MATERIAL FLOW OPTIMIZATION AND SYSTEMS ANALYSIS
FOR BIOSOLIDS MANAGEMENT:
A STUDY OF THE CITY OF COLUMBUS MUNICIPAL OPERATIONS

A Thesis

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ABSTRACT

Businesses, communities, managers, politicians and others face difficult management and operational decisions due to escalating energy prices and heightened awareness of the social and ecological impacts of industrial activities. The development and application of EcoFlow™, a material flow optimization tool, represents a novel use of operations research and network theory to facilitate such decision making by synthesizing financial, environmental and technical material processing data. This tool provides a general framework to solve a broad variety of resource and waste management problems.

EcoFlow™ has been utilized to model municipal solid waste management systems, university waste management operations and complex industrial waste reuse networks. The primary application developed here is the City of Columbus network of municipal biosolids treatment and disposal processes. Due to both economic and environmental concerns, the City of Columbus is closely analyzing the resource efficiency of its operations in order to deliver sustainable, cost-effective solutions to improve wastewater treatment. The City has partnered with the Center for Resilience at The Ohio State University (OSU) to apply advanced analytical tools for improved
management of biosolids generated from wastewater treatment plants (WWTP) using a material flow optimization decision framework that accounts for financial and environmental impacts when analyzing operational policies and capital investments.

A systems model was developed in EcoFlow™ for the City of Columbus to analyze three main objectives associated with biosolids operations management: cost reduction, energy conservation and greenhouse gas (GHG) reduction. A systems analysis was performed for the current operations of the City’s two WWTPs and Compost Facility to compare baseline operations against model optimized solutions. The WWTPs currently have four options for final disposal: incineration using multiple hearth incinerators, land application of liquid sludge, and disposal of sludge cake at the Compost Facility or landfill. The baseline model was constructed from 2007 annual cost, energy and material flow data gathered from facility databases and operating managers. These data were also utilized to construct the EcoFlow™ network model material flow constraints.

Modeling results indicated that operational costs, energy consumption and GHG emissions can each be reduced by at least 10% and potentially over 50%. Current analysis shows that the most cost effective solution is to incinerate all of the sludge generated by Southerly and to land apply the solids generated at Jackson Pike. Landfill disposal consumes the least amount of energy, but is the most costly. In order to lower GHG emissions the model suggests a combination of land application, composting, and
landfilling. Tradeoff analyses were conducted to understand the cost efficiency of operational scenarios that minimize energy consumption and GHG emissions. Results from these analyses show potential savings of $1.6 to $3.5 million dollars, up to 19,678 MT eCO$_2$ and 65 to 254 TJ of energy annually. Sensitivity and scenario analyses show the network solutions to be resilient in a variety of market conditions including the increase in energy costs and the price of carbon credits.

The model will continue to be developed beyond the baseline scenario and optimization for the current system. New technologies will be added to the model to determine if they will provide additional potential for carbon credits, energy efficiency, or cost savings. This analysis will identify new biosolids treatment and disposal technologies with the potential to assist the City in meeting goals.

The EcoFlow™ network optimization tool provides a flexible framework for the management of waste materials and can model a variety of technologies and processes that are not available with other tools. Existing waste management decision tools do not provide the flexibility to model systems beyond the end disposal process. They do provide specific modules to address waste technologies of interest, but have limited or no flexibility when considering upstream or preprocessing technologies. However, other tools allow for simulation of multi-period nonlinear future scenarios while EcoFlow™ is
a static, linear model that is designed for detailed short-term planning and is not suited for multi-period long-term planning.
DEDICATION

Dedicated to those who believed I could finish
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CHAPTER 1

INTRODUCTION

1.1 Background

Businesses, communities, managers, politicians and others face difficult management and operational decisions due to escalating energy prices and heightened awareness of the social and ecological impacts of industrial activities. Traditional methods to analyze solid waste management systems rely on financial analysis (Najm & El-Fadel, 2004; MacDonald, 1996; Haith, 1998), while the long term viability of these systems depends on additional factors. Multidimensional metrics (Sikdar, 2003) that capture financial, ecological and social impacts are necessary to analyze the sustainability and resilience of complex systems. Presented here is the development and application of an operations research-based systems analysis tool, EcoFlow™, that facilitates complex decision making processes by synthesizing financial, environmental and technical material processing data. Operations research, network theory and industrial ecology provide a broad systems approach that accounts for economic, environmental and social concerns by optimizing the use of resources, energy and capital (Allenby, 1999). By
utilizing methods of analysis from operations research and industrial ecology, EcoFlow™ can be applied to a broad class of problems and can assess the impact of a variety of environmental, ecological and economic issues that will allow decision makers to evaluate complex scenarios that involve a variety of decisions and multiple objectives.

Within this framework the City of Columbus evaluated the resource efficiency of their biosolids management program including broader system impacts outside the boundaries of each facility. The Columbus wastewater treatment plants (WWTP) represent the single largest consumer of energy and resources for the City of Columbus. Treating and disposing of WWTP biosolids is one of the most significant challenges in wastewater management due to the odorous nature of biosolids and the intense energy requirements for treatment and disposal (Metcalf and Eddy, 2003). Understanding the impacts of various WWTP biosolids management practices provides opportunities to optimize resource efficiency as well as reduce operational costs, energy consumption and greenhouse gas (GHG) emissions. The City operates two WWTPs, Jackson Pike and Southerly WWTP, and a compost facility that together process over 50,000 dry tons per year of biosolids, which result from the treatment of approximately 64 billion gallons per year of wastewater from the Columbus metropolitan area.

The mission of the City of Columbus public utilities is to enhance the quality of life, now and into the future, for people living, working and raising families in central Ohio through the economic, efficient, and environmentally responsible stewardship of superior public utilities (Public Utilities). As part of the Get Green Columbus sustainability initiative (Get Green Columbus), the City is working with the WWTPs and
compost facility to reduce costs, energy consumption and GHG emissions by applying an industrial ecology approach that mimics natural cycles of reuse and recycling.

The City has partnered with the Center for Resilience at The Ohio State University (OSU) to apply advanced analytical tools to improve the management of biosolids generated from the WWTP in Columbus. EcoFlow™, a material flow optimization tool, was utilized by OSU for the City of Columbus to analyze three main objectives associated with biosolids operations management: cost reductions, energy conservation and GHG reductions. These objectives were selected to address the major goals of the City of Columbus Get Green Initiative (Get Green Columbus). A systems analysis of the current operations of City’s two WWTPs and composting facilities was performed to understand the impacts of future management and operational policy decisions.

The City of Columbus intends to reduce its GHG emissions by 5% of its 2005 baseline emissions by 2010 and by a total of 20% by 2025. A significant portion of these reductions will come from the continuously improving services of Columbus Department of Public Utilities, including the use of low-carbon and energy-efficient pathways for biosolids management. With the use of EcoFlow™ the City can:

1) Analyze the potential for GHG emissions reductions from WWTP operational changes

2) Assess the impact of future GHG legislation and GHG emission pricing on WWTP operations

3) Establish resilient operational systems in the face of increasing utility costs
4) Utilize a material flow optimization decision framework for analysis of future technology investments

1.2 Research Objectives

The following work was completed for this thesis and to support the above tasks for the biosolids application:

1) Construct a material flow optimization model in Microsoft Excel to represent the biosolids processing and disposal systems
2) Collect the appropriate financial, environmental and technical material processing data to support the model and represent the three objective functions: cost, energy consumption and GHG emissions
3) Provide analysis of the results to City of Columbus for policy development
4) Train City personnel for general use of the EcoFlow™ biosolids model
5) Utilize the lessons learned from the biosolids application for development of the graphical EcoFlow™ software program

1.3 Industrial Ecology

The industrial ecosystem metaphor was originally popularized by Frosch and Gallopoulos (1989) as a philosophy to transform the existing, traditional industrial system into a system based on material recycling, energy cascading and use of direct and indirect solar energy. This article has led to textbooks (Allenby, 1999; Graedel & Allenby, 2003),
entire journals (Journal of Industrial Ecology and Journal of Cleaner Production), as well as tools and applications dedicated to the subject (Korhonen, Huisingh, & Chiu, 2004).

Within the field of Industrial Ecology, the use of the term “industrial” is interpreted loosely to encompass all impacts related to human activity. Industrial ecology is a broad field of study that seeks to mimic the designs of nature in order to eliminate waste. Like biological systems, the practice of industrial ecology rejects the concept of waste (Graedel & Allenby, 2003). While this idea may seem elementary, the implementation of such a design philosophy can be extremely complex or difficult due to economic, technical, political or regulatory barriers. Pioneering examples have demonstrated the economic, environmental and social value of implementing industrial ecological designs that mimic natural material and energy flows and have shown strategies to remove barriers to implementation (Erkman & Ramaswamy, 2003).

