter2 < NumberYcons:
   counter3 = 0
   while counter3 < Number_of_Companies:
      A3a[counter * NumberYcons + counter3 * Number_of_Companies + counter] =
QIN_QOUT_RatioFLIP[counter * Number_of_Companies + counter3]
      counter2 += 1
      counter3 += 1
   counter += 1
##############################################################################
######################################
```

```
####FOURTH - add the energy constraint coefficients - i.e., a list that is 1 x 576 units
#### long to represent a 1 by 576 matrix.  This is the difference between the transfer
####energy and the energy required to get the water from the pumphouse and dispose of
#### it.
####Left Hand Side of EQUATION 18

InitialEnergy = 0.0
counter  = 0
while counter < Number_of_Companies:
   InitialEnergy += QOUTBIG[counter][0] * InletEnergy[counter] / 0.8
   counter += 1

A4a = [0] * NumberYcons
counter = 0
counter2 = 0
counter3 = 0
while counter2 < NumberYcons:
   A4a[counter2] = QINBIGCONSTRAINT2[counter2] * TransferEnergy[counter2] -
((InletEnergy[counter] - .8 * OutletEnergyMultiplier ) * QOUTBIGRavelled[counter2] /
0.8 ) - (OutletEnergyMultiplier * QINBIGCONSTRAINT2[counter2])
   counter3 += 1
   counter2 += 1
   if counter3 == Number_of_Companies:
      counter += 1
      counter3 = 0


A3 = A1a + A2a +A3a +A4a
#####Now format the matrix for Matlab
matA = 0
A = "A = [" + str(A3[matA])
count = 1
count2 = 0
while matA < NumberYcons * Number_of_Companies + NumberYcons * NumberYcons
+ NumberYcons * Number_of_Companies + NumberYcons - 1:
   matA += 1
   A += " " + str(A3[matA])
   count += 1
   if count == NumberYcons:
     count2 += 1
     if count2 != NumberYcons + Number_of_Companies + Number_of_Companies + 1:
        A += ";"
        count  = 0
A += "]"
print A
```

```
##############################################################################
###### NOW MAKE THE b vector.

sumINfracs = numpy.ravel(maxINfractions1)
sumOUTfracs = numpy.ravel(maxOUTfractions1)

b = "b = ["

count = 0
###### Add the constraint on each outlet fraction
while count < NumberYcons:
   b += str(outfracs[count]) + "; "
   count += 1
count = 0
###### Add the constraint on each inlet fraction
while count < Number_of_Companies:
   b += str(sumINfracs[count]) + "; "
   count += 1
count = 0
while count < Number_of_Companies - 1:
   b += str(sumOUTfracs[count]) + "; "
   count += 1
b += str(sumOUTfracs[count]) + "; "
###############################
counter = 0
counter2 = 0
FinalE1 = 0
FinalE2 = 0
while counter < Number_of_Companies:
   FinalE1 += ((InletEnergy[counter] - .8 * OutletEnergyMultiplier ) *
QOUTBIG[counter][0] / 0.8 )
   FinalE2 += OutletEnergyMultiplier * QOUTBIG[counter][0]
   counter += 1
   counter2 += Number_of_Companies

