Quantifying Potential Industrial Symbiosis: A Case Study of Brick Manufacturing

by

Matthew M. Hodge

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Signature of Author...……………………………………………………………………….
Technology and Policy Program, Engineering Systems Division

Certified by……………………………………………………………...………………
John A Ochsendorf
Associate Professor of Building Technology
Thesis Supervisor

Certified by……………………………………………………………...………………
David H Marks
Morton and Claire Goulder Family Professor of Civil and Environmental Engineering
and Engineering Systems
Thesis Supervisor

Accepted by…………………………………………………………………………...
Dava J Newman
Professor of Aeronautics and Astronautics and Engineering Systems
Director Technology and Policy Program

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ABSTRACT

Humanity is currently on an unsustainable path of growth and development. One tool to address sustainability in industrial activities is Industrial Symbiosis, which is the study of cooperation across industry boundaries to increase sustainability. Past efforts to generate these relationships have struggled. Central to these failures is the difficulty of identifying and motivating stakeholders. This thesis proposes a new approach to analysis that directly addresses these failures.

The approach analyzes an entire domestic industry for attractive opportunities to cooperate. By making the profit of stakeholders the primary criteria for investigation, this approach identifies opportunities where existing incentives to cooperate are greatest. This research demonstrates the new approach in a case study of brick manufacturing in the United States. Through the use of life cycle assessment, geographic information systems, and decision analysis, this thesis identifies the brick manufacturing facilities that are most likely to gain substantial economic benefit from the use of processed glass cullet as a fluxing agent. Additionally, the analysis demonstrates that these economic benefits are connected to environmental benefit.

The results of this case study indicate that the approach is not only feasible, but if it is transferable to other industries, it taps into a substantial competitive advantage for data rich manufacturing sectors like those in the United States. These economic benefits will also lead to increased environmental sustainability.

Thesis Supervisor: John Ochsendorf
Title: Associate Professor of Building Technology

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Table of Contents

Appendix A: Cost Model ... 74

1. Introduction

1.1. Problem Statement

Humanity is currently on an unsustainable path of growth and development. Unless changes are made in behavior the earth will one day no longer be able to support human activity at a level anywhere near what exists at present. Efforts to make the necessary changes in behavior have had many forms in the last hundred years ranging from conservation to recycling to lean manufacturing. "Industrial Ecology" (Frosch and Gallopoulos 1989) has emerged as a field of study that focuses specifically on research and analysis of just how human institutions like business, government, and other groups can begin to achieve increased sustainability in their growth and development.

Central to all efforts of achieving increased sustainability is a clear definition of the term "sustainable." A 1987 United Nations report entitled "Our Common Future" states that, "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs"(World Commission on Environment and Development 1987). It is worth noting that simply avoiding development now is neither realistic nor desirable. Therefore it becomes important to identify what is the least sustainable aspect of a product or process and prioritize efforts to reduce these environmental impacts.

For example, how can a product or process more appropriately use non-renewable resources? Approaches to increased sustainability have many forms and no individual method is appropriate for all products and processes. A detailed understanding of the life cycle of a product is the only way to identify potential strategies that can lead to increased sustainability. Opportunities may exist outside the life cycle of an individual product.

Within the field of Industrial Ecology, Industrial Symbiosis studies the potential for increased sustainability through greater levels of resource efficiency. Approaches to develop gains in industrial sustainability through this mechanism have faltered. One reason for this has been the inability to demonstrate clear economic gains from inter-industry cooperation (Jackson and Clift 1998).

The results of the current research speak directly to this need. Through a detailed analysis of a case study an approach to valuing potential industrial linkages is developed. By quantifying both the environmental benefits and economic benefits of an industrial link, market incentives will be able to motivate implementation of the improvements to a life cycle by identified stakeholders. Real experience and historical anecdotes support the position that the market is the most effective way to develop increased industrial complexity and consequently increased sustainability.

The industry of focus for the case study is the structural clay (brick) manufacturing industry. The material and energy use of buildings and construction materials is a major contributor to overall unsustainable growth and development. Bricks are a common part of this built environment and in this thesis the same question is asked about brick manufacturing that is now asked about all types of human activity. How can the industry be more sustainable?

1.2. Chapter Outline

Chapter 2 provides a literature review of the framing concepts for research. From the original definition of sustainability, the first section presents a refined definition for this particular study. The subsequent sections describe the tools and frameworks, collectively known as the field of Industrial Ecology, that have been developed to quantify and analyze efforts to increase sustainability. After clearly describing Industrial Ecology, the chapter presents past life cycle assessment (LCA) studies of brick manufacturing. The final section reviews studies in Industrial Symbiosis that inform the analysis of potential life cycle changes in the production of brick.

Chapter 3 outlines the methodology used in this thesis to analyze potential changes to the life cycle of brick. This methodology is composed of four elements. The first element is research of the industrial context of domestic brick manufacturing. The second element is feasibility analysis in terms of environmental factors, economic factors and regulatory factors. The third element is the determination of the net impact for alterations in the life cycle of brick. The final element quantifies the environmental and economic benefits and assesses which firms stand to gain these benefits through the use of important economic analysis tools such as discounted cash flows and decision analysis. These tools are also described in this chapter.

Chapter 4 presents the results of analysis from the previously described methodology. This chapter indicates historical production levels, trends in production related to economic indicators, existing environmental regulation specific to the industry, and market conditions for new brick, salvaged brick, and glass cullet. For considerations of feasibility the economics of brick manufacturing are informed by data available from the Bureau of Census' Annual Survey of Manufacturers. Regulatory feasibility deals with building codes and industry specific regulations promulgated by the United States Environmental Protection Agency (EPA). Finally the environmental feasibility considers any unintended costs or benefits of changes to the life cycle of brick.

Chapter 5 continues the analysis of utilizing glass cullet as a fluxing agent in brick manufacturing. The thesis uses a portfolio of tools that ranges from geographic information systems (GIS) to life cycle assessment databases in order to quantify benefits of the proposed strategies. This chapter concludes by quantifying the economic and environmental benefits that might be realized through a change in the life cycle of brick manufacturing. It also identifies the facilities that stand to gain the most economically. These are the stakeholders with the greatest incentive.

Chapter 6 provides a brief discussion of the findings of the research. General recommendations are made concerning policy options to increase sustainability in the case study of brick manufacturing. Finally, the chapter considers the transferability of this method of analysis to other industries.

Chapter 7 draws overall conclusions from the presented analysis, recommendations, and research. Amongst these conclusions are that real opportunities exist for green house gas emission reductions through a symbiotic relationship between the brick industry and the glass packaging industry, and that the associated economic benefits are not evenly distributed throughout the brick manufacturing industry. As such, the thesis pin points which potential links might be the most fruitful. Finally the thesis concludes that this type of research is transferable to other industries and that it represents a competitive advantage for US manufacturers and will potentially lead to substantial environmental and economic benefits for the country.

1.3. Summary

Growth and development continues in unsustainable directions around the world. If increased sustainability is to be achieved, it will require methods to quantify the benefits of more sustainable behavior to help create incentives to adopt more sustainable activity. This thesis reviews the field of Industrial Ecology and applies its tools to the domestic brick manufacturing industry. The thesis proposes a method for evaluating potential economic and environmental benefits of brick manufacturing and concludes by considering options to transfer this analysis to other industries in the hopes of increasing the overall sustainability of development.

2. Literature Review: Theoretical Framework

2.1. Introduction

The focus of this thesis is the search for Industrial Symbiosis precursors in the United States. The brick manufacturing industry serves as a test case for an approach to identifying stakeholders, quantifying economic benefits, and quantifying environmental benefits. This chapter provides a literature review of the framing concepts for research. From the original definition of sustainability, the first section presents a refined definition for this particular study. The subsequent section describes the tools and frameworks, collectively known as the field of "Industrial Ecology", that have been developed to quantify and analyze efforts to increase sustainability.

After clearly describing Industrial Ecology, the chapter presents past Life Cycle Assessment studies of brick manufacturing. The chapter then moves to review studies in Industrial Symbiosis that inform the analysis of potential life cycle changes in industry. As a part of this review, the chapter discusses past commentary on the apparent difficulties in involving stakeholders in industrial symbiotic relationships.

2.2. Sustainability

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development. 1987). This clear statement of sustainability is necessarily abstract. The definition must be narrowed for application to any individual element of development be it environmental, economic, or societal. For the purposes of the current study the definition is limited to environmental sustainability specifically the consumption of non-renewable resources.

2.3. Industrial Ecology

The intended result of this research is to make an individual industry more sustainable. To do this it is necessary to have a framework for understanding industrial activity and its consequences. The emergent field of Industrial Ecology provides such a structure. The work of researchers like Robert U. Ayres spawned the descriptive metaphor (Frosch 1992). The concept behind the term is that natural ecosystems manage to achieve local sustainability by efficient utilization of resources creating minimal waste and utilizing waste from one process as a resource in another process. By analogy, the idea suggests that industry might achieve greater sustainability in the same way, maximizing efficient use of materials and creating minimal levels of waste (Frosch and Gallopoulos 1989). In the same way that a pond contains algae that benefits from the waste created by fish, Frosch and Gallopoulos envision one industry taking the waste from another industry to create a product that contributes to the industrial system.

From its initial description, Industrial Ecology has grown rapidly in the last eighteen years. Ehrenfeld (2004) argues that Industrial Ecology had become well enough established to be considered a new field of research. The criteria he presents to demonstrate this are:

> 1. A system of beliefs about how the world works,
> 2. Strategies and norms governing what one should do when addressing a particular domain of action,
> 3. A common set of tools and technologies to be used towards meeting one's objectives in that domain,and
> 4. A set of legitimating authorities.

Arguments continue about the proper characterization of Industrial Ecology, but there is no disagreement about the value of some of the tools that constitute the elements of

Industrial Ecology that fulfill Ehrenfeld's second criteria. These tools are Material Flow Analysis and Life Cycle Assessment.

2.4. Industrial Ecology Tools

2.4.1. Material Flow Analysis & Life Cycle Assessment

Material Flow Analysis (MFA) is a method that categorizes and compiles all flows into and out of a particular artifact. It is the application of the principle of conservation of mass to a society or particular part of society (Wernick 1998). While MFA has been a useful tool for analysis, critics have pointed out that it is not appropriate for use in comparative studies(Low 2005). The current study focuses on comparing strategies and therefore a more appropriate tool within Industrial Ecology is Life Cycle Assessment (LCA).

2.4.2. Life Cycle Assessment (LCA)

LCA is a "comprehensive method for analysis of the environmental impact of products and services" (Bauman and Tillman 2004). It is considered a "cradle-to-grave" analysis in that it considers all inputs and outputs from raw material extraction to disposal. The method considers the entire production system for a "functional unit" and all other needs over the life of the item to determine the total inputs and outputs for an artifact. Unlike MFA, LCA need not be site specific and is an attractive tool for analysis because it is highly structured, quantitative in nature, and can be applied for comparative purposes (Bauman and Tillman 2004).

The original studies that lead to the formal development of LCA were indeed comparative studies. Early examples include a 1969 study in the United States by the Coca-Cola Company and a 1972 study by the Glass Manufacturers Federation in the UK. The Coca-Cola study focused on the environmental impacts associated with alternatives in packaging choices (glass bottles versus plastic bottles versus cans). The Glass Manufacturers Federation paid to conduct a study comparing returnable and non-returnable beer bottles (Bauman and Tillman 2004). From these early studies, LCA has advanced rapidly and now has a clear format and structure as described in the International Organization for Standards series ISO 14040 (ISO 14001 Information Zone: ISO 14040 Life Cycle Assessment 2002). Thousands of studies have now utilized LCA methods to evaluate impacts from various products and services.

2.5. Environmental Impact of Brick Manufacturing

Before considering the actual environmental impacts of brick manufacturing, it is useful to consider a life cycle diagram of typical structural clay products.

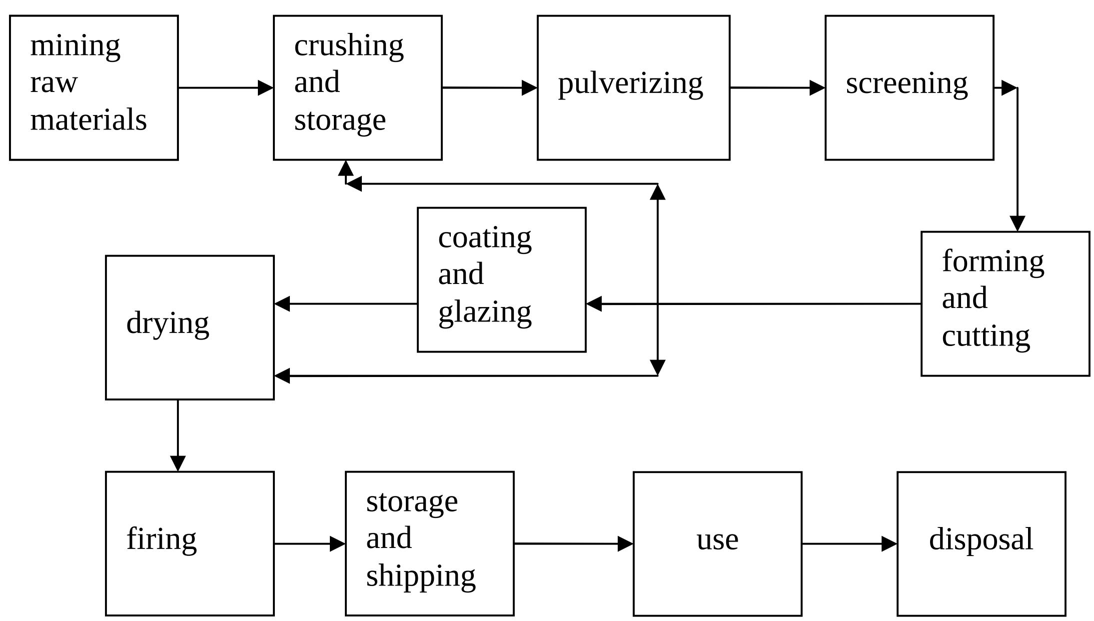

Figure 2.1 Life Cycle Diagram Structural Clay Products [adapted from (Venta 1998)]

This flow diagram demonstrates the general life cycle of brick. Unlike many other common products in the technosphere that have extensive inputs during the use phase of their life cycle, many building materials lie dormant during their use phase without requiring regular inputs beyond maintenance. Schematically the use phase of brick is not noteworthy. However, in terms of comparable building materials, the use phase is noteworthy in deed. The typical service life of brick is in excess of 100 years (Illston and Domone 2001). Other comparable cladding materials typically have life spans of less than 50 years. In certain situations, long maintenance free life cycles can increase sustainability. Unfortunately, in terms of LCA, the long life is not a benefit if it is not utilized.

Applying LCA to structural clay products has been the focus of three past studies. Each study has focused on a different geographic region. The Athena Sustainable Materials Institute conducted a study in 1997 that focused on Canadian production (Venta 1998). The Swiss Centre for Life Cycle Inventories included brick as a component in their study of building materials in Europe (Kellenberger 2003). Lastly, the Building for Environmental and Economic Sustainability (BEES) Program, administered by the National Institute of Standards and Technology, included brick in its inventory of exterior wall materials (BEES 3.0 Building for Environmental and Economic Sustainability 2002).

Direct comparison of these studies is complicated. While the strength of LCA is its ability to compare, that ability exists only when there is a single set of assumptions. For these studies this is not the case.

Component	Athena	Swiss Centre for LCI	BEES
Geographic focus	Canada	Europe	United States
Functional Unit	1 Kg finished brick	1 Kg Brick	1 Kg brick
Life Span	Unspec.	Unspec.	50 yrs
Raw material input (clay)	1.00 kg	1.35 kg	1.00 kg
Raw material input (water)	0.14 l	0.07 l	1.89 l
Energy Consumption	4.58 MJ	2.84 MJ	4.95 MJ
Carbon Emissions (CO_2)	232.25 g	230.29 g	288.72 g
Total Suspended Solids	0.21 g	0.03 g	0.68 g
Solid Waste (mfg)	0.01 kg	Unspec.	0.36 kg

Table 2.1 Comparison of Various LCA Studies of Structural Clay Manufacturing(Venta 1998; Kellenberger 2003; BEES 3.0 Building for Environmental and Economic Sustainability 2002)

Table 2.1 demonstrates difficulties due to variations in scope of LCA's and geographic preferences can do. In particular the BEES study is not comparable to the other studies because it considers surface area of installed brick. Therefore, the data has been normalized to 1 Kg of Raw Material and this yields generally comparable results, but it must be stressed that because of the different original functional unit (finished product surface area) that this study can only loosely be compared to the first two studies. For all of these studies the final results represent averages taken across a sample of actual brick manufacturing facilities that provided data to the studies. Given these limitations, the above life cycle studies do not accurately describe any individual manufacturer, but still provide valuable information for considering strategies for increased sustainability.

The Swiss Centre for LCI study is the most useful study for the purposes of this thesis. It is the study that is used in the EcoInvent Database. Databases and related software packages are a powerful tool for modeling life cycles without collecting original data. In this thesis, the EcoInvent Database and SimaPro 6.0 are used to model modifications to the life cycle of brick.

2.6. Industrial Symbiosis and Location

There is substantial research into life cycle changes that can have an environmental benefit in specific cases. An important question is how can these individual cases be expanded to the industry as a whole? Industrial Ecology has an area of research that attempts to answer this question.

The concept of Industrial Symbiosis considers the geographic proximity of different industries and the potential for them to cooperate for increased efficiency in the use of materials (Chertow 2000). This element of Industrial Ecology is inspired by the level of industrial cooperation that is found in Kalundburg, Denmark. In this town, four facilities exchange waste materials, water, and heat to reduce total consumption and waste. Kalundborg has developed completely through free market means and with no central planning other than the four participating facilities (Gertler 1995).

2.6.1. Past Approaches: Eco-Industrial Parks and Region Based Studies

Efforts to recreate the high level of sustainability in Kalunborg have centered on the development of "Eco-Industrial Parks" (EIPs). The ideology behind the development of EIPs is that central planning allows for an optimal selection of participants that can all derive benefit from the wastes generated by neighboring facilities. Pilot projects were built in the United States, Canada, and the Netherlands. Initial enthusiasm regarding this approach has been replaced with concern that EIPs are not resilient in case where the members of the EIP change (Lambert and Boons 2002). EIPs have also been criticized for their genesis as centrally planned projects. Heeres et al. (2004) have published a study comparing examples of centrally planned EIPs in the US to free market development in Europe. They conclude that centrally planned EIPs have fared less well than symbiotic relationships that have been generated by market forces. This finding is supported in a historical context by Desrochers (2004) who used historical case studies of Victorian England and mid-twentieth century Hungary to conclude that “market mechanisms” yield both more efficient and more long-lasting industrial symbiotic relationships. The continued struggles of centrally planned new developments have lead to research focused on Industrial Symbiosis within the existing industrial network. The current thesis and supporting research draws heavily on this work and makes a contribution to the analytical techniques that are currently used.

Kincaid and Overcash (2001) describe an effort to review a particular region in North Carolina for potential Industrial Symbiosis. Some linkages were found and established, but the study concludes that the lacking element for success “is an agent to promote the vision of a web of materials, water, and energy flowing between neighbors and to gather the local information about by-products available or raw material requirements needed to build this web”(2001). In a conceptually related study, Ozyurt and Realff (2001) analyze an industry and region for potential linkages. The goal of their study is to optimize utilization of material, but to do so the researchers are forced to “assume cooperation” amongst stakeholders in order “that the best system performance be identified as a target” (2001).

How can this “agent” be created? What can guarantee “cooperation”? The answer is the same as has been described by Desrochers. The market mechanism is the most efficient way of developing an efficient industrial ecology. A major focus of future research into Industrial Symbiosis must be methods for evaluating economic and environmental benefits associated with linking industries. Past work by Chertow and Lombardi speaks to this need by "Quantifying Economic and Environmental Benefits of Co-Located Firms" (2005). This study presents a detailed accounting of savings from the cooperation between an energy plant and a chemical plant. The findings of this study serve as a strong example that can motivate replication. Indeed, profit generation causes an industrial entity to become its own agent for investigation and development of a symbiotic link. Similarly, environmental gains may motivate government and non-government groups to also advocate and explore the potential for linking together different industries.

While it is possible to quantify benefits of existing symbiotic relationships, the problem faced by Kincaid and Overcash, and by advocates generally, is how to value the economic and environmental benefits of a potential connection between two or more industries. The methods used in this case study of brick manufacturing speak to this need and provide an approach to quantify benefit in the face of economic and technical uncertainty.

2.6.2. Stakeholders and Motivation

The importance of quantifying potential benefits is in that it serves as a motivation for potential stakeholders to become active developers of symbiotic relationships. Jackson and Clift (1998) describe the need for Industry Ecology to develop a "theory of agency." The idea is that knowledge about agents and their motivations will inform what are appropriate choices and who must have responsibility for action to realize the benefits. Jackson and Clift conclude that since most industry exists in a profit driven market, the agents are the decision makers in industry and the motivation is, obviously, profit. They also find, however, that the “tension” between resource efficiency and low cost of disposal may serve to paralyze the concept of Industrial Ecology. This idea is taken up by Esty and Porter in their paper, “Industrial Ecology and Competitiveness” (1998). They support the idea that regulatory reform may be necessary to sharpen incentives for firms to participate in environmentally friendly practices. As a part of this argument, Esty and Porter identify many examples where profit did generate changes at the firm level, changes that increased the sustainability of industrial activity. A range of analysis (see Gertler, Desrochers, Jackson and Clift, and Esty and Porter) has concluded that firms will be the stakeholders who can enter into industrial symbiotic relationships and profit is the incentive that will motivate them. As such, it is reasonable to use the same economic analysis tools that these firms already use to quantify the potential economic benefits of Industrial Ecology.

2.7. Conclusion

The field of Industrial Ecology has grown rapidly in the last 18 years. Many cases of success exist, particularly at Kalundborg, Denmark. At present wider adoption of Industrial Ecology lacks an ability to speak to many of the agents that can act to realize increased sustainability. There is a need for analysis that gets the attention of firms. The current thesis utilizes economic profit as the highest priority for analysis with the belief that this is the language of agents. Through this approach, the results of analysis will be able to effect real change in the relevant industrial systems.

3. Methodology

3.1. Introduction

The goal of this research is to find an approach to value potential inter-industry links. The purpose of such an activity is to attract industrial stakeholder attention to the benefits of Industrial Symbiosis. Developing their interest is a prerequisite for establishing increased sustainability through Industrial Ecology. Economic benefit is the motivation that will activate "market mechanisms" to establish links. As has been described in the literature, market motivations are the most efficient and effective way to begin to form industrial ecosystems.

The selected approach focuses on an individual linkage as opposed to past studies that have focused on multiple uses for a single material, or past studies that have focused on a region or EIP. The methodology of the research follows a similar pattern to past investigations of industrial links. The first step in the approach is to identify a target industry (in this case the brick industry) and relevant spatial context (e.g. The United States). Second, understand the life cycle of the chosen industry, either from an original LCA or from a review of relevant past studies. Next, identify potential changes to the life cycle that can result in increased sustainability. Fourth, assess the feasibility of these life cycle changes in terms of the economic, regulatory, technical, and capacity limitations that implementation might face.

The next stage of analysis involves acquiring the physical locations of the industrial nodes into a geographic information system (GIS). In addition to transportation distances, an understanding of the uncertainties that exist in the new industrial link must be developed. Finally, applying the modified life cycle and an appropriate cost model for the industry will yield an indication of the expected value of the economic and environmental benefits from the industrial link.

3.2. Identify Target Industry and Relevant United States Context

The selection of an industry for study can be arbitrary, but for the purposes of this exploratory effort an industry that produces a complex product is attractive because there are potentially many avenues of industrial exchange that can be explored. Conversely, a simple product will prove easier to analyze because of reduced levels of uncertainty and availability of reliable information. Regardless of the industry that is selected it is important to understand the state of the industry.

Many life cycle studies, especially those conducted by the Athena Institute, provide some industry information. Industrial trade groups are often a strong source of industry statistics and trends as well. Within the United States, the EPA and the Census Bureau also tend to have published information relevant to an industry. This is particularly true if the industry is regulated by the EPA. This information gives an appropriate context to base the findings of relevant LCA studies.

3.3. Review Industry Life Cycle Research

A literature search is necessary to find life cycle studies of a particular product. There can be many sources for this material, from life cycle inventory databases to private and academic studies. The source of studies is an important consideration as the framing of the findings may be influenced by the interests of those conducting or funding the study. The purpose of reviewing past LCA studies is to identify the priority environmental impacts of a product. The United Nations statement on sustainability implicitly advocates this prioritization by indicating that the current generation must meet its needs as well as provide for the future generations.

3.4. Identify Potential Life Cycle Changes

Changes to the life cycle can involve infinite forms of process or product modifications. Within this study the focus is on a product that is dormant in its use phase. Consequently the greatest likelihood of finding beneficial changes is bound to focus on the front end and the back end of the life cycle of the industrial product. These are the two stages of a life cycle where material and energy are consumed in the greatest quantities and waste is produced in the greatest quantities. These are also the phases of a life cycle where industry stakeholders have the greatest control over products.

3.5. Assess Feasibility in United States Context

Industrial activity is subject to many constraints. Technical limitations created by physical attributes of materials and manufacturing processes drive how much industrial activity is carried out. A telling example of this comes from the Overcash and Kincaid study of a metropolitan region of North Carolina. In this study, methanol from a resin producer was identified as useful to a wastewater treatment plant, but the existence of elevated levels of nitrogen in the methanol made it inappropriate for use at a wastewater treatment plant that had initially expressed interest in establishing the industrial link (Kincaid and Overcash 2001).

Closely related to this concept is the capacity for a change. Are the resources available to carry out a particular activity? The use of salvaged brick leads to as much as a 25% savings in the energy consumption of new residential construction (Thormark 2000). However, the scarcity of salvageable brick reduces the total beneficial environmental impact of this change to less than 1% of the energy consumed annually in the production of new brick.

Meanwhile, economic constraints drive many decisions from a business perspective. Few published examples of this case exist, but a hypothetical example can be considered. A cement manufacturer may wish to use fly ash as an additive to its raw material flow, but the savings associated with the fly ash maybe less than the cost of transporting the waste material from the nearest supplier to the cement plant. Thus, the cement manufacturer will choose not to utilize the waste product. In the same way, if the cost of freight to transport a material causes a net economic loss to the cement manufacturer they will not adopt the change in raw material sourcing.

Lastly, regulation can impact decisions and processes in industry. Each of these requirements for feasibility may drive or prevent adoption of a new industrial linkage. Examples of this include any situation where the use of some waste product can only be carried out by a facility with a Resource Conservation and Recovery Act license for handling hazardous waste materials. A limitation from any of these spheres of influence (technical, capacity, economic, and regulatory) can prevent the development of inter-industry links.

3.6. Quantify Economic and Environmental Benefit

3.6.1. Economic Benefit

To quantify economic benefit a potential link, it is necessary to understand the cost and revenue that the focus industry faces. The Bureau of Census provides this information for all large scale manufacturing industries in the United States through the Annual Survey of Manufacturers (ASM). Similarly, the production of an industry is measured by the Census Bureau in its quarterly Current Industry Reports (CIR). The data available from the federal government is not limited to economic and production information. With this information as a base, the cost model can be tailored to incorporate information that is available for individual facilities and cost information that is of interest regarding modifications to the life cycle of the focus industry. Additionally, to deal with uncertainties associated with cost information well known financial methods can be employed to include uncertainty in the analysis.

3.6.2. Economic Analysis Tools

Two financial tools are central to the current analysis, discounted cash flow and decision analysis. The first tool deals with the value of money over time and the second proscribes rational decisions for a single decision maker.

Discounted cash flow is a method for dealing with economic costs and benefits that will be accrued over time. It is generally understood that costs and revenues in the future are worth less than costs and revenues in the present (De Neufville 1990). To account for this future benefit or cost the future value is discounted by a discount rate. This rate accounts for the earning power of money over time. Thus a cash flow or cost in the future has a present value that is determined by the following equation.

$$PV(x,n,r) = \frac{x}{(1+r)^n}$$

Equation 3.1 The Calculation of Present Value of Future Costs and Benefits (Clemen 1996)

In Equation 3.1, x represents the future value, r is the discount rate, and n is the number of time periods between the future and present values. Utilizing this tool allows decision tools like cost-benefit analysis, net present worth, payback period, and internal rate of return to be used in the evaluation decisions that influence future results. Another valuable tool is decision analysis.

Decision analysis is "a method of evaluation that leads to three results: structures the problem…defines optimal choices…(and) identifies an optimal strategy…" (De Neufville 1990). In deterministic cases, this method allows a decision maker to rationally identify optimal decisions based on preferences for outcomes. In stochastic cases, decision analysis is still an incredibly valuable tool. Outcomes can be associated with the probability that such a set of events occur. With both outcomes and probabilities determined, mathematical evaluation methods like expected value, variance, and Monte Carlo simulation can be used in combination with other decision tools to aid in decision making. The current research uses decision analysis based on a decision maker who looks to maximize the expected monetary value of outcomes for their respective firm/facility. In this way the behavior of industry stakeholders is predicted based on uncertain outcomes in the future.

3.6.3. Environmental Benefit

Assessing the environmental benefit is the reverse of the approach used to quantify the economic benefit. In the economic case, industry wide data was scaled down to an individual firm and product. In the environmental case, product specific information must be scaled up to individual firm and then to industry. The data provided by the life cycle studies of an industry can be combined with the production information in CIR to determine the difference between the impacts of existing life cycles compared to modified life cycles.

3.6.4. Life Cycle Modeling: SimaPro 6.0

In considering these life cycle changes, even a simple modification leads to changes in many inputs and even more outputs. To accurately model alternative life cycles quickly database software is necessary. SimaPro (SimaPro 6.0 2006) is a software specifically designed to allow the user to compare life cycles of alternative products and processes. The software offers many ways to consider the impact of a life cycle. For the purposes of this study the Cumulative Energy Demand 1.03 (Frischknecht R. 2003) impact assessment methodology is use to consider total energy consumption for various life cycles. Instead of utilizing another impact assessment method to determine global warming potential for an individual life cycle, the total amount of emitted carbon dioxide composes the largest portion of warming potential. In the specific life cycle of brick manufacturing, other green house gases compose less than 1% of the total warming potential production (See Appendix B).

3.6.5. Elements of Uncertainty

The economic analysis and environmental analysis must incorporate uncertainties associated with the potential change to the life cycle. Uncertainty about economic value is an obstacle to adoption of any change. If the uncertainty can be included in a model then a much more informative estimation of the potential environmental and economic gains can be presented to stakeholders who will decide whether to adopt the change in their manufacturing life cycle.

3.6.6. Modeling Uncertainty

Attempting to determine the value of the life cycle change in the face of uncertainty requires that one considers the expected value of the use of glass cullet in brick manufacturers. Instead of considering a deterministic analysis with fixed values, a stochastic model takes into account the uncertainty and associates an outcome with the probability of that outcome.

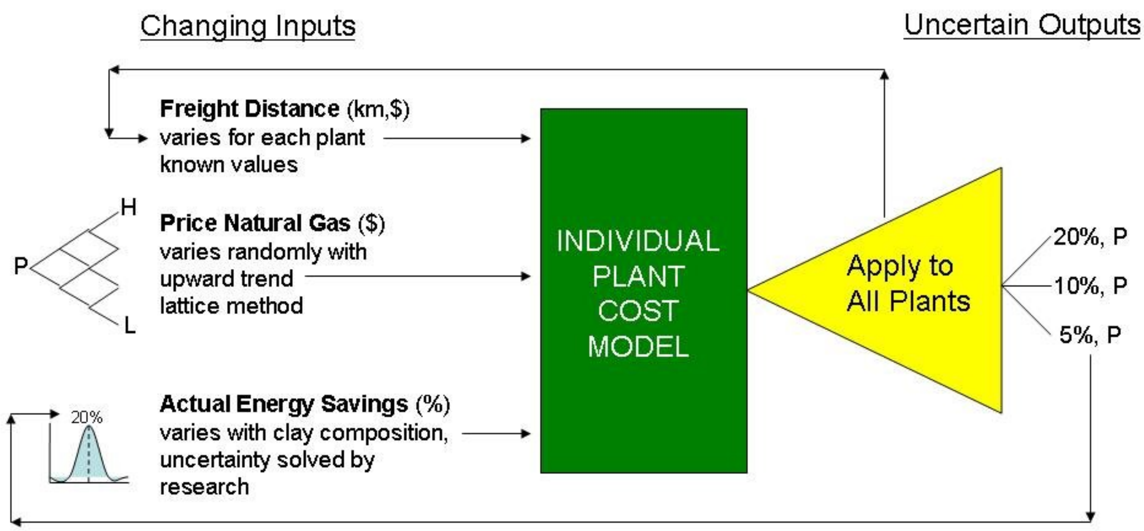

Figure 3.1 Schematic Diagram of Approach to Modeling Uncertain Values and Determining Industry Wide Impact

Through the use of Monte Carlo simulation the information that characterizes the uncertainty about the expected environmental and economic benefits of a brick manufacturer adopting glass cullet as a fluxing agent to the life cycle trade offs described in Section 4.4.2 can be utilized in the cost model described in Appendix A. Given that three of these variables are uncertain, the most appropriate form of analysis is a Monte Carlo simulation.

3.7. Nomenclature

In describing the results of this analysis the thesis refers to Industrial Symbiosis. This area of study considers the exchange of wastes and byproducts from one industry to raw materials or resources for another industry. Chertow (2007) proposes a more detailed nomenclature to define various levels of cooperation. She describes 2 terms:

> Industrial Symbiosis – "at least 3 different entities must be involved in exchanging at least two different resources"

Kernels or Precursor of Symbiosis – “bilateral or multilateral exchange of these types that have the potential to expand, but do not yet meet the fuller 3-2 definition of industrial symbiosis”

This thesis utilizes this same classification system to differentiate between an industrial system and individual elements of the system.

3.8. Conclusions

This chapter has indicated the source of much of the data used to carry out analysis in the next chapter. Both industry wide data available from government agencies and manufacturing information from life cycle studies are available for use in the case study of brick manufacturing. The approach described in this chapter will be applied to the available data in the subsequent chapters of this thesis.

4. Analysis

4.1. Introduction

The United States brick industry is the focus of the current study. This chapter reviews the relevant life cycle studies of brick that have been conducted by the Athena Sustainability Institute, the National Institute of Standards and Technology, and the Swiss Centre for Life Cycle Inventory. In the context of these studies the research considers two potential life cycle changes. These potential changes are the use of glass cullet as a fluxing agent and the use of salvaged brick in new construction. The final section of this chapter evaluates the feasibility of adopting these changes.

4.2. Target Industry and Context

4.2.1. Selecting the Target Industry

The United States brick manufacturing industry has been selected for multiple reasons. First, it is a well established industry that has reached maturity (Venta 1998). Second, information about the industry is widely available because it has a trade association that represents a majority of the approximately 200 facilities across the country. It is regulated by the EPA, so all manufacturing locations are in the Envirofacts Database and economic data is available from the Annual Survey of Manufacturers. Third, the manufacturing process has only three main inputs, clay, water, and energy in the form of heat. Lastly, energy consumption and green house gas (GHG) emissions have a time sensitive value as the potential for climate change legislation becomes more real in the United States.

Selecting the spatial context for evaluation is not arbitrary. Many factors support the selection of the continental United States as the focus of the current study. Due to low levels of imports, and use of domestic natural gas resources and almost exclusively domestic sales, the industry is essentially an island, useful in making definitions about the limits of the system. Given these facts, brick manufacturing is ideal for approaching potential industrial links in a new way.

4.2.2. Description of the Industry

In the United States brick is used primarily as a cladding material for residential and commercial buildings. Use as a cladding material makes up greater than 95% of demand for brick (Clay Construction Products: 2005 2005). As a cladding material, brick faces competition from many different materials. Brick's market share of new house construction is stable, demonstrated in Figure 4.1. Since the introduction of vinyl siding, brick has maintained a relatively constant 20% share of new housing starts.

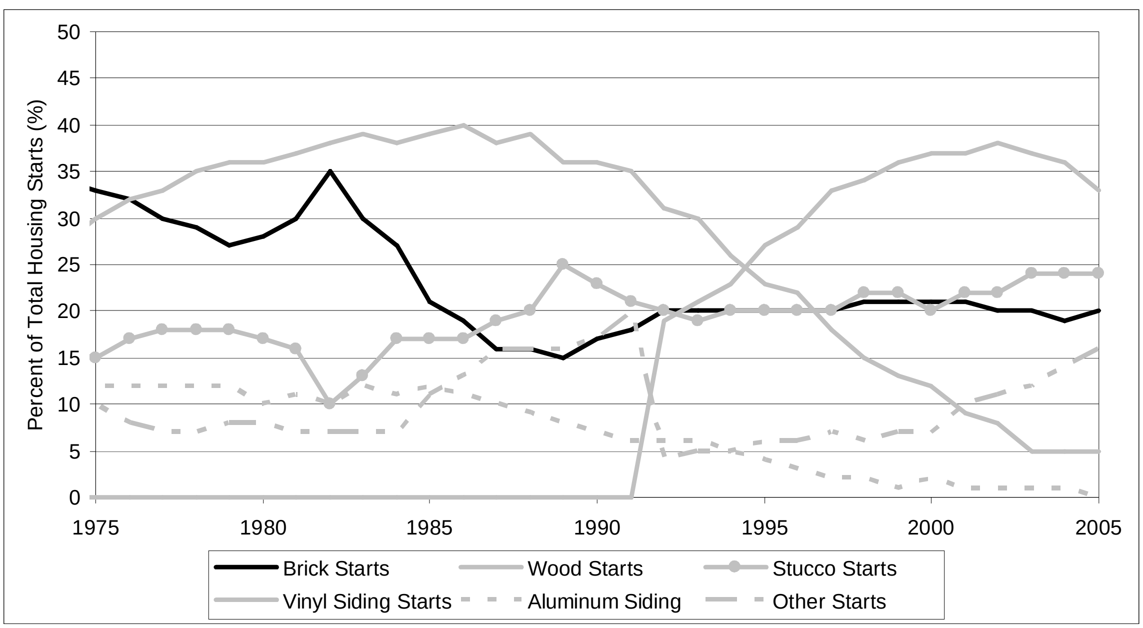

Figure 4.1 Percent of New Housing Starts by Cladding Material Type (US Census Bureau: Manufacturing 2005)

While the material has maintained a constant share of the new housing market, total production has fluctuated along with the new housing starts (show in Figure 4.2). Since "new housing starts" is considered a leading economic indicator, it is reasonable to say that the level of domestic brick production depends heavily on the overall health of the economy.

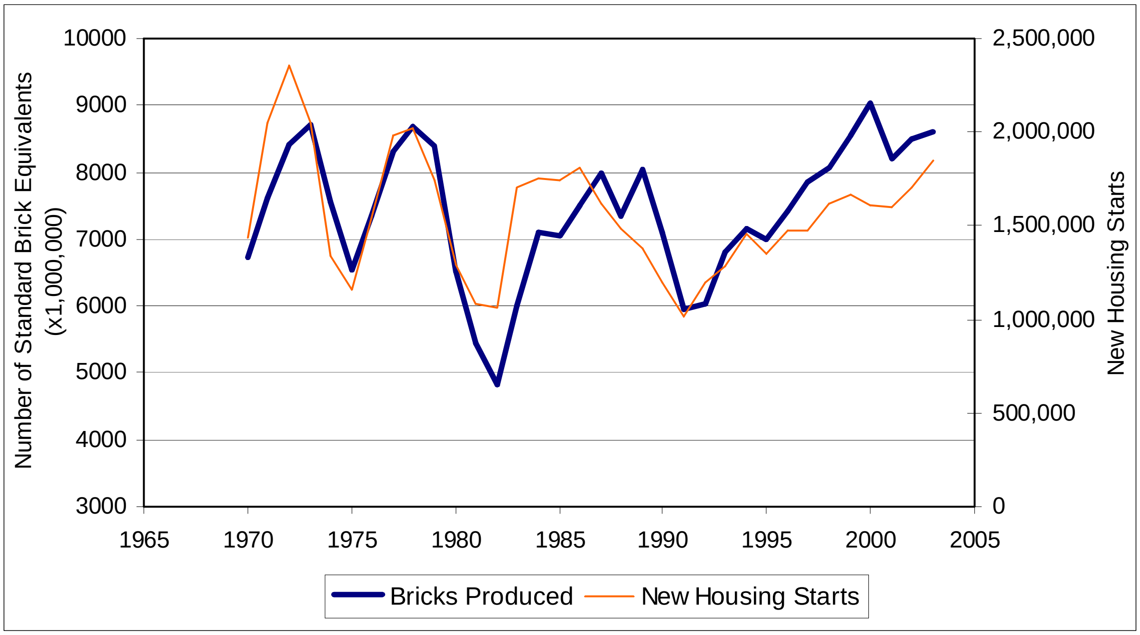

Figure 4.2 Annual Total Domestic Brick Production and Annual New Housing Starts(Speer 2005; US Census Bureau: Manufacturing 2005)

The 200 plus facilities that manufacture bricks are spread across the US, but the highest concentration of these facilities occurs in the Southeastern states (Georgia, South Carolina, North Carolina, and Florida) and Texas. The overwhelming majority of brick is also used in the southern states as well (US Census Bureau: Manufacturing 2005). Multiple factors cause this geographic distribution of facilities ranging from architectural preferences, to availability of raw materials, to the seismic characteristics of the region. Amongst the manufacturers there are multiple manufacturing methods and fuel types, but the defining characteristic of a particular manufacturer's product is the color of manufactured brick. While the consumer is often most concerned with the color of brick, it is in fact the energy consumption that drives the life cycle assessment of brick.

4.3. Life Cycle Assessment of Industry

Energy consumption in the firing process is the most substantial environmental impact of brick. This has been verified in the previously mentioned studies of the life cycle of brick. These studies, conducted by the Athena Sustainability Institute, The Swiss Centre for Life Cycle Inventories, and the National Institute of Standards and Technology have already been described in Chapter 2 of this thesis. The details of the actual consumption of energy and materials in the life cycle of brick also provide valuable information. A typical brick produced in the United States requires 1.8 kg of clay, 0.15 kg of water, 4.5 MJ of energy in the form of heat, cement mortar during the use phase, and transportation through its life cycle including at the disposal phase. The major environmental impact of a typical brick is carbon dioxide emissions totaling approximately 230 g. It is clear that the two most significant inputs into brick manufacturing are clay raw materials and energy. In considering the definition of sustainability for this thesis, both of these inputs must be evaluated in terms of consumption of non-renewable resources.

Clay and shale, consumption is monitored by the United States Geological Survey and it characterizes the availability of clay resources as “extremely large” (Virta 2006). Energy in the form of fossil fuels are also abundant, but concerns about shrinking reserves have prompted substantial reforms in the consumption of what is now considered a scarce and non-renewable resource. This view is supported by statements in the latest National Energy Policy Act (About the Department of Energy: The National Energy Policy 2007). Coincident with concerns about the limits of fossil fuel availability is the growing concern over climate change. The combustion of all forms of fossil fuels produces carbon dioxide and other GHG emissions. Given these concerns of energy and emissions the sustainability priority in brick manufacturing must be the consumption of natural gas. Changes to the life cycle that improve the sustainability of brick should focus on reducing the total energy consumption in manufacturing.

4.4. Strategies for Increased Sustainability

Substantial research has been conducted on the "greening" of brick (Dondi 1997b, 1997a). The overwhelming majority of this work has been conducted in Europe. There are two classes of proposed changes. One is to use salvaged brick in new construction (Gregory 2004) and the second is the use of waste material as a substitute for clay (Dondi 1997b).

4.4.1. Salvaged and Reused Brick

4.4.1.1.Past Research

The first strategy for increasing sustainability in structural clay products is closed loop recycling for brick. There is limited information about the use of "salvaged brick," but one study conducted an analysis of a new house built using salvaged materials (Thormark 2002). Figure 4.3 demonstrates the results of that study.

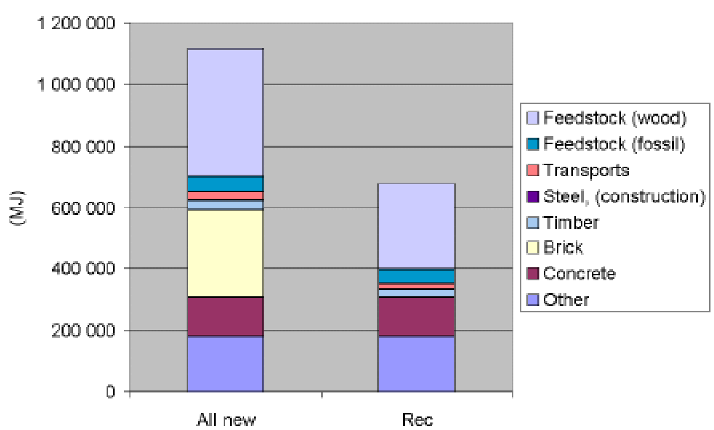

Figure 4.3 Total Energy Consumption All New Materials vs. Reused and Recycled Materials (Thormark 2000)

Salvaged brick offers substantial savings for the embodied energy of new construction under the assumptions in this study. The findings are that salvaged brick reduces energy use for brick by almost 100% and reduces the embodied energy for the whole building by approximately 20%. These results are logical because one salvaged brick avoids nearly all of the resource use for a new brick (fossil fuels and clay minerals). This is the advantage of having such a long life span.

Information is scarce regarding how much salvaged brick is used as well. The US EPA commissioned a study of construction waste in 1998. This report is the only indicator of how much brick exists in domestic waste streams. This meta-study estimated that 65 million tons of construction waste is generated each year in the United States. Approximately 30% of this waste comes from residential sources. Within this study, specific examples were presented to indicate the various components of the total waste stream. Brick composed 14% of residential demolition debris, according to the National Association of Home Builders, and 1% of industrial demolition debris, according to 19 demolition project conducted in Washington (Franklin Associates 1998). This information provides a useful, but limited picture of brick salvage operations in the United States.

4.4.1.2.Analysis of Life Cycle Change

In considering the net benefit of this life cycle change, it is important to consider what the major components are. In the case of using salvaged brick, the trade off is between avoided new production and transportation required to convey the salvaged brick to the site of new construction. Based on the life cycle of brick that is provided in SimaPro 6.0 (Kellenberger 2003), it becomes clear that transportation distance is the only contributor to reducing the environmental benefit of closed loop recycling. Given this fact, a maximum travel distance can be established. Figure 4.4 graphs how environmental benefit drops as travel distance increases. The travel distance can be thought of as the additional distance that an architect should be willing to look for a source of salvaged brick, beyond the distance to a source of new brick.

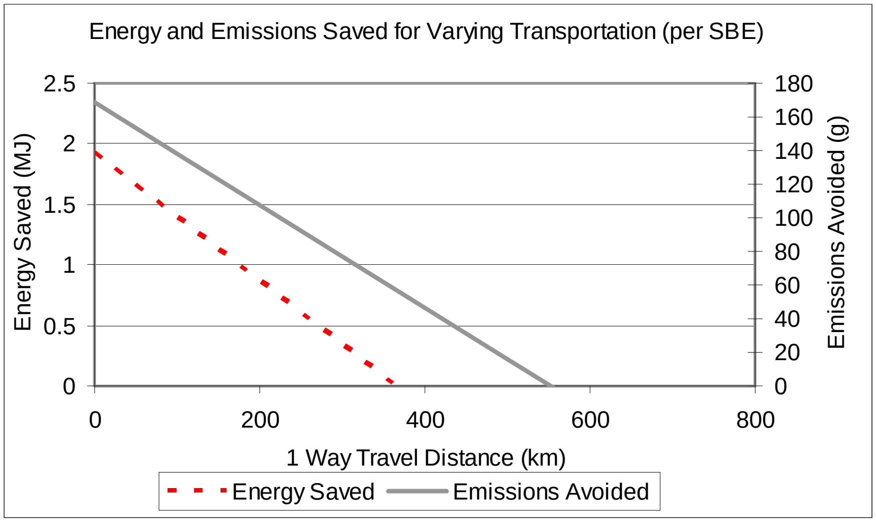

Figure 4.4 Energy and Emissions Saved for Varying Transportation of Salvaged Brick (SimaPro 6.0 2006)

4.4.2. Glass Cullet as a Fluxing Agent

4.4.2.1.Past Research

The second alternative for increasing sustainability of brick is a change in manufacturing, through the use of processed glass cullet as a fluxing agent. A fluxing agent is a material that lowers the vitrification temperature of ceramic. A lower vitrification temperature for a ceramic body means reduced use of energy in firing and consequent reductions GHG emissions. The possibility of using glass cullet was originally studied by CERAM Building Technology and the Waste and Resources Action Programme. In both laboratory and full scale industrial testing, the study found that processed glass cullet did indeed act as a flux. For the particular clay used in the industrial testing, savings were 20% compared to brick bodies without the flux (Smith 2004b). In this study Smith (2004a) also points out that there is substantial uncertainty regarding the scalability of these savings to the entire industry. Based on the three clay types tested in this sample, he speculates that high temperature clays stand to gain the most from such a technology. The work by CERAM is a landmark study for this particular application of glass cullet, but a related study focusing on another type of ceramic found similar results.

In 2004, Tucci et al. (2004) focused on the use of soda-lime scrap glass as a fluxing agent in porcelain stoneware. In a small industry scale study it was concluded that the use of scrap glass lead to “a considerable decrease in firing temperature.” Two studies are not enough to accept beyond doubt the benefits of utilizing processed cullet as a fluxing agent. However, exploring other forms of ceramic materials lends support to the idea that glass cullet can act as a fluxing agent. The glass industry recognizes the benefits of using cullet in the raw material flow. Both fiberglass and glass packaging manufacturers use cullet to reduce total energy consumption (Glass Packaging Institute 2005).

The work by Smith and Tucci et al. represent an industrial link between waste products and ceramics which is distinct from nearly all other studies that have investigated the use of waste in brick manufacturing (Dondi 1997b, 1997a). Most other studies have shown feasibility of using waste, but have failed to show a clear benefit to the brick manufacturer. In considering the potential for new links in Industrial Ecology, a mutually beneficial relationship is a prerequisite. Indeed the potential benefit to brick manufacturers is what makes investigation of processed cullet worthwhile.

4.4.2.2.Analysis of Life Cycle Change

In considering this change to the life cycle of brick, it is again valuable to determine what the tradeoff is for the net energy consumption and emissions of the life cycle. In this case as well the tradeoff is essentially between the energy and emissions savings at the plant versus energy and emissions savings consumed in transportation of the glass cullet to the brick manufacturer. Figure 4.5 graphs this tradeoff and shows a feasible one way transportation distance of 500 km.

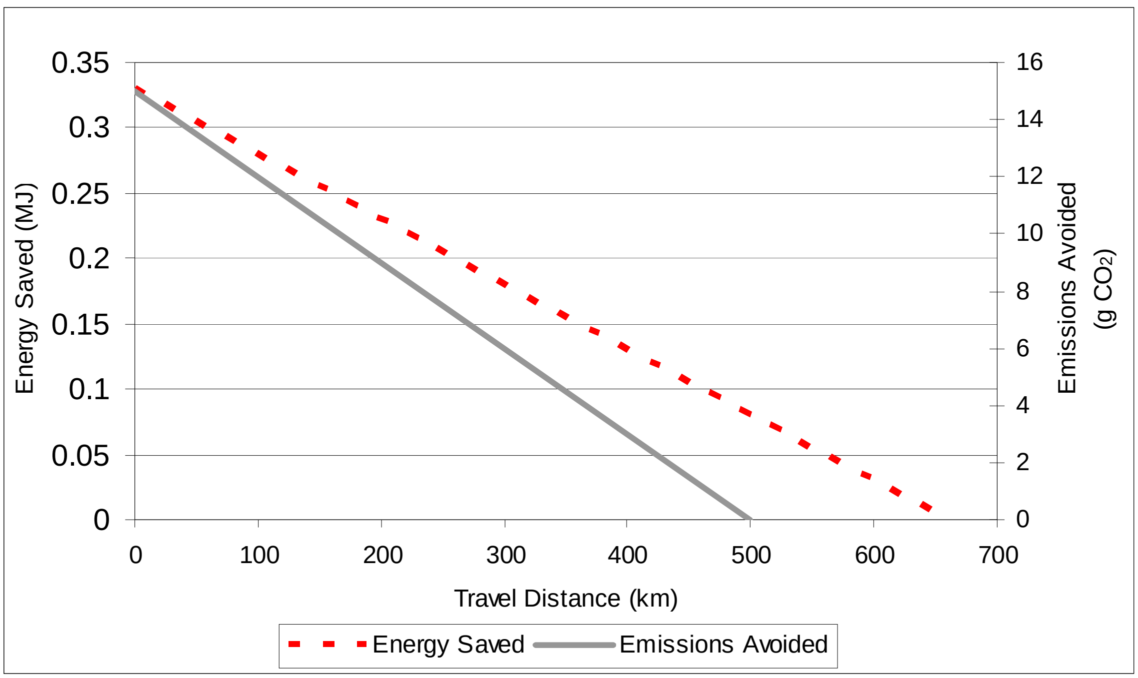

Figure 4.5 Energy and Emissions Saved for Varying Transportation for the Use of Glass Cullet per Standard Brick Equivalent (See Appendix B) (SimaPro 6.0 2006)

The use of salvaged brick and the use of glass as a fluxing agent are not an exhaustive list of life cycle changes that might reduce energy consumption. However, past research into these two changes has shown energy savings at least conceptually and for this reason they warrant extra consideration above any changes that are unproven even at the conceptual level.

4.5. Feasibility

The feasibility of a life cycle change can be limited by a single factor or by a combination of many factors. These factors can serve as an obstacle from any sphere of activity that interacts with the life cycle. This thesis categorizes the range of obstacles to implementation into three groups: technical, economic, and regulatory.

4.5.1. Salvaged Brick

4.5.1.1.Technical

Salvageable brick is generated by the demolition of existing brick buildings. The process of sorting and cleaning bricks from a demolition site is usually conducted by demolition contractors who use only manual labor to complete the process. The limiting factors within this process are whether bricks maintain their structural integrity during the demolition process and how much brick can be salvaged.

Regarding structural integrity, it is generally understood that a solid brick that was manufactured prior to 1945 will likely survive the demolition process and be reusable. However, after that time two changes in the typical life cycle of brick leads to fewer salvageable bricks. The first change began well before 1945. A shift from lime based mortars to Portland Cement based mortars has meant that the bond strength of the mortar is often higher than the strength of the brick itself. Thus, in the demolition or cleaning process the brick is significantly damaged and no longer salvageable. The second change is the shift to extrusion forming. Extrusion processing is what leads to the familiar set of 3 to 5 holes in the body of a brick. This change also reduces the ability of brick to withstand demolition. Additionally, cement mortar often bonds within these extrusion holes and again the cleaning of such a brick becomes impossible. An exception to this is “pavers” (bricks used in decorative pavements), which are still solid body bricks.

Additionally, they are often set with sand and not mortar. However, pavers make up less than 5% of the total brick demand in the United States each year (Clay Construction Products: 2005 2005).

These historic changes indicate that there will be a continual decrease in availability of salvageable bricks from the waste stream of demolished buildings. The current availability of bricks in the waste stream is not known, but the 1998 EPA study estimated that there were approximately 136 million tons (57% residential) of building related construction and demolition debris generated in the United States in 1996 (Franklin Associates 1998). Fifteen percent of this debris is from residential demolition and 33% is from non-residential demolition. Additionally, from extremely limited case studies from the Pacific Northwest, 1% of non-residential demolition debris is brick and 6% of residential demolition debris is brick (Franklin Associates 1998). Totaled together, this means that in 1996 there was approximately 500 million bricks in the waste stream from demolition projects across the country. If it is assumed that building being demolished are all at least 30 years old, but no older than 100 years old, then approximately 50% of the available bricks would predate the 1945 cut off date. Additionally, if a salvage rate of 75% is assumed, then this means that there were 190 million bricks available for salvage in 1996. A single point in no way indicates a trend, but this first cut analysis gives a descriptive picture of the prospects for salvaging brick. Given the manufacturing and installation changes that help to limit overall availability, it is probable that salvaged brick could only fill between 2% to 2.5% of the brick consumption in the United States annually.

4.5.1.2. Economic

No conclusive analysis has been conducted as to the comparison of costs between new brick and salvaged brick. Price quotes from vendors that sell both used and new brick indicate that the cost of salvaged brick can range anywhere from 50% of new brick to 150% of new brick (Watkins 2007). Another relevant conceptual point is that since brick is often selected based on color, it is nearly impossible to maintain a consistent color when utilizing salvaged bricks, so the market for salvaged brick may not be as large as that of new brick.

4.5.1.3.Regulatory

A lack of information regarding the price limits economic analysis of salvaged brick, but there is plenty of information regarding about the use of salvaged brick. Multiple building codes, particularly the Uniform Building Code, require that the allowable working stress of "reused" masonry be 50% of new brick and that the structural properties of "reused" brick must be determined by approved testing methods. In addition to these requirements, the Standard Building Code requires that salvaged brick may not be used in external surfaces that are also structural (BIA Technical Notes 15 - Salvaged Brick 1988). These requirements place restrictions on a project manager or architect in any attempt to use salvaged brick.

4.5.2. Glass Cullet as a Fluxing Agent

4.5.2.1.Technical

Many of the questions about the technical feasibility of using cullet in brick manufacturing were answered by Smith and the CERAM study (2004a). The potential limiting factors in this area are generated by the availability of processed glass cullet in the United States. According to the CERAM study, particle sizes ranging from 1 micron to 40 microns should make up as much as 85% of the cullet that is used. Strategic Materials Inc. is the largest glass processing firm in the United States and they indicate that they are able to produce material that passes the .325 sieve which is equivalent to particle sizes less than 44 microns (Strategic Materials Capability Chart 2007). While they have the capability to produce, according to a company spokesperson, there is not a pre-existing market for this material and as such, no material of this particle size is produced in large quantities (Dudak 2007).

This raises the question of whether there is sufficient capacity for processors to meet the increased demand for processed cullet if brick manufacturers began to utilize it. At present, the United States recycles approximately 25% of the 10.9 million tons of glass packaging that is generated every year (Municipal Solid Waste in the United States: 2005 Facts and Figures: Executive Summary 2006). Of the glass packaging that is recycled, nearly 80% is used in manufacturing new glass packaging (Glass Packaging Institute: Recycling News 2007). Much of the remaining 20% goes to other glass products like fiberglass. So while the existing recycled material is near capacity, there are significant resources that can be tapped. If the entire industry were to utilize glass cullet at the rate of 5% per brick this would cumulatively represent the use of 810,000 tons of recycled glass each year. This is 10% of the waste glass that is currently not recycled. Increased glass recycling rates can lead to greater availability of processed cullet. All that is necessary to generate this change is a market demand for more high value product like processed glass cullet.

Before turning to economic limitations, the last and most critical technical limitation must be considered, the specific interaction between a source of clay and glass cullet. There is no empiric relationship between clay chemistry and glass cullet chemistry that will indicate what the correct amount of glass cullet to include in the raw material flow might be for optimal energy savings. Smith (2004b) points this out in his study. This fact is corroborated by Dr. Denis Brosnan, Director of the National Brick Research Center. In fact, research needs to be conducted for each source of raw material. The duration and cost of this work can be between six and twelve months and can cost $500,000 to $1,000,000 for reliable results (Brosnan 2007). However, preliminary investigations can be conducted for as little as $10,000 and the findings of this analysis will give a strong indication of what the potential benefits might be (Smith 2007).

4.5.2.2.Economic

The economic feasibility of using cullet is closely related to the market demand for more processed glass cullet. Assuming that a brick manufacturer will only adopt life cycle changes if they increase the firm's economic wealth then it is necessary to determine whether it might be cost effective for a brick manufacturer to use glass cullet in the raw material flow. Figure 4.6 shows the average cost of manufacturing in the United States.

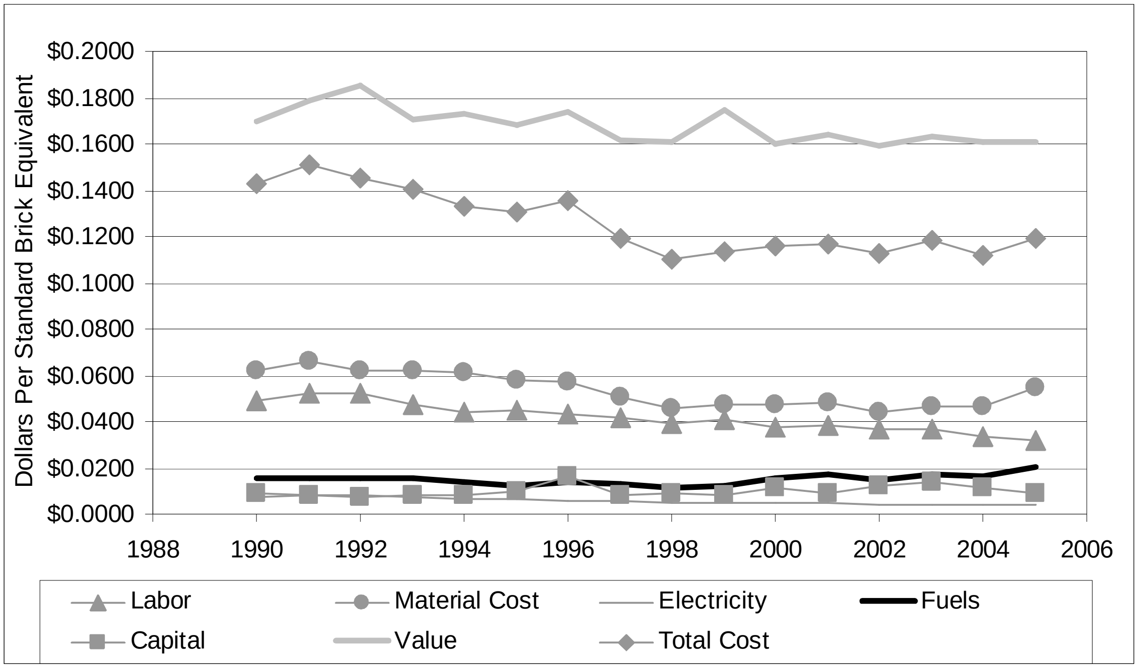

Figure 4.6 Cost and Revenue for Heavy Clay Materials Industry Normalized to Per Standard Brick Equivalent Basis, 1992 Constant Dollars (Annual Survey of Manufacturers: Statistics for Industry Groups and Industries 1990-2005)

This graph clearly demonstrates that the costs that the industry faces are relatively stable and there are no dramatic changes that have affected the cost of production over the last 15 years. Given this situation, it is reasonable to construct a cost model of a typical brick manufacturer based on values from the 2005 industry averages (see Appendix A). Given these costs, applying them to the life cycle of brick developed by Kellenberger et al. (2003) Figure 4.7 shows that the use of glass cullet can already be feasible for glass cullet prices that are prevalent in the industry at present.

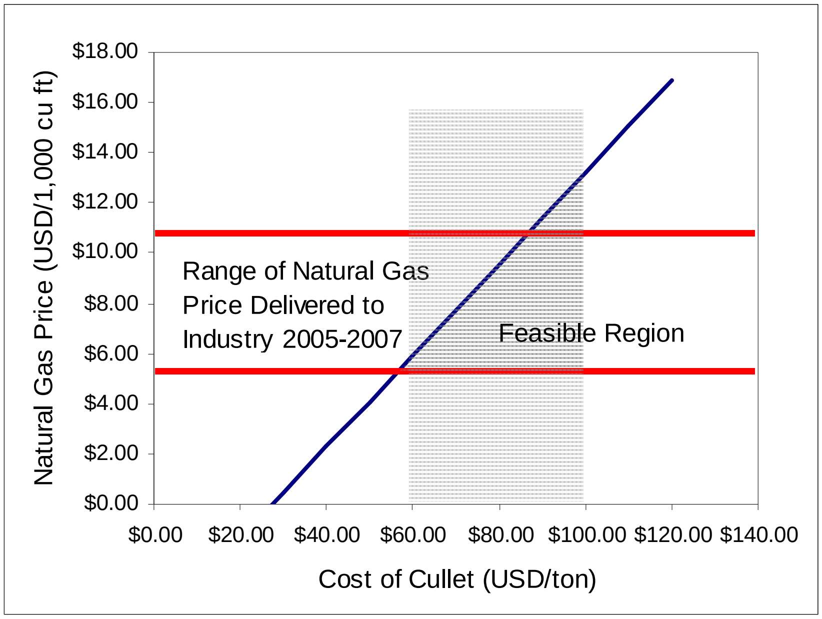

Figure 4.7 Break Even Price of Natural Gas for Vary Costs of Acquiring Glass Cullet with 20% Energy Savings (Energy Information Agency: Natural Gas Navigator 2007; Dudak 2007; Poole 2007)

While this graph indicates potential economic feasibility, it also evidences an important consideration that will further inform analysis of whether market forces can motivate this change to the life cycle. The price of natural gas delivered to industry will have a substantial effect on the desirability of utilizing glass cullet. A second consideration that is not apparent in this graph is the transportation distance of cullet will have a large impact on economic feasibility in the form of freight charges for transporting the material. These considerations will be valuable in future analysis.

4.5.2.3.Regulatory

Regulatory feasibility has two potential impacts on the use of glass cullet in brick manufacturing. The first potential source of limitation is regulation relevant to the change in the life cycle of brick. The second source of potential limitation is whether or not the change in product characteristics are within the acceptable limits of building code requirements for construction materials. Regarding changes to the life cycle, no regulation prohibits additives in brick manufacturing, glass cullet is not considered a hazardous waste material under the RCRA. There are no apparent regulatory limitations on the change to the life cycle. Regarding bricks made with this modified life cycle, it must meet the same standards as a regular brick. The International Building Code refers to the American Society of Testing and Materials standards C62, C652, and C216. The results reported by Smith meet the material property requirements set forth in this these standards (C216-07 Standard Specifications for Facing Brick (Solid Masonry Units for Clay or Shale) 2007). So it would appear that there are no regulatory limitations on this change to the life cycle of brick.

4.6. Conclusion

Previous research has demonstrated that the use of glass cullet as a fluxing agent and closed loop recycling through salvaged bricks can reduce the environmental impact of the life cycle of brick. This research has examined the feasibility of both of these options. From the findings of the current work it is found that the feasible travel distance for salvaged brick is approximately 400 km. However, regulation in the form of building codes limits the ability of builders to use salvaged brick. The analysis concludes that because of the limitations of building codes and the shrinking stock of salvageable brick, closed loop recycling is unlikely to be scalable to industry wide savings.

In contrast to salvaged brick, the use of glass cullet as a fluxing agent is highly feasible. The research finds that a transportation distance of up to 500 km will still yield environmental benefit. Economic feasibility also appears to be reasonable and there are no limitations placed on the life cycle change by regulation. Therefore, the use of glass cullet as fluxing agent has the potential to scale to the entire industry.

5. Quantification of Environmental and Economic Benefit

5.1. Introduction

The previous chapter outlined the challenges to making brick a more sustainable product. Also in the previous chapter, the comparison of two life cycle changes was presented. The conclusion of this comparison was that the focus of efforts to increase sustainability should be at the front end of the life cycle of brick. The current chapter determines the net economic and environmental benefit to the brick manufacturing industry for the potential adoption of using glass cullet as a fluxing agent. Of particular importance in the results is the ability to identify not only cumulative values, but to pinpoint which locations stand to gain the most from the adoption of this change. In this way the analysis identifies stakeholders and motivation for these stakeholders.

5.2. Findings

In this study the probable benefits are considered over the next 6 years (in this case 2007-2012). Figure 5.1 shows the results of the Monte Carlo simulation for the expected economic value based on the cost faced by the industry (see Section 4.5.2.2 and Appendix A). The following figure graphs the cumulative distribution function of potential economic outcomes and can be read as, in the case the Binomial Pricing scenario, there is a 60% probability that the economic benefit to the industry will be $30 million or higher (for details see Appendix C).

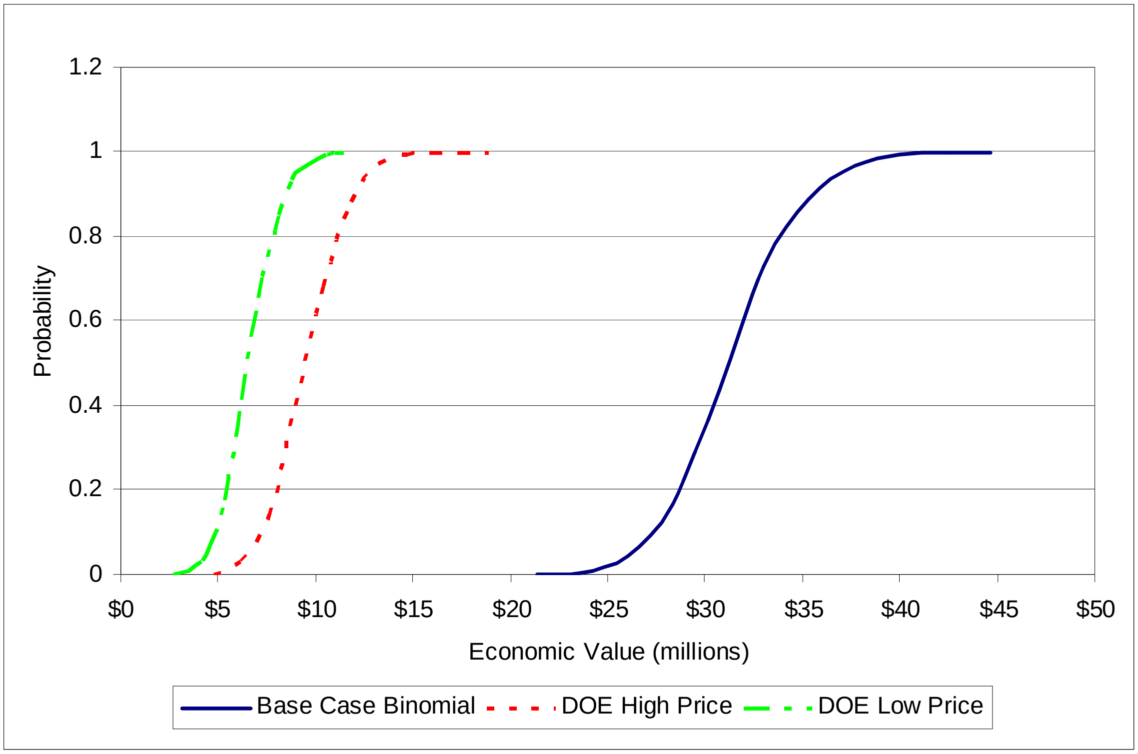

Figure 5.1 Cumulative Distribution Function of Economic Value to Industry over 6 Years with a Discount Rate of 10%

Reading the information on this graph, if one considers uncertainty in the price of natural gas to be best modeled by the binomial lattice approach, there is a 99% probability that the expected benefits to the industry will be $25 million.

The results of this are based on the assumption that a plant decision maker will only choose to use glass cullet if it is of a positive economic benefit to their individual plant. In looking at Figure 5.1, the Department of Energy: Energy Information Agency's (EIA) predictions of natural gas prices are substantially lower than some of the outcomes that the binomial approach considers. This illustrates just how large an effect prices will have on rates of adoption this technology. Consequently natural gas prices will have a substantial effect on the environmental benefits as well. Figure 5.2 graphs the expected emissions avoided given the same future price scenarios.

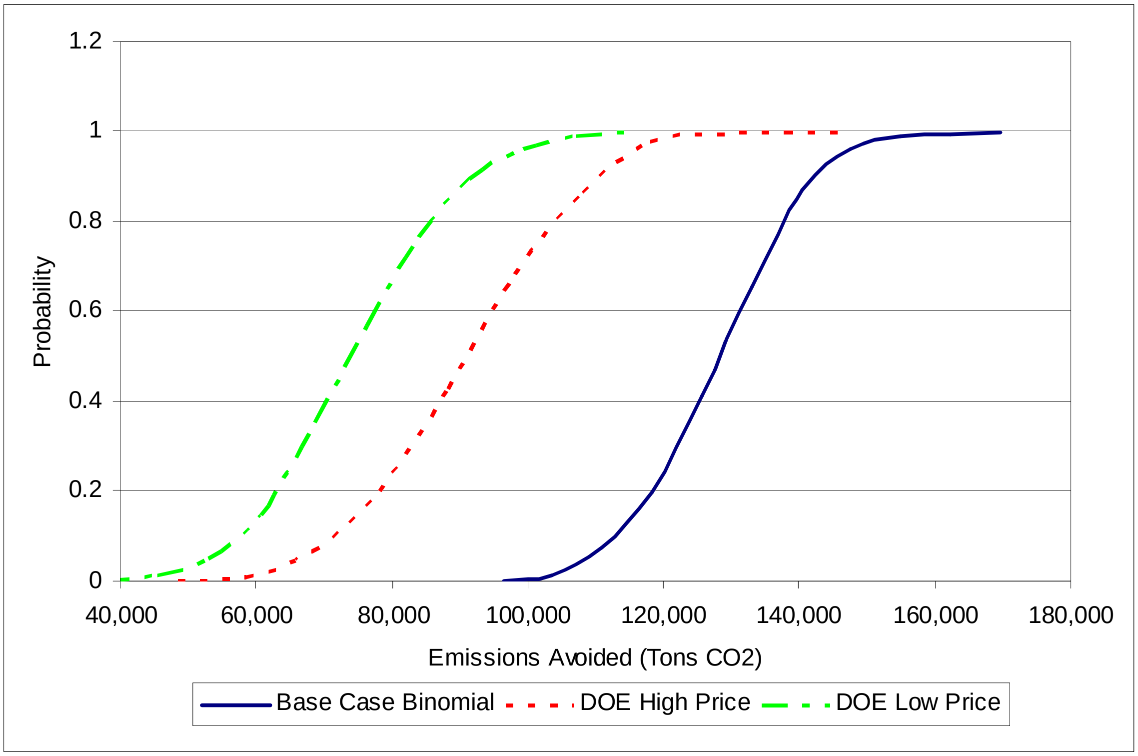

Figure 5.2 Cumulative Distribution Function for Emission Avoided in Industry Over 6 Years with no Discounting

As can be seen in Figure 5.2, higher natural gas prices will motivate more brick manufacturers to choose to use glass cullet as a fluxing agent because of the increased value in saving energy. Another valuable insight that can be gained from Figure 5.2 is that under the current economic conditions there is no risk of efforts to use glass cullet generating costs to the environment. The cost of transportation prevents situations where a brick manufacturer would look beyond the feasible travel distance discussed in Section 4.4.2.2. The connection between cost of energy use and emissions avoided leads one to consider the impact of GHG emissions legislation in the United States.

Figure 5.3 considers potential outcomes under different decision criteria. The first decision criterion is the case where all brick manufacturers begin to utilize glass cullet as a fluxing agent regardless of cost. In this case net environmental benefits are clearly negative. The second case is where every brick manufacturer that stands to reduce net emissions chooses to use glass cullet regardless of cost. In this case the net benefits are obviously positive and as can be seen in Figure 5.3 under the assumptions the binomial prediction of future natural gas prices, approximately 80% of the environmental benefit would already be achieved without any form of incentive.

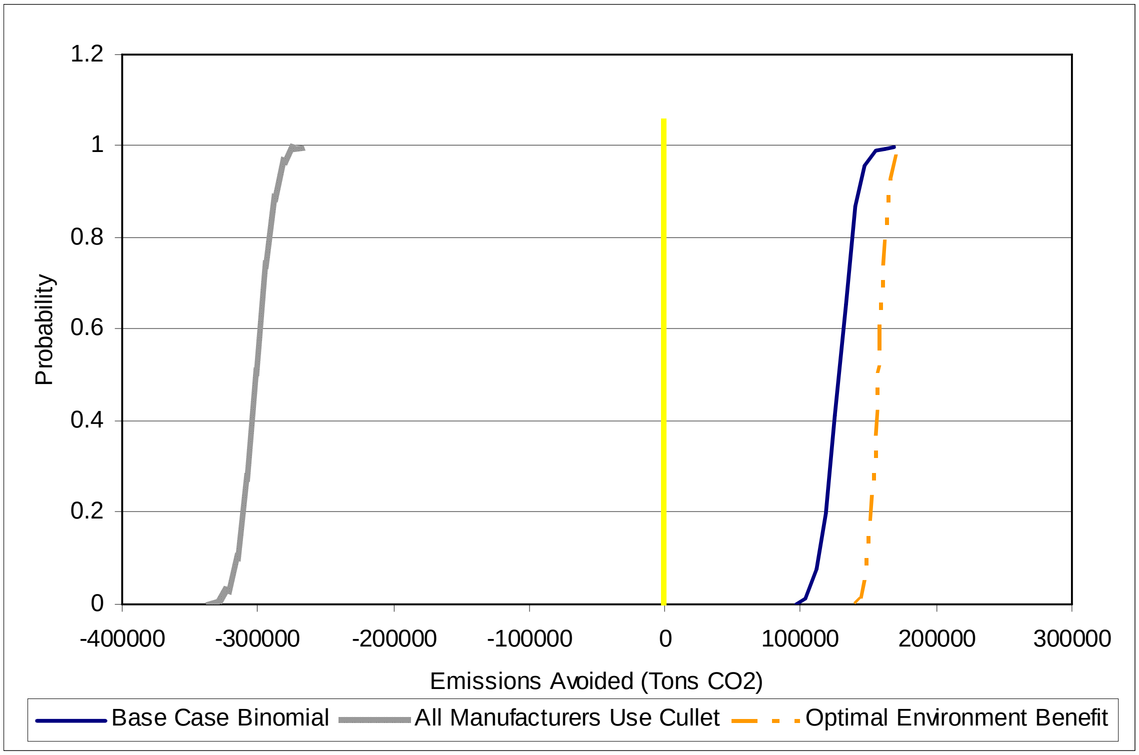

Figure 5.3 Cumulative Distribution Function for Emissions Avoided in Industry Over 6 Years with No Discounting

Additional incentive increases the economic benefit to the manufacturers who would already use cullet, but it would required a carbon tax of on the order of $40 per ton CO_2 to motivate additional firms to adopt the life cycle change in their facilities (see results in Appendix C). Regardless of carbon taxation, the economic and environmental benefits are clear. Within this cumulative effect, specific locations exist that will garner the largest share of these benefits.

5.3. Spatial Context and Industrial Symbiosis Precursor Identification

As has been mentioned frequently, the benefits to be received from the use of an artificial fluxing agent are dependent on the local chemical composition of clay for brick manufacturers. And since an empirical relationship does not exist to determine optimal cullet amounts and energy savings a research program would be required to determine the necessary changes to the raw material stream. The cost of such a research program and the necessary infrastructure changes might range between $500,000 and $1,000,000 for a facility (Brosnan 2007) while initial investigations could cost as little as $10,000 (Smith 2007). So to implement this life cycle change for the entire industry would require research projects and process modifications totaling as much as $200,000,000. Taken collectively in this way, the costs clearly outweigh the benefits. However, the benefits are not evenly distributed across the entire industry. This means that the change need not be implemented across the industry. In some locations benefits outweigh facility specific costs.

This is an important point; indeed this is the most important point of the thesis. The benefits are not evenly distributed across the industry. A subset of those plants that might adopt this life cycle change stands to gain the lion share of benefits, both economic and environmental. Identifying which plants these are is of great value in finding industrial links that will have agents to act and realize the benefits of improved resource use. As a part of developing the model for analysis, it was necessary to determine the distance between glass cullet processors and brick manufacturers. This work really informs the spatial contexts where the highest benefits are located. Figure 5.4 shows the location of brick manufacturers and glass cullet processors in the United States.

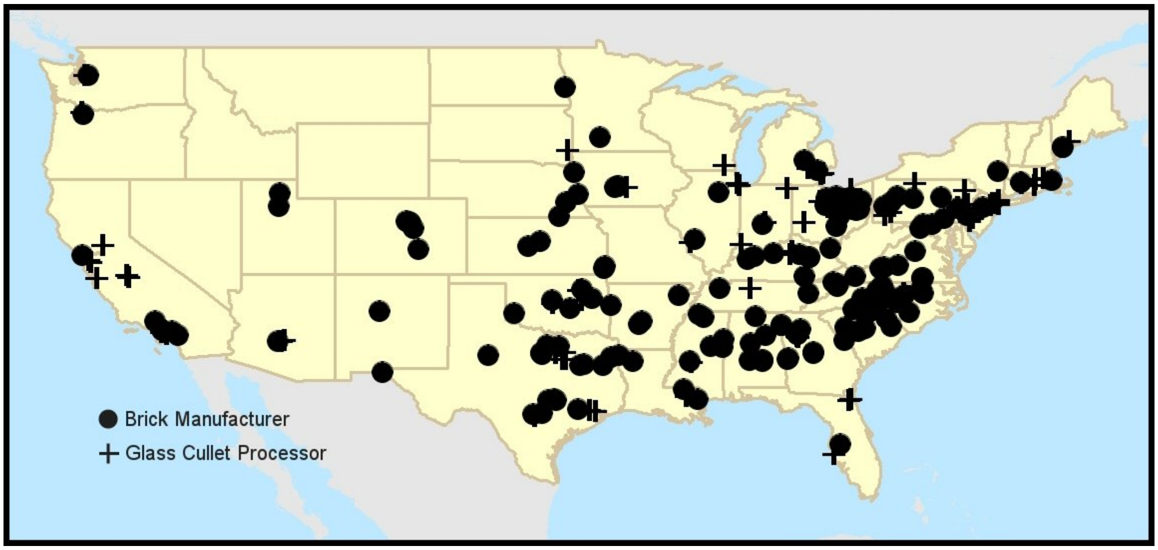

Figure 5.4 Map of Location of Brick Manufacturers and Glass Cullet Processors in US

Through the analysis conducted in this research this messy and relatively difficult to read map can now be screened to only include facilities that are likely to have substantial economic gains. Figure 5.5 identifies the