Kalundborg, Denmark is the city of the original and most studied example of industrial ecology. Figure 1.1 shows the current resource reuse pathways in the industrial network (Jacobsen, 2006). These beneficial relationships and efficient use of resources have led to the following impacts:

- The water demand of the main three participants has dropped 20 to 25 per cent through water reuse between the power plant, oil refinery, and the pharmaceutical company. This is a reduction of 1.2 million cubic meters per year, in an area where fresh water is scarce.
• Oil consumption has been reduced by 19,000 tons per year due to substitution of power plant heat for municipal heating and refinery gas for oil at Gyproc and Novo Nordisk.

• Coal consumption has been reduced by 30,000 tons per year, or about 2 per cent of the power plant's requirements, by substituting with refinery flue gas.

• CO$_2$ emissions have been reduced by 130,000 tons per year, or about 3 per cent. This reduction is due in part to the use of refinery gas instead of coal at Aesnes.

• SO$_2$ emissions have been reduced by 25,000 tons per year or 58 percent. This reduction is mostly due to scrubbing at Aesnes and at Statoil. The resulting scrubber waste is utilized for the production of plasterboard.
The Kalundborg example illustrates the benefits of waste reuse that result from applying an ecological framework for industrial systems design. Korhonen, Huisingh, and Chiu (2004) provide an overview of the theory, tools and applications that have developed from the field of industrial ecology. Although there still exist political and technical hurdles, the theory and tools of industrial ecological design have matured to reduce the major analytical barriers for implementing industrial ecological designs as seen by the growth of case studies throughout the work and in a variety of industries (Erkman & Ramaswamy, 2003; Indigo Development, 2005; USBCSD, 2007).
1.4 Biosolids Generation

Biosolids are produced from suspended solids or particulate matter present in WWTP influent. These solids collect and settle to the bottom of clarification tanks during primary and secondary treatment. Two different types of solids are produced: total primary sludge (TPS) and waste activated sludge (WAS). Primary sludge is the result of physical/mechanical separation of solids from influent wastewater in primary clarification tanks while waste activated sludge is separated from wastewater during secondary clarification (Metcalf and Eddy, 2003).

Primary clarification is an efficient, preliminary method for reducing suspended solids due to the low flow rates (less than 1 foot per minute) that facilitate particle settling (Malcolm Pirnie, 2006). Thus, gravity separates suspended particles from water and requires little energy relative to other biosolids processes and no chemical inputs (Droste, 1997). Waste activated sludge is the result of biological activity that removes soluble organic matter from wastewater influent. Microorganisms consume organic matter and form clusters initially suspended in the wastewater. As these clusters grow, they become large enough to settle to the bottom of the clarification tank. The solids are collected and a portion is recycled back to the beginning of the secondary treatment process to select for beneficial microorganisms to continue the degradation of organic matter. The remaining accumulated solids, waste activated sludge, are pumped to the solids handling system for treatment and combined with primary sludge (Metcalf and Eddy, 2003). Initially, biosolids are approximately 1 to 2% solids by weight. As they move through the solids handling process, liquids are reduced until the material is approximately 25 to
30% solids. The purpose of reducing the water content of the solids is to reduce transportation costs and odors for composting and land application or increase calorific heating value for incineration (National Biosolids Partnership, 2008).

1.5 Current Operations

The WWTP managers select each final treatment option based on resource availability, costs, solids storage capacity, compost odor constraints, daily ozone conditions, current solids loading and expected short-term loads. While this process works well for short-term planning, a more comprehensive approach will be required to incorporate greenhouse gas emission goals and to optimize operations in the face of rising energy costs. Figure 1.1 presents a systems diagram of existing pathways for biosolids to be processed.

![Figure 1.2: Conceptual biosolids management systems diagram]

Currently, incineration is used to process the majority of biosolids annually, approximately 60%, due to the benefit of on-site processing that requires no transportation and high operational setup costs, making short-term shutdown of
incinerators cost prohibitive. In the City of Columbus application, no heat is recovered from the incineration process for cogeneration. The ash from incineration is stored in gravity fed lagoons adjacent to the incineration facilities. It is excavated and disposed of approximately every few years. Although beneficial reuses have been explored, the ash is generally sent to the landfill (Malcolm Pirnie, 2006). Biosolids can also be composted and sold as a landscaping product, or transported directly from the WWTP to be applied to farm fields as fertilizer by an outside contractor. The most costly option is to send biosolids to the landfill. Landfill disposal is also generally the least favorable due to no nutrient recycling or energy recovery (Everard, Seeley, & Bond, 2002).

1.6 Biosolids Processing Network Description

Figure 1.3 shows a complete diagram of the system of interest, the biosolids handling system and final treatment processes. At the Columbus WWTP, biosolids treatment processes include gravity thickening, centrifugal thickening, centrifugal dewatering and anaerobic digestion. Currently, only Jackson Pike WWTP has anaerobic digestion. The existing equipment and design only allow for digester gas to be flared or a limited amount to be utilized in the incinerators. By 2009 the Southerly WWTP will also have an anaerobic digestion process for solids reduction as well as methane capture and reuse. The thickening and dewatering processes reduce the water content of the material flowing through the system, while anaerobic digestion reduces the mass of solids through microbial degradation and produces methane and carbon dioxide that is pumped from the digestion tanks for reuse in the incinerators.
Gravity thickening, utilized by both WWTPs, allows the primary solids to settle by gravity on a conical tank bottom and is pumped to dewatering and/or anaerobic digestion. WAS is thickened by centrifugal thickening with the addition of polymer to aid in the egress of water from the centrifuge. WAS is pumped continuously into the centrifugal tank and is moved by a rotating screw toward the tapered end of the tank and water is pumped out the opposite end of the tank, reducing the water content of the WAS. Thickened WAS can then be sent directly to dewatering and/or anaerobic digestion. Anaerobic digestion processes encourage microbial activity in the absence of oxygen in order to reduce pathogens, odors, putrefaction as well as the volume of output solids. The gas produced from digestion can be flared or utilized in the incinerators. After TPS and WAS have been thickened and/or digested, an additional centrifugal process, dewatering, is used to reduce the water content of the solids before end of use treatment or disposal (Metcalf and Eddy, 2003).
Figure 1.3: Complete biosolids treatment network
After the solids have been dewatered, there are four processing options available to the WWTP operators: to incinerate, landfill, compost and/or land apply. The incineration process utilizes natural gas to combust the biosolids and greatly reduces the mass of solids that flow to the ash lagoons. Generally, one of the two incinerators at each WWTP is processing biosolids while the other is on standby. When local ozone levels are high and there is available storage or compost capacity, the Jackson Pike facility operates both incinerators on standby in order to reduce risk of high ozone levels for Columbus residents. The Jackson Pike incineration facilities also utilize anaerobic digester gas to supplement natural gas in incinerators. Incineration also results in the direct emission of air pollutants regulated by the US EPA. Both facilities are constrained by hourly biosolids incineration rates in order to comply with US EPA air permits. Future incineration costs and GHG emissions at Southerly will decrease with the addition of the anaerobic digester gas.

Although the operational energy consumption and resulting GHG emissions are relatively low, sending biosolids to landfills is generally the least preferred option for WWTP managers due to high costs and poor use of biosolids nutrient value. The current landfill utilized by the City of Columbus in Brownsville, Ohio is not constrained by capacity within the next 25 years. Additionally, the local landfill, operated by the Solid Waste Authority of Central Ohio, may potentially open its doors to accept biosolids again. This would reduce transportation costs and emissions and provide a competitive market for landfill tipping fees with more than one local landfill accepting biosolids.
Compost facilities preprocess the biosolids by mixing them with a bulking agent like wood chips, aerate the compost piles to encourage aerobic degradation and finally screen the material to remove non-biodegradable materials. Each step in the composting process requires materials to be transported throughout the compost facility by diesel front end loading equipment. Electricity is consumed by aeration fans drawing air through the compost piles. Daily biosolids processing is permitted to process 50 dry tons per day, but has an internal limit of 33 dry tons per day in order to reduce odor complaints from neighbors.

Land application of biosolids is the spreading of biosolids on agricultural land just below the surface by injection. Biosolids provide nutrients and enhance soil diversity characteristics that improve agricultural productivity and displace expensive fertilizers. Land application is limited by weather and soil conditions as well as potential social concerns. Nutrient runoff, pathogens, and heavy metals also present challenges for long and short-term sustainability of land application.

All the processes in the biosolids treatment network result in indirect GHG emissions from electricity consumption. GHG emissions per kWh in Ohio are relatively high when compared to other states due to the use of coal for the majority of electricity generation. Direct GHG emissions result from the consumption of diesel fuel for transportation and equipment operation.

Transportation of biosolids is required for all post-dewatering processes except incineration. Although a small amount of transportation is required for landfill disposal of ash every few years. Each WWTP has an incineration facility on site. The City of Columbus owns and operates three solids handling semi trucks. These trucks are utilized
to handle transportation between the two WWTPs and the compost facility.

Transportation for land application and to the landfill is handled by outside contractors.

Figure 1.4: System boundary of the biosolids treatment system (dashed circle).

The system boundaries and inputs of interest are depicted in Figure 1.4. In the City of Columbus biosolids management system, solids from WWTP clarification, electricity, natural gas, diesel, money and polymer are modeled as inputs into the system.

The major limitations of this study are not accounting for various life cycle components of this system that could potentially impact the outcome of the optimal operational scenarios. The scope of this analysis did not include the financial and material resources for construction and decommissioning of facilities and processes. This life cycle approach was not taken for this study because only a relative comparison of operational scenarios and existing technologies was conducted. This analysis also did not include the potential negative impacts of land application of biosolids. It is assumed that the contractors will only land apply with optimal conditions and within all Federal, State and Local regulations and therefore have negligible negative impacts (Agency, Biosolids
Frequently Asked Questions, 2007). If the City moves forward with a significant increase in land application, additional studies may need to be conducted to evaluate the environmental impact to land, water and air.

1.7 Biosolids Management Research

Trends in biosolids management over the last two decades have gradually shifted away from landflling and ocean dumping towards increased beneficial reuse of biosolids. This includes nutrient recycling through compost and land application as well as recovery of the energy content of biosolids through anaerobic digestion. Incineration has seen the shift from multiple hearth to fluid bed incinerators (Bastian, 1997). Krogmann et al. (1998) provides a broad overview of the scope of research conducted in the areas of biosolids management. Previous research has focused primarily on regulations, environmental impacts, performance and results of individual treatment processes or technologies (Crohn, 1996).

Matthews (1998) presents a qualitative rating system to provide relative sustainability metrics for biosolids technology and biosolids management practices. These sustainability rankings are a method to compare a variety of attributes to make relative recommendations for processes or technologies. A similar sustainability rating system is utilized by Cartmell et al. (2006) for the purpose of screening biosolids co-combustion processes for further analysis. Each process was rated on a five point scale for economic performance, social impact, environmental performance and flexibility. Unlike Matthews (1998), no weighting factors were utilized for each category in this
analysis. Co-combustion of biosolids with municipal solid waste was most favorable from net energy and global warming potential perspectives due to the minimal requirement to preprocess the biosolids after dewatering. Other processes required drying of the biosolids either at the WWTP facilities or at the facilities where the solid were combusted.

Several studies have been conducted utilizing life cycle analysis (LCA) as a method to compare a wide variety environmental impacts of WWTP system planning (Lundie, Peters, & Beavis, 2004) and solids disposal technology (Peters & Lundie, 2002; Lundin, Olofsson, Pettersson, & Zetterlund, 2004). The aim of LCA is to capture the indirect impacts of the systems being analyzed from “Cradle to Grave.” For example, a LCA for a particular technology would include impacts from material resource extraction, raw material processing, construction and production of the technology and the material and resource extraction required to supply the energy for operations in addition to the direct impacts and emissions from operations. LCA waste management analyses are linear, static models that output a life cycle impact per mass of waste treated (Ekvall, Assefa, Bjorklund, Eriksson, & Finnveden, 2007). Although LCA was not applied to the Columbus biosolids project, EcoFlow™ can be utilized to combine optimization and LCA factors with the appropriate data.

Lundie, Peters, and Beavis (2004) applied LCA to a large scale water and wastewater system. The scope of the analysis included water demand from residential, industrial and commercial customers, treatment and discharge. A variety of scenarios were analyzed to understand the potential impacts of possible future operating scenarios. Population changes, equipment upgrades and operational policies were analyzed for their
impact on energy and water use, climate change, eutrophication, photochemical oxidant potential, as well as human, freshwater, marine and terrestrial toxicity potential. Utilizing these LCA categories and others would enhance the analysis of biosolids land application and other disposal processes utilized by the City of Columbus and could provide insight into the long-term environmental implications of each disposal process.

Lundin et al. (2004) utilized LCA to analyze four biosolids disposal processes: land application, co-incineration of biosolids with municipal solid waste, incineration with phosphorous recovery and fractionation by hydrolysis and acidification for recovery of phosphorous. From an environmental perspective, land application was considered the least favorable option as it was the only process with a net negative energy balance and relatively high emissions to land and air. Positive energy returns were achieved in the three scenarios with energy recovery from incineration. Hospido et al. (2005) show land application in combination with anaerobic digestion to be preferable over thermal processes from an environmental perspective due to the generation of new wastes from incineration and pyrolysis as well as no nutrient recovery. Although Hospido et al. did not perform an economic analysis, Lundin et al. did find land application to be the most cost efficient method of biosolids disposal. Both studies conclude additional study is required to fully understand the impact of heavy metals on the environment in order to improve the usability of LCA analyses.

1.7.1 Waste Management Decision Tools

A well-developed research base for solid waste management decision models exists (Najm & El-Fadel, 2004; MacDonald, 1996; Haith, 1998). Models focus on
minimizing the system cost of an integrated solid waste management system, the
optimization of the design of a particular solid waste technology or the minimization of
transportation required for solid waste collection. Many of these concepts can be
extended to biosolids management. Haith (1998) utilizes a mass balance methodology to
track the financial impacts of a solid waste management system and focus on the
tradeoffs between solid waste management options, but provides no insight into
programming formulation to optimize the flow of material through a variety of disposal
processes. This study incorporates environmental concerns by utilizing the social cost to
abate the pollution associated with the process and includes these environmental costs as
a component of the objective function system cost. This does not allow for clear
environmental goals to be set and does not provide an accurate representation of scenario
costs to decision makers.

A multiobjective function model was developed for land application of biosolids.
The objectives were to minimize cost of operations as well as odor (Gabriel, Sahakij,
Ramirez, & Peot, 2007). ORWARE (ORganic WAste REsearch), developed in Sweden
is a municipal waste simulation tool. It simulates the life cycle impacts of waste flows
through various standard solid waste treatment technologies. ORWARE initial started as
an analysis tool for the organic portion of the municipal solid waste stream and has been
extended to include wastewater treatment and biosolids management (Dalemo, et al.,
1997). This tool has been applied to analyze organic waste management for cities in
Sweden, Chile and others (Sonesson, Dalemo, Mingarini, & Jonsson, 1997; Ramirez,
Frostell, & Galindo, 2002).
While LCA and financial optimization of biosolids management scenarios have been conducted, no work has been done to study the optimization of a biosolids system operations and analyzed the tradeoffs between environmental and financial objectives.

To the best of our knowledge, this paper presents the first application of a systems analysis tool that utilizes network optimization to maximize economic and environmental benefits.
CHAPTER 2

TECHNICAL APPROACH

2.1 Introduction

Complex decisions require the analysis of large amounts of data and scenarios within operational constraints, but are often done by intuition or “back of the envelope” calculations. Presented here is the theory behind EcoFlow™ that integrates financial, operational and environmental data within a systems network optimization framework as well as the development of EcoFlow™ applications.

2.2 Relevant Operations Research Background

The EcoFlow™ methodology is a novel and flexible application of operations research network theory that enables the representation of complex flows of materials, energy and wealth. Ahuja, Magnanti, and Orlin (1991) provide an overview of applications of advances in network theory that have led to the increased efficiency in network algorithms and computational solvers similar to what is utilized in the EcoFlow™ tool. The tool is based upon the theory of minimum cost flow networks with nodes, arcs and flow conservation constraints (Weintraub, 1974). EcoFlow™ utilizes
several network features that are new to the standard minimum cost flow problem such as such as merging and splitting of flows. These generalizations requires the development of ways to modify existing network methods and are implemented in the EcoFlow™ structure.

EcoFlow™ has expanded the range of applications of the minimum cost network by incorporating sustainability metrics into the objective function. In addition to cost minimization, material intensity and energy intensity of system operations can be optimized. Given the flexibility of the current implementation of EcoFlow™, the range of application extensions of the minimum cost network is only limited by the creativity of the modeler and the availability of realistic data to support the model.

Other advances in the application of network theory include the use of mixed integer programming (MIP) to allow the user to include setup costs and fixed costs for additional capacity expansion and investment. This application of MIP greatly expands the capability of minimum cost flow networks to model the impacts of process or system capacity investments. Whereas, MIP applications are typically utilized in portfolio investment analysis, scheduling and site selection applications (Hillier & Lieberman, 2005).

2.3 EcoFlow™ Development

Initial model development of EcoFlow™ was done in collaboration with the Solid Waste Authority of Central Ohio (SWACO), as part of a vision for an eco-industrial park. Figure 2.1 is a network representation developed for Central Ohio that shows the currently known pathways for waste to flow through the available processing
technologies. The initial Eco-Flow™ model was conceived as a tool to maximize the profitability of the eco-industrial park in Figure 2.1. However, it rapidly became apparent that the tool could be useful for modeling flows of resources within any network of industrial enterprises. SWACO was interested in developing a tool to account for the total system impacts of a network of waste processing technologies to evaluate technology proposals from a public bidding process. The model utilizes energy purchases, processing and transportation costs and commodity selling prices to capture the financial impacts of the system. The flexible methodology allowed for other impacts to be accounted for, but initial models were developed for testing purposes only.

Model implementation, calibration (described in section 2.3) and testing was performed in Microsoft Excel. Excel was selected as an initial platform for ease of demonstrating the tool without special software requirements.

Figure 2.1: Systems analysis of potential waste pathways in Central Ohio.
After successful model calibration and demonstration to the SWACO personnel, a computer-based model corresponding to Figure 2.1 was developed. The complete modeling network can be seen in Figure B.1. Figure B.2 shows a screenshot of the user interface developed for the SWACO EcoFlow™ model. The following capabilities are included in this tool:

- **Control Panel** screen (see Figure 4) provides a compact representation of all input data and output calculations, including the optimal solution. The user can directly modify processing costs, commodity prices, transportation costs, tipping fees, process capacities, commodity demands and solid waste inputs.

- **SOLVE** button triggers the linear programming procedure to derive the optimal (highest profitability) solution for the current set of inputs and constraints.

- **Network** screen provides a manually drawn visual representation of the Central Ohio Resource Transformation Center network, including material flow data associated with each process (node) and pathway (arc).

- **Sensitivity Report** shows how the optimal solution will change if selected model variables (costs, commodity prices, process capacities, etc.) are changed, enabling sensitivity analysis.

- **Installation** and **Help** screens provide guidance to new users.

Although this model was highly customized and relatively static, and only an advanced user familiar with Microsoft Excel optimization could modify the structure of the network, it provided the first opportunity for users to modify the model inputs or “turn the dials” of the system parameters in the EcoFlow™ model to see how the output responded.
After the SWACO personnel developed a functional understanding of the intent and use of the EcoFlow™ model, a new conceptual model was developed as seen in Figure 2.2. This system represented the portion of the Central Ohio waste stream that SWACO controlled and could allocate as it or the EcoFlow™ saw fit. A model was implemented to represent this system, enabling SWACO to evaluate proposals from their competitive bid process and has been delivered for exploratory use. A description of the current EcoFlow™ software implementation can be found in Appendix D.

![SWACO Solid Waste Stream](image)

Figure 2.2: Systems analysis of SWACO controlled waste stream

2.4 Initial Applications

The classic example of industrial ecology, the network of industrial partners in Kalundborg, Denmark, was utilized to calibrate the model. The Kalundborg complex was analyzed using Eco-Flow™ in order to validate the applicability of the model to a broad range of industrial ecology networks. The research team used publicly available
data (Jacobsen, 2006) on material flows, capacities, and costs and remaining data gaps were filled with realistic estimates. The primary purpose of this exercise was to demonstrate the feasibility of modeling an actual industrial network; therefore data precision was not a concern. The resulting model had a number of features that were not included in the SWACO model; for example, atmospheric emissions, including CO$_2$, SO$_x$, and NO$_x$, were estimated for several major processes, and constraints were added to place an upper bound on total emissions.

EcoFlow has also been utilized by The Ohio State University to analyze the sustainability of its solid waste management practices. An analysis and optimization of existing operations was performed to understand the potential for reducing environmental impacts through policy change (Naumoff, 2007). A more detailed analysis of campus waste management practices was conducted in order to determine the impact of utilizing novel solid waste processing technologies on system costs and emissions (Barylak, 2008). EcoFlow™ successfully demonstrated alternative policy and technology options for the University to analyze further to improve their solid waste management system.

2.5 Biosolids Application

A customized EcoFlow™ model was developed for the City of Columbus biosolids management system in Microsoft Excel in order to provide unique analysis tools to compare optimal and baseline operations. The tool was developed in close consultation with Malcolm Pirnie and the City of Columbus to ensure working knowledge of the tool for all personnel involved with the tool use. The experience of
developing the customized model has contributed to the ongoing development of the user-friendly, EcoFlow™ tool (Figure D.1) built in a graphical editing software platform.

2.5.1 Data Collection

A variety of data were required to support the EcoFlow™ biosolids model. Data for the objective function coefficients were transportation costs, operations and maintenance costs, energy costs, energy consumption and GHG emissions. All costs, model data and objective coefficients are from 2007. The process input output ratios (flow conservation constraints), throughput constraints and economic data were organized with data collection templates (example shown in Figure C.1) for both WWTPs and the compost facility. The solids handling process input-output ratios were based upon previous GPS-X model modeling outputs (Hydromantis Consulting Engineers, 2008). Malcolm Pirnie calculated energy consumption coefficients for each process with flow data, an inventory of equipment for each process and runtime hours to get the total energy consumption per dry ton of biosolids processed. GHG emissions were calculated based on process energy or fuel consumption and transportation fuel consumption. Emission factors were drawn from Brown and Leonard (2004), the Energy Information Administration (2007) and the US EPA (2006).

Initial small group meetings were set up to collect data from Malcolm Pirnie and the City of Columbus. The data template was utilized to facilitate that process. Several iterations of the small group meetings occurred to resolve any data availability issues. Reasonable ranges of flows for each flow variable were defined and utilized for eliminating any outliers in WWTP flow data. The majority of outliers was generally the
result of errors in manual entry of data due to the addition or subtraction of a digit. Final data gathering meetings with operations managers were conducted at each of the facilities to resolve any remaining data inconsistencies and assumptions.

2.5.2 Model Verification

Models are approximations of the “real world” and no model can ever be exact, but with the appropriate experience and understanding of modeling and the system of interest, a model’s applicability can be verified. According to Barlishen and Baetz (1996):

Model verification involves ensuring the mathematical equations and the solution procedure are correctly represented, and that the model correctly implements its specifications (O’Keefe, Balci, & Smith, 1987). Model validation is concerned with substantiating that a model is sufficiently accurate for the intended use. In addition to its representation of the behavior of the real system, a mathematical model’s validity must also be judged based on its usefulness, usability and cost (Landry, Malouin, and Oral, 1983; O’Keefe et al. 1987).

Thus, incorporation of the system mass balance constraints were reviewed by WWTP engineers as well as City personnel from the Department of Public Utilities to ensure the mathematics were reasonably representing the annual flows of biosolids through the system analyzed. The baseline model, Figure C.3, was utilized for the verification process. Once the baseline model flows were calibrated and EcoFlow™ was able to replicate historical annual flow data within +/- 5%, the model was deemed reasonable for the City of Columbus application.
Model outputs are reported to the nearest whole number. While the precision of data does not support the number of significant figures output by Excel’s optimization, the modeling results are only for relative comparison and thus the use of 3 to 4 significant digits is acceptable and reasonable for the scope of this analysis. No formal analysis of the precision of data and significant digits for model output was done.
CHAPTER 3

RESULTS

3.1 Overview

EcoFlow™ was utilized in order to understand the biosolids system performance under a variety of operating scenarios and goals. Presented below are minimizations of each objective: cost, GHG emissions and energy consumption. A cost efficiency tradeoff analysis between emissions and energy reductions as well as sensitivity analyses of the system performance with increasing energy prices and a price on carbon emissions is described.

3.2 Baseline Scenario

The baseline solids flow network was constructed by calibrating GPS-X solids flow coefficients (Hydromantis Consulting Engineers, 2008) with existing WWTP data. At all processing nodes, the GPS-X data were used as process ratios. At each decision node, percentage allocations based on actual data were utilized to calculate baseline flow. Baseline operations were utilized as a reference point to demonstrate savings with optimized operational scenarios.
Figure 3.1 is a simplified representation of the biosolids network system for the purpose of displaying results. The numbers on the arcs from the Southerly and Jackson Pike nodes are biosolids flows in dry tons per year. The percentages are the allocation of biosolids to each treatment process from each WWTP. The flows on the arcs from the digester methane and natural gas nodes are in MMBtu per year while biosolids flows are dry tons per year. Jackson Pike and Southerly incinerate the majority of biosolids produced by the WWTPs. A graphical representation and table of the baseline results can be found in Appendix C.2 and C.3.

<table>
<thead>
<tr>
<th>Biosolids Baseline Operations</th>
<th>Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total System Cost/yr</td>
<td>$9,800,153</td>
</tr>
<tr>
<td>Total GHG Emissions/yr (MT)</td>
<td>42,812</td>
</tr>
<tr>
<td>Total Energy Consumption/yr (MJ)</td>
<td>358,567,817</td>
</tr>
</tbody>
</table>

Figure 3.1: Simplified baseline solution with resultant objectives

3.3 Single Objective Optimization

Each of the three objective functions, cost, GHG emissions, and energy, were minimized separately to find the operational scenario that satisfies the model with the least of each objective. Figure 3.2, 3.3 and 3.4 are the solutions for each objective.
minimization, respectively. Savings for each objective are simply the difference between the baseline solution and the modeling optimization.

**Minimize Operational Costs**

<table>
<thead>
<tr>
<th>Biosolids Optimal Solution</th>
<th>Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Cost/yr</td>
<td>$6,229,764</td>
</tr>
<tr>
<td>GHG Emissions/yr (MT)</td>
<td>36,696</td>
</tr>
<tr>
<td>Energy Consumption/yr (MJ)</td>
<td>279,791,705</td>
</tr>
</tbody>
</table>

Figure 3.2: Minimized cost operational scenario

Minimizing operational costs, as seen in Figure 3.2, results in the allocation of all biosolids from Southerly being incinerated and the biosolids from Jackson Pike land applied. Incineration and land application represent the least expensive pathways for biosolids treatment and given the biosolids production during 2007 no operational constraints were exceeded. Thus, all the flow from each plant is able to be treated by only one process. Incineration is the least expensive pathway for the Southerly WWTP as a result of not being able to land apply and the direct feed of biosolids to the incineration facility that eliminates the need for transportation. Jackson Pike land
application contracting costs are low due to the close proximity of the farm field application sites to the WWTP and the relatively low amount of processing required for disposal. Historically, Southerly was able to land apply after stabilizing the biosolids with lime. In the future, Southerly will be able to land apply solids stabilized by anaerobic digestion facilities.

<table>
<thead>
<tr>
<th>Biosolids Optimal Solution</th>
<th>Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Cost/yr</td>
<td>$8,684,983</td>
</tr>
<tr>
<td>GHG Emissions/yr (MT)</td>
<td>23.134</td>
</tr>
<tr>
<td>Energy Consumption/yr (MJ)</td>
<td>127,344.69</td>
</tr>
</tbody>
</table>

Figure 3.3: Minimized GHG operational scenario

Disposing of biosolids by land application provides a carbon credit for Jackson Pike and emits the least GHG emissions relative to the other disposal processes. The carbon credit is generated by offsetting the use of fertilizers with biosolids (Brown & Leonard, 2004). Given the operational scenario in Figure 3.3, all digester methane is
flared. Additional energy and GHG reductions could be realized through beneficial reuse of anaerobic digester gas instead of flaring.

The compost facility is the disposal process that results in the least GHG emissions for Southerly due to the carbon credit associate with sequestering carbon in compost. The annual flow of 12,045 tons of biosolids is the maximum flow permitted with the City of Columbus internal compost odor limit. The remaining solids are processed at the landfill which has a relatively low rate of emissions per ton of waste treated due to the methane collection system and flare as well as the high volume of waste disposed relative to the energy resources consumed for operations and maintenance.

Due to utilizing the maximum capacity of the compost facility, the facility odor capacity had a shadow price of -0.32962 MT eCO2 per dry ton increased capacity. In this case, shadow price reflects the marginal change in total emissions per unit increased capacity, not marginal price. Thus, by decreasing composting odors through pretreatment or other method and increasing the daily handling capacity of the compost facility by one ton would yield a net GHG reduction of 120 MT eCO2 per year.
Given the low energy requirements to compact and cover waste disposed at the landfill and the large quantity of waste disposed per year, the per ton energy consumption for the landfill is relatively less than the other disposal processes. Currently, there is no limitation on the quantity of biosolids disposed at the landfill and the most energy efficient scenario is to landfill all of the biosolids generated at the City of Columbus WWTPs. The resulting cost of this modeled scenario is negative and thus, higher than the baseline operations.
Table 3.1: Summary of objective function minimizations

<table>
<thead>
<tr>
<th>Objective</th>
<th>Cost ($/yr)</th>
<th>GHG (MT)</th>
<th>Energy (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>$9,800,153</td>
<td>42,812</td>
<td>358,567,817</td>
</tr>
<tr>
<td>Cost</td>
<td>$6,229,764</td>
<td>36,696</td>
<td>279,791,705</td>
</tr>
<tr>
<td>GHG</td>
<td>$8,084,983</td>
<td>23,134</td>
<td>127,344,691</td>
</tr>
<tr>
<td>Energy</td>
<td>$12,674,485</td>
<td>30,240</td>
<td>104,161,961</td>
</tr>
</tbody>
</table>

The results from the three objectives from Figures 3.1-4 are presented in Table 3.1 for comparison purposes. This table shows the potential range of improvements for all optimized scenarios over the baseline. All improvements are positive except for the cost of energy minimization.

3.4 Multi-Objective Optimization

In order to enable multi-objective optimization, a normalized, weighted function was constructed combining cost per ton of GHG emission and cost per MJ of energy consumed. The weight was varied from 0 to 1 in small increments to capture all the possible scenarios in which the optimal solution would change. The resultant range of operational scenarios represents the efficient system frontier, or the most efficient scenarios possible. Figure 3.5 shows the cost vs. GHG emissions tradeoff and Figure 3.6 shows the cost vs. energy consumption efficient frontier. Given the operational constraints of the system, it is not possible to operate in a scenario that would produce fewer emissions at a lower cost than what is found on the GHG efficient frontier. The four most cost efficient energy consumption scenarios in Figure 3.6 correspond to the four GHG efficient frontier scenarios denoted by the diamond points.
Figure 3.5: GHG reduction efficiency tradeoff analysis, cost vs. GHG emissions

Figure 3.6: Energy reduction tradeoff analysis, cost vs. energy consumption
3.5 Sensitivity Analysis

Figure 3.7 shows the energy price multiplier necessary to cause a change in the optimal scenario. Baseline energy prices (multiplier of 1) are from annual average rates paid by the City of Columbus. The 2007 rates were $0.077/kWh for Southerly, $0.067/kWh for Jackson Pike, $9.50/MMBtu and $3.00/gal diesel. The texture filled bars are the minimized cost operational scenario at the current energy prices. The solid bars represent the cost of the baseline operational scenario with the multiplied energy prices. The line graphs represent the net change of both the baseline and optimized scenarios over the initial system cost.

Analysis of Increasing Energy Prices

Figure 3.7: Model sensitivity analysis for rising energy prices
Figure 3.8 represents an analysis of scenario changes with a price applied to GHG emissions. The GHG emissions associated with each process is assigned a cost and gradually increased to record how the system performs over a wide range of prices. The objective is still to minimize costs. The line graphs show the relative different in response of the optimized scenario and the baseline scenario.

**Analysis of CO₂ Price Implications**

![Graph showing CO₂ price impacts on minimizing system costs](image)

*Figure 3.8: Analysis of CO₂ price impacts on minimizing system costs*

Table 3.1 provides model users with marginal process metrics that capture the total cost, emissions and energy for one dry ton of biosolids to pass through the entire solids handling network and disposal technology.
<table>
<thead>
<tr>
<th></th>
<th>Incineration</th>
<th>MT eCO2/dt</th>
<th>MJ/dt</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Southerly</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Incineration</td>
<td>$203.42</td>
<td>1.244</td>
<td>10,595</td>
</tr>
<tr>
<td>Landfill</td>
<td>$325.80</td>
<td>0.774</td>
<td>2,684</td>
</tr>
<tr>
<td>Compost</td>
<td>$272.47</td>
<td>0.445</td>
<td>3,433</td>
</tr>
<tr>
<td><strong>Jackson Pike</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compost</td>
<td>$255.66</td>
<td>0.435</td>
<td>3,417</td>
</tr>
<tr>
<td>Landfill</td>
<td>$318.30</td>
<td>0.763</td>
<td>2,609</td>
</tr>
<tr>
<td>Land Application</td>
<td>$190.59</td>
<td>1.036</td>
<td>5,829</td>
</tr>
<tr>
<td>Incineration</td>
<td>$155.23</td>
<td>1.069</td>
<td>4,710</td>
</tr>
</tbody>
</table>

Table 3.2: Unit system objective coefficients (per dry ton)
CHAPTER 4

DISCUSSION

Results of initial modeling of the City of Columbus baseline biosolids management system reveal great potential to improve the overall system efficiency for all three objective functions: cost, energy and GHG emissions. The results show the main drivers for optimal GHG and energy reductions are driven by processes with low processing energy requirements per dry ton treated (Figure 3.5, 3.6, Table 3.2). For example, Jackson Pike land application (5,829 MJ/dt) and composting (3,433 MJ/dt) Southerly’s biosolids provides a cost efficient reduction of GHG emissions and energy consumption. Baseline model costs were not driven by energy costs. Labor and maintenance were larger drivers of baseline costs.

Four types of optimizations were performed to analyze the overall biosolids system performance: minimization of costs (Figure 3.2), emissions (Figure 3.3), energy (Figure 3.4) and a weighted average of all three objectives (Figures 3.5 and 3.6). Comparisons and evaluations yielded the following solutions and recommendations for each important modeling question or policy decision:

- How should processed biosolids be allocated among the existing end-use technologies or processes?
Figures 3.6 and 3.7 depict the cost efficiency tradeoffs for GHG and energy reductions. The position of the current operations relative to the efficient operational frontier, demonstrates the potential for cost, emissions and energy reductions simultaneously. The shape of the efficient frontier is what determines how cost-effectively emissions or energy reductions can be made. The level part of the curve in Figures 3.6 and 3.7 are where relatively larger reductions can be achieved for low cost. As the efficient frontier moves upward and increases its slope, the cost per reduction increases. Thus, a “sweet spot” on the operating curve can be determined by decision makers, where the marginal costs are worth the marginal reductions in GHG emissions or energy consumption. With the Columbus biosolids model, Figures 3.5 and 3.6 show that land application at Jackson Pike and utilizing Southerly’s biosolids for compost represent the most cost efficient method for GHG emission and energy consumption reductions.

Currently, incineration is the primary destination for processed biosolids for both WWTPs due to low operational costs, high setup costs if processing needs to be stopped/restarted and lack of human resources to expand land application at Jackson Pike. Reallocating biosolids to land application and composting from the current operational allocation yields cost efficient reductions in energy use as well as large reductions in system greenhouse gas emissions (Figures 3.5, 3.6). Additional GHG reductions or credits could be achieved through beneficial reuse of the anaerobic digester gas in scenarios where incineration is no longer utilized. With increased land application, it is assumed that the average distance traveled to the farms will not increase due to the spatial distribution of current and potential customers. Current land application farm sites are to the north west of the WWTP facilities. Future expansion would most likely
occur directly west and southwest of the facilities and would most likely maintain a similar average annual travel distance.

As the City utilizes EcoFlow™ to analyze future scenarios it is recommended that alternatives to incineration need to be developed due to the potential for major fluctuations in operational costs if energy prices continue to rise (Figure 3.7) or for future GHG emission regulations and pricing (Figure 3.8). When the incinerators reach the end of their useful life, it is recommended that they be decommissioned and reallocate the available space for alternative technology for biosolids processing.

- Are there needs for capacity expansion among components of the biosolids handling system?

While minimizing GHG emissions, the compost odor capacity GHG shadow price is -0.32962 MT eCO2/dry ton of increased capacity. This would result in the reduction of 120 MT eCO2 for every dry ton of daily capacity added. Capacity could be added through the incorporation of sawdust or paper production wastes to reduce odors (Hoff, 2008). The magnitude of potential odor reduction would need to be analyzed in detail and costs would be expected to be minimal as only extra processing of biosolids with paper waste would be required. The market demand for compost produced from the Columbus facility has always been strong with very little marketing done (Hoff, 2008). Tyler and Goldstein (2004) suggest that investing in consumer marketing and education can strongly drive demand and commodity prices for compost.

Figures 3.2, 3.3, and 3.4 represent rigid optimized extreme point solutions to a holistic network problem. In real-world applications the theoretical optimum extreme
point solution may in fact not be “optimal.” If certain model parameters are unknown, uncertain or highly sensitive in the model, the extreme point solution may be subject to system brittleness (Callaway, Newman, & Strogatz, 2000). A small change in a parameter or technological coefficient may result in a sub-optimal solution significantly different from the original optimal solution. Real world variability requires a “Resilient” solution that is not subject to model parameter or coefficient perturbations (Fiksel, Sustainability and Resilience: Toward a Systems Approach, 2006).

Once an optimal solution is discovered, it is possible to test the resilience of this solution. A resilient solution is close to the optimal solution, but less sensitive to changes in process parameters or constraints. A variety of biosolids operational scenarios can be tested for their sensitivity to parameters of interest. Table 3.1 can be utilized to estimate the impact of moving from one operating scenario to another by multiplying the change in allocation by the appropriate coefficients. Operational allocations can be at or near an optimal solution but may be very sensitive to certain parameters. Table 3.1 can be utilized to adjust the operational scenario and track the changes in the objective functions, while reducing the sensitivity to model parameters.

Figures 3.7 and 3.8 both display different characteristics of system resilience. The large range of market prices for energy the system can endure without drastic operational changes is evident in Figure 3.7 that requires energy prices to increase by a factor of 2.8 and again 5.2 before the optimal solution scenario changes. The relative financial performance of the model scenarios in both Figure 3.7 and 3.8 is shown by the two lines series on the graph. As prices increase, the relative operational costs between
the baseline and optimal solution grow. Thus, by operating at or near the optimal solution scenario, costs would be less on an absolute basis and operations would be less sensitive to changes in energy prices.

While EcoFlow™ captures economic and environmental data related to systems operations, there are other practical issues related to realizing the benefits of resilient operations. In order to see significant expansion in the compost and land application management processes, the City needs to provide additional human resources to manage those functions. While limited by current odor complaints, an additional manager or engineer at the compost facility can test the use of certain carbon sources, like paper production wastes, to allow for larger quantities of biosolids to be treated at the existing facility. Figures 3.2, 3.3, 3.5, 3.6, 3.7 and 3.8 all point to increased utilization of land application. Although the availability of farm land and accepting customers exists, the City of Columbus does not have the personnel to manage the contractual relationships and operations of the land application contractors (Hoff, 2008).

While detailed modeling results are very dependent on local conditions (WWTP performance, operators, market prices) as well as the scope of the analysis, the overall EcoFlow™ methodology and general biosolids recommendations apply to a broad variety of waste management problems. The flexibility of EcoFlow™ allows for the expanded analysis of upstream processes that are beyond specific waste management processes and can be utilized to represent a broad variety of companies. This allows materials management models to not only reduce inefficient uses of “waste materials,” but to also optimize the beneficial reuse of resources within a network of producers, manufacturers,
consumers AND waste disposers. The methodology has the flexibility to overcome a major limitation of the biosolids application, additional environmental analysis. This expanded problem solving capability has the potential to improve the resource productivity of the major struggling industries in the United States such as manufacturing and industrial production.

Focusing on low carbon and energy efficient technologies that do not require intensive energy inputs for processing and capture all the valuable resources contained within the waste stream will clearly see a significant competitive advantage as energy prices rise. EcoFlow™ has successfully demonstrated realistic savings and implementable solution scenarios for the biosolids management network. The tool will be utilized by the City for evaluation of management decisions, future operating scenarios and technology investments and to demonstrate these scenarios to stakeholders, politicians and the board of directors.
CHAPTER 5

CONCLUSIONS

The development of EcoFlow fills a void in quantitative decision tools for sustainable materials management by coupling a user friendly network development interface with the optimization of sustainability metrics. By extending the application of state-of-the-art operations research tools, EcoFlow™ has become a systems analysis tool that can be applied to a represent a broad variety of complex industrial networks. EcoFlow™ has been successfully applied to a variety of waste management systems. A detailed analysis of the biosolids management EcoFlow™ model was presented to demonstrate the advanced analysis capabilities of the EcoFlow™ tool and methodology. Results from the analysis of the Columbus biosolids management system show significant potential for both reductions in operational costs and process emissions by implementing low carbon decision metrics for disposal options.

The biosolids management model serves as a baseline analysis for the City of Columbus solids operations. Future model development will involve analyzing the impacts of incorporating new solids processing or disposal technology. The EcoFlow™ biosolids management model can be utilized to help the City of Columbus manage its
GHG emissions, but must ensure that all categories included in the biosolids model are accounted for in the City’s baseline inventory.

Modeling results show the most energy conservative operation is to landfill all of the dewatered biosolids. Meanwhile, in order to lower GHG emissions the model suggests a combination of land application, composting, and landfilling. Tradeoff analyses were conducted to understand the cost efficiency of operational scenarios that minimize energy consumption and GHG emissions and show a combination of incineration and composting disposal for the Southerly WWTP and utilization of land application for the Jackson Pike WWTP.

The current implementation of EcoFlow™ will be continuously updated to improve usability and functionality. Priority updates include accessing and utilizing the solver’s sensitivity analysis to aid in the analysis of network and process capacity as well as many simple user features such as copy and paste.

EcoFlow™ has successfully represented several complex networks and provided valuable insight into improving system sustainability. The biosolids management application provides the greatest potential for model scenario implementation given the promising analysis, resilience of model solutions and stakeholder understanding of the model outputs. EcoFlow™ has demonstrated the potential for sustainability improvements in Central Ohio and will continue to be an important analysis and planning tool for complex industrial networks as energy prices continue to rise.
REFERENCES


Hospido, A., Moreira, M., Martin, M., Rigola, M., and Feijoo, G. (2005). Environmental evaluation of different treatment processes for sludge from urban wastewater treatments:


APPENDIX A

MODEL FORMULATION

Sets

\[ E = \text{Set of arcs} \]

\[ V = \text{Set of nodes} \]

\[ V^{fm} = \text{Set of fixed merging nodes} \]

\[ V^{fs} = \text{Set of fixed splitting nodes} \]

\[ V^{i} = \text{Set of input nodes} \]

Parameters

\[ m = \text{Number of Arcs} = |E| \]

\[ n = \text{Number of Nodes} = |V| \]

\[ K = \text{Amount of input flow to network} \]

\[ R_i = \text{Gain or loss ratio for node } i \in V \]

\[ r_{ij}^I = \text{Fixed input flow merging ratio of node } j \text{ through input } (i, j) \text{ where } j \in V^{fm} \text{ and } (i, j) \in E. \text{ Note that } \sum_{(i,j) \in E} r_{ij}^I = 1 \text{ for } j \in V^{fm} \]

\[ r_{jk}^O = \text{Fixed output flow splitting ratio of node } j \text{ through output arc } (j, k), \text{ where } j \in V^{fs} \text{ and } (j, k) \in E. \text{ Note that } \sum_{(j,k) \in E} r_{jk}^O = R_i \text{ for } j \in V^{fs} \]

\[ T_{ij} = \text{Unit transportation cost of arc } (i, j) \in E \]

\[ E_{ij} = \text{Unit energy consumption of arc } (i, j) \in E \]

\[ G_{ij} = \text{Unit greenhouse gas emissions of arc } (i, j) \in E \]

\[ P_i = \text{Unit processing cost for node } i \in V \]

\[ A_{ij} = \text{Flow capacity of arc } (i, j) \in E \]

\[ N_i = \text{Flow capacity of node } i \in V \]
Variables

\( x_{ij} = \) Amount of flow sent through arc \((i, j) \in E\)

The Model

Min \( \sum_{i \in V} \sum_{j \in V} T_{ij} x_{ij} + \sum_{j \in V} P_j x_{ij} \) Min transportation and process

Min \( \sum_{i \in V} \sum_{j \in V} E_{ij} x_{ij} + \sum_{j \in V} E_j x_{ij} \) Min transportation and process energy consumption

Min \( \sum_{i \in V} \sum_{j \in V} G_{ij} x_{ij} + \sum_{j \in V} G_j x_{ij} \) Min transportation and process greenhouse gas emissions

Subject to

\[ \sum_{i \in V} x_{ij} = K \quad \text{for } j \in V \] All inputs must flow through the network

\[ R_j \sum_{i \in V} x_{ij} = \sum_{k \in V} x_{jk} \quad \text{for } j \in V \] Process node flow in equals flow out

\[ x_{ij} = r^i_j \sum_{i \in V} x_{ij} \quad \text{for } j \in V^{m} \] Input flow for process node \( j \)

\[ r^0_j \sum_{k \in V} x_{jk} = x_{jk} \quad \text{for } j \in V^{s} \] Outputflow for fixed splitting node \( j \)

\[ \sum_{k \in V} x_{jk} = x_{ij} \quad \text{for } j \in V^{a}, i \in V \] Output flow for abitrary splitting node \( j \)

\[ x_{ij} \leq A_{ij} \quad \text{for } (i, j) \in E \] Transportation (arc)capacities

\[ \sum_{i \in V} x_{ij} \leq N_{ij} \quad \text{for } j \in V \] Process (node) capacities

\[ x_{ij} \geq 0 \quad \text{for } (i, j) \in E \] All positive flows
Figure B.1: Modeling network for the SWACO solid waste processing system
Figure B.2: SWACO EcoFlow™ model user interface developed in Excel
APPENDIX C

BIOSOLIDS MODEL DATA

<table>
<thead>
<tr>
<th>Wastewater Treatment Plant Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
</tr>
<tr>
<td>Input Output Ratio</td>
</tr>
<tr>
<td>Input</td>
</tr>
<tr>
<td>Output</td>
</tr>
<tr>
<td>Design/Permit Capacity</td>
</tr>
<tr>
<td>Average Flow</td>
</tr>
<tr>
<td>Operating Cost</td>
</tr>
<tr>
<td>Polymer (gal)</td>
</tr>
<tr>
<td>Energy Cost</td>
</tr>
<tr>
<td>Man Power (Op &amp; Maint)</td>
</tr>
<tr>
<td>Other</td>
</tr>
<tr>
<td>Air Emissions Rates</td>
</tr>
<tr>
<td>Carbon</td>
</tr>
<tr>
<td>Nox</td>
</tr>
<tr>
<td>Sox</td>
</tr>
<tr>
<td>Energy Utilization Rates</td>
</tr>
<tr>
<td>Electricity (kWh/unit)</td>
</tr>
<tr>
<td>Natural Gas (MMBtu/unit)</td>
</tr>
<tr>
<td>Material Utilization Rates</td>
</tr>
<tr>
<td>Polymer</td>
</tr>
</tbody>
</table>

Figure C.1: Sample EcoFlow™ data template for a WWTP
## Biosolids Baseline Flows

<table>
<thead>
<tr>
<th>Network Label</th>
<th>Node Name</th>
<th>WWTP</th>
<th>Type</th>
<th>Flow (dpy)</th>
<th>Source</th>
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</thead>
<tbody>
<tr>
<td>0110</td>
<td>Gravity Thickening</td>
<td>SOU</td>
<td>Process</td>
<td>13,688</td>
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<tr>
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<td>Thickening</td>
<td>SOU</td>
<td>Process</td>
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<td>Process</td>
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<td>0614</td>
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<td>SouthernXP mb</td>
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<td>Process</td>
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<tr>
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<td>Allocation</td>
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<td>JP Power</td>
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<td>Process</td>
<td>5</td>
<td>JP Power</td>
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<td>2726</td>
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<td>1450</td>
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<td>GPS-X</td>
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<td>2951</td>
<td>Compost Product</td>
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<td>2652</td>
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<tr>
<td>3053</td>
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<td>-</td>
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</tr>
</tbody>
</table>

S Power = SWWTP Power tabulations dry only.xls

JP Power = JPWWTP Power tabulations dry only xls

Figure C.2: Biosolids baseline flows and data source table
Biosolids Network Baseline Operations

Figure C.3: Biosolids baseline model results
APPENDIX D

ECOFLOW™ METHODOLOGY

Eco-Flow™ is the first software tool that couples visual editing of network structures with real-time mathematical optimization. The tool consists of two main components: a graphical human interface used to construct and edit material flow networks, and a computational solver which finds the optimal flow pattern for a given network. The graphical interface (see Figure D.1) enables users to visualize the structure of complex networks and to modify them almost effortlessly. The solver gives immediate feedback about the financial and environmental performance of a network, enabling iterative exploration of network design improvements or extensions.

The principle behind the solver is a well-known mathematical optimization method called linear/integer programming or mixed integer programming (MIP). While many “real world” problems involve nonlinearities, these functions are often too difficult to support with sufficient data or they can be simplified with linear assumptions. With EcoFlow™ it is possible to approximate nonlinear functions through piecewise linear estimations.
MIP is used in many industrial and commercial applications, such as airline fleet scheduling, to find the lowest-cost or highest-value allocation of resources to meet a set of constraints on supply, demand, and/or capacity. The most innovative aspect of Eco-Flow™ is that it completely shelters the user from the underlying mathematical representation of the network, allowing expert users to rapidly create and solve models. After the user draws a network diagram and enters appropriate parameters, Eco-Flow™ automatically formulates the model, finds the best solution, displays the optimal material flows on the network diagram, and provides detailed reports on resource utilization and performance metrics. Although the construction of a network within EcoFlow is relatively simple, a user must be familiar with the principles of linear programming in order to appropriately model a system.

Figure D.1: Eco-Flow™ Graphical Interface
The Eco-Flow™ decision support tool was originally developed through an alliance between the Solid Waste Authority of Central Ohio and the Center for Resilience at OSU. Through a unique user interface, Eco-Flow™ enables a systems approach to sustainable materials management. By facilitating the design of waste reuse networks that maximize financial and environmental benefits, material use can be managed in an economically efficient and environmentally effective manner (Fiksel, A Framework for Sustainable Materials Management, 2006). It also helps to speed up the configuration, analysis, and change management of waste reuse networks. The tool has already been applied to several challenging problems involving separation, processing, transportation, and recovery of solid wastes.

Examples of decisions include:

- For an individual company/technology/process
  - How can we maximize profit by exploiting available byproduct synergies?
  - What are the total environmental benefits associated with these synergies?
- For a collective regional network
  - What is the maximum amount of waste that can be diverted from landfills?
  - What reductions in greenhouse gases or other emissions can thus be achieved?
  - How might new technologies benefit the region economically and environmentally?

The Eco-Flow™ model is based on a standardized representation of material flow networks involving material processing or storage facilities (nodes) and material transport
pathways (arcs). An example of a material flow network is shown in Figure 1. The flows are depicted as black dots for solid wastes and green dots for byproducts.

![Sample Material Flow Network](image)

**Figure D.2: Sample Material Flow Network**

Network models offer a useful means for representing complex flows of materials, energy, and wealth. A recent surge of work in network theory has produced a host of useful techniques for analyzing the structural and functional characteristics of different types of networks (Ahuja, Magnanti, & Orlin, 1991; Callaway, Newman, & Strogatz, 2000). In the Eco-Flow™ system it is assumed that the output of any industrial process (a node in the network) can be split into either (a) resources that can be used as feed stocks for other industrial processes or (b) unrecoverable wastes that are sent to disposal sites. The model allows the definition of transportation costs for resource flows and operating costs for industrial processes, as well as a variety of other process characteristics, including mass balance and capacity constraints.

**Figure D.3 illustrates the different types of network problems that can be modeled using Eco-Flow™. A problem is defined by choosing a single objective and any combination of constraints. The example below involves minimizing the total cost of operating the network (including processing and transportation costs) subject to**
constraints on available supplies of input materials, demands for by-product outputs, process capacities, and a cap on the maximum allowable CO₂ emissions. By utilizing the eco-impacts feature, EcoFlow™ can incorporate any type of environmental impact or lifecycle analysis within the powerful optimization framework.

<table>
<thead>
<tr>
<th>Objective (Minimize or Maximize)</th>
<th>Network Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>☐ Total network cost (or profit)</td>
<td>☐ Supplies of input materials</td>
</tr>
<tr>
<td>☐ Facility-specific cost (or profit)</td>
<td>☐ Demands for outputs</td>
</tr>
<tr>
<td>☐ Total flow through the network</td>
<td>☐ Transportation capacities</td>
</tr>
<tr>
<td>☐ Facility-specific input (or output)</td>
<td>☐ Extra transportation resources</td>
</tr>
<tr>
<td>☐ Total processing or transport cost</td>
<td>☐ Process capacities</td>
</tr>
<tr>
<td>☐ Facility processing or transport cost</td>
<td>☐ Extra process resources</td>
</tr>
<tr>
<td>☐ Total eco-impacts (e.g., CO₂ emissions)</td>
<td>☐ Cap on total greenhouse gas emissions</td>
</tr>
<tr>
<td>☐ Facility-specific eco-impacts</td>
<td>☐ Cap on waste disposed in landfills</td>
</tr>
</tbody>
</table>

Figure D.3: EcoFlow™ objective and network constraint options

Modeling Limitations

While Eco-Flow™ represents an innovative systems approach toward modeling complex networks, the current implementation has certain limitations:

- It represents a static view of the network in terms of long-run average processing rates, and does not capture temporal dynamics at either a micro (enterprise) or macro (economy) scale.
- It is strictly deterministic and does not include probabilistic information for uncertain parameters, although it is amenable to Monte Carlo simulation.
- It is based on a first-order linear model of process capabilities, a simplification of reality.
Economy of Scale – Nonlinear functions

The current modeling methodology does not explicitly address economy of scale for technological processes (process nodes). However, the flexible network optimization capabilities of EcoFlow™ allow a modeler to represent a process or technology at a variety of scales. Instead of a nonlinear economy of scale function, a piecewise linear approximation can be made by using a process node for each scale of the technology desired. EcoFlow™ will select the optimal scale of technology for an optimal network flow.

Temporal Scale

EcoFlow™ is designed as a decision tool for capacity planning and resource investments. Typical modeling temporal scales applied have been daily, monthly, seasonally and yearly. The tool can be applied to model shorter or longer time periods, but the model was not intended as a long-term, multi-period simulation or forecasting tool. Although currently no applications have been developed for short-term or small temporal scales (shorter than daily), given appropriate data this methodology can still be applied.

Modeling Framework

The biosolids processing system can be represented as a network of arcs and nodes that captures the costs, energy consumption and total emissions of the processes. Each process can be represented by a node with a processing cost, capacity, material flow ratios and emission factors. Arcs represent the flow of material between processes and
can also have variable costs and capacity constraints. This is either the pumping of solids through the WWTP or transportation by truck to compost facilities, farms for land application or the landfill.

There are five major components that can be utilized to construct a network model within EcoFlow™: input nodes, allocation nodes, process nodes, output nodes and arcs. A complete mathematical formulation of the biosolids network model can be found in Appendix A.

1. Input node: Input material that flows into the system being modeled is designated by \( i \). Model inputs include: primary sludge, waste activated sludge, natural gas and centrifuge polymer. Primary and waste activated sludge are the main materials that flow through the system, while the polymer and natural gas are purchased inputs that are consumed at the process node they feed. The mathematical formulation for fixed consumable input to a process node is:

\[
x_{ij} = r_{ij} \sum_{i \in V} x_{ij} \quad \text{for } j \in V^m \quad \text{Input flow for process node } j
\]

2. Allocation nodes: The output from this node type represents the optimization of material flow. The solver decides how to allocate flow through the available pathways and calculates the optimal decision that could be made by a system operator or manager. This node type is designated by \( j \). Current model decision nodes are the allocation of primary and waste activated sludge as well as
the input allocation of natural gas and digester gas for incineration at Jackson Pike, and the allocation of dewatered solids to the final treatment processes for both WWTPs. The mathematical formulation for these node types is flow of material in is equal to the flow of material out.

$$\sum_{k \in V} x_{jk} = x_{ij} \text{ for } j \in V^n, i \in V$$ Output flow for allocation node j

3. **Process nodes**: This node is designated by and represents the conversion of material by user specified coefficients. For example, for every dry ton of biosolids processed by incineration 28.9% by mass ends up as ash. Process nodes can have multiple commodity conversions or flows. The process nodes in biosolids network include gravity thickening, thickening, dewatering, anaerobic digestion, compost, incineration, land application, gas flaring, and the landfill.

The mathematical formulation is as follows:

$$R_j \sum_{i \in V} x_{ij} = \sum_{k \in V} x_{jk} \text{ for } j \in V$$ Process node flow in equals flow out

4. **Output nodes**: Output nodes are flows that leave the system of interest. From Figure 2.4 the outputs from the biosolids modeling network are compost, fertilizer and GHG emissions. These nodes are represented by

5. **Arcs**: Arcs connect the various processes in the biosolids network and represent the flow of material between processes through the solids handling system or by
truck transportation to the final treatment process. Arcs are represented by arrows in the network diagram.

Model Objectives

\[ \text{Min } \sum_{i \in V} \sum_{j \in V} T_{ij} x_{ij} + \sum_{j \in V} P_j x_{ij} \]  
Min transportation and process costs

\[ \text{Min } \sum_{i \in V} \sum_{j \in V} E_{ij} x_{ij} + \sum_{j \in V} E_j x_{ij} \]  
Min transportation and process energy consumption

\[ \text{Min } \sum_{i \in V} \sum_{j \in V} G_{ij} x_{ij} + \sum_{j \in V} G_j x_{ij} \]  
Min transportation and process greenhouse gas emissions

The 3D sustainability metrics proposed by Sikdar (2003) are represented here as energy intensity and GHG intensity for the biosolids management system. A sustainability tradeoff analysis was conducted to understand the economic efficiency of each of the energy and GHG efficient scenarios generated by the EcoFlow™ model. The results of this analysis can be found in Appendix C

Model Constraints

\[ x_{ij} \leq A_{ij} \]  
for \((i,j) \in E\)  
Transportation (arc) capacities

\[ \sum_{i \in V} x_{ij} \leq N_{ij} \]  
for \(j \in V\)  
Process (node) capacities

The solids thickening, dewatering and digestion processes were all designed with excess capacity to exceed future loads and therefore are unconstrained. Current capacities incorporated into the model are daily composting odor limits to eliminate
residential odor complaints and daily incineration air emission permit limits for Jackson Pike and Southerly incinerators. A complete system GHG emission constraint has been considered for future policy planning for the City to achieve its GHG emission targets, but is not currently implemented.