b += str( (1.0 - float(PercentReduce) / 100) * InitialEnergy - FinalE1 - FinalE2)  + "]"
print b
```

$$End of PRINT MATLAB

APPENDIX C – MATLAB Linprog Function Call

This Appendix provides the Matlab syntax. The outputs from Appendix B are used as follows:

Function: linprog
Description: linprog solves linear programming problems
Equation:
Finds the minimum of a problem specified by

$$\min_x f^T x \cdot such \cdot that \begin{cases} A \cdot x \leq b \\ Aeq \cdot x = beq \\ lb \leq x \leq ub \end{cases}$$

Where f, x, b, beq, lb, and ub are vectors, and A and Aeq are matrices.
f = Linear objective function vector f
Aeq = Matrix for linear equality constraints
beq = Vector for linear equality constraints
lb = Vector of lower bounds
ub = Vector of upper bounds

Syntax
x = linprog(f,A,b,Aeq,beq,lb,ub)

where
x = linprog(f,A,b,Aeq,beq,lb,ub) defines a set of lower and upper bounds on the design variables, x, so that the solution is always in the range lb ≤ x ≤ ub. Set Aeq = [] and beq = [] if no equalities exist.

[x,fval] = linprog(...) returns the value of the objective function fun at the solution x: fval = f'*x.

This information can be accessed online from
http://www.mathworks.com/access/helpdesk/help/toolbox/optim/index.html?/access/helpdesk/help/toolbox/optim/ug/bqnk0r0.html&http://www.mathworks.com/products/optimization/description5.html

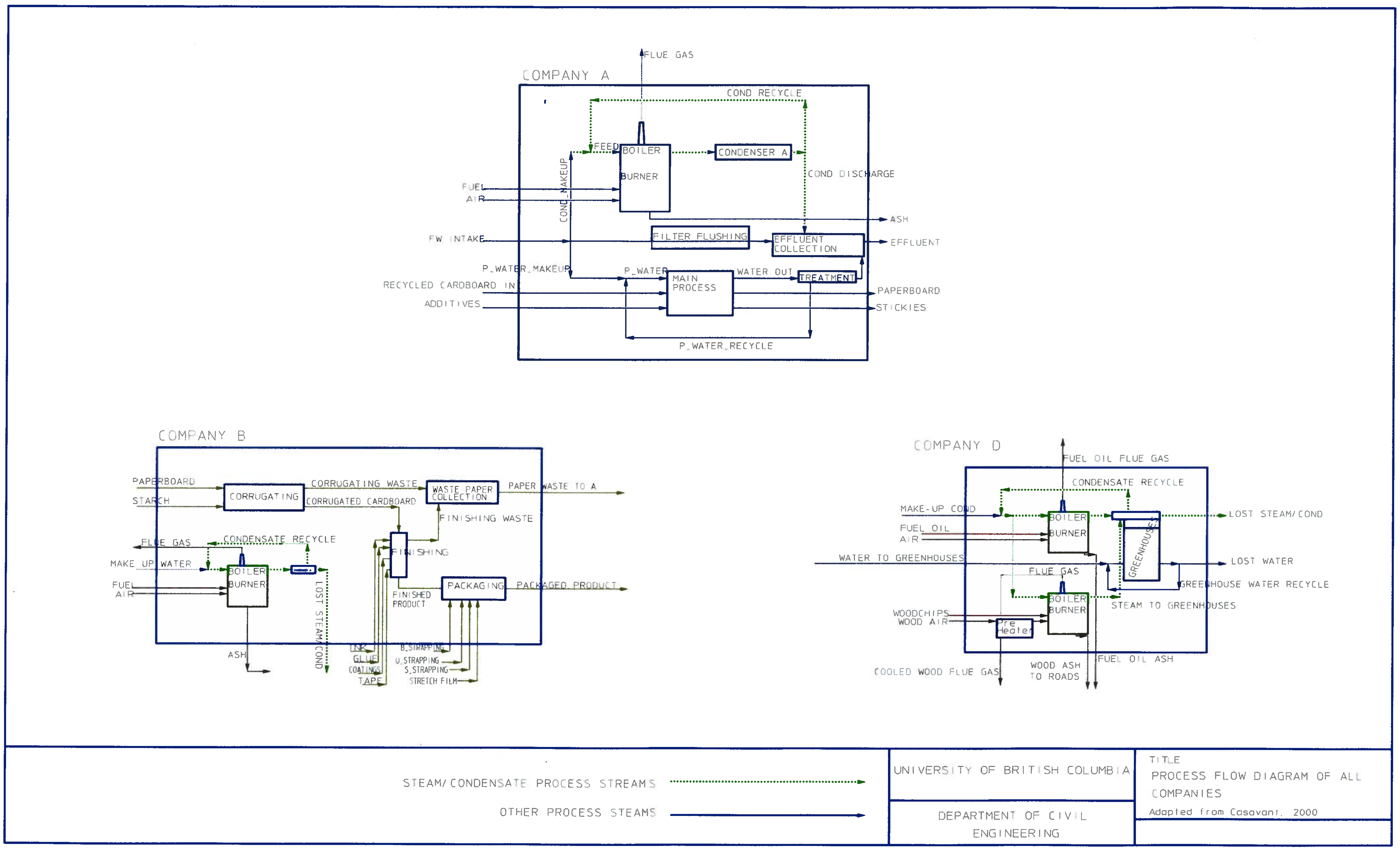

Figure 12 - EIN Process Flow Diagram (All Companies Included)

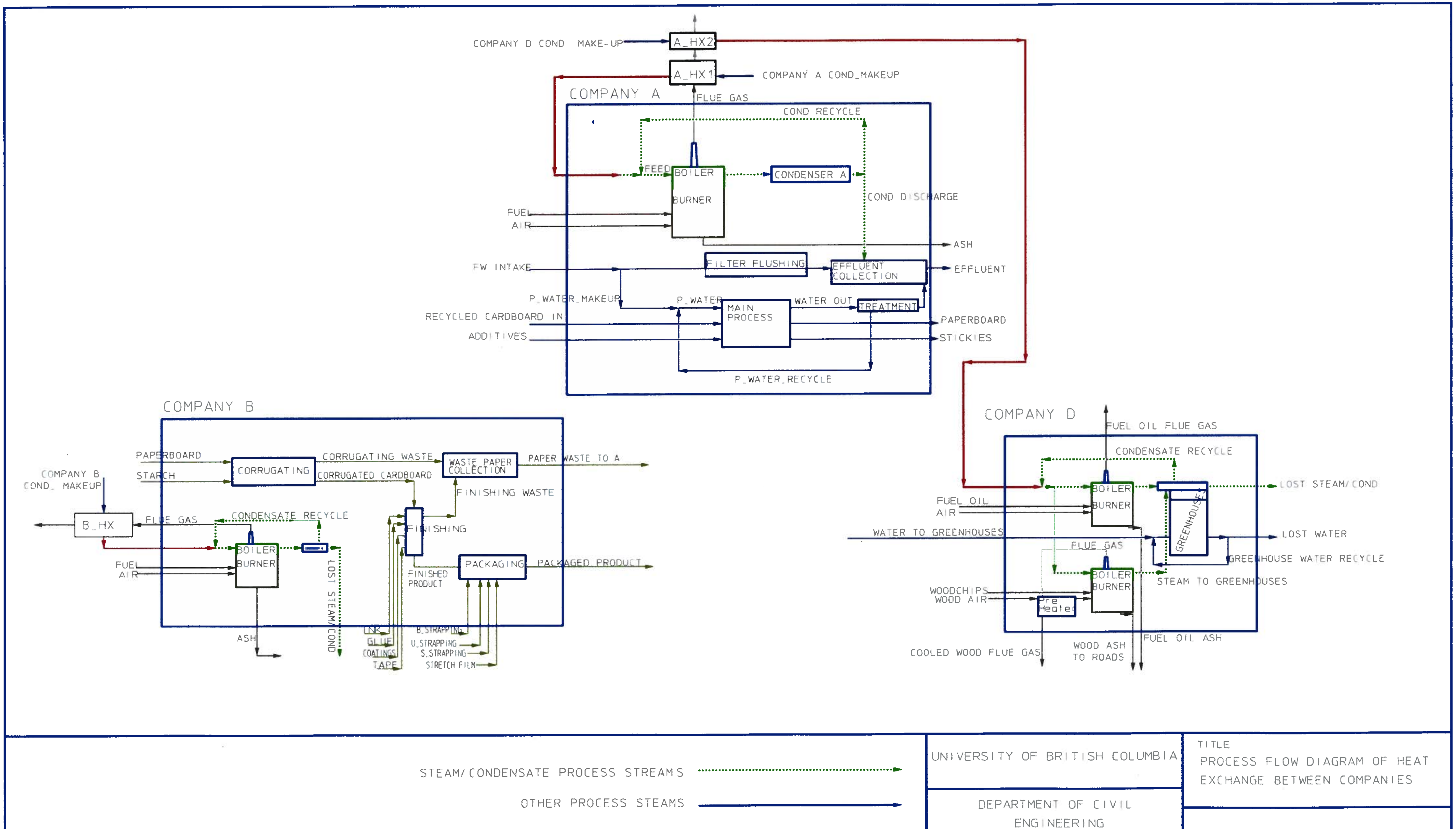

Figure 21 - Process Flow Diagram of Heat Exchange Scenario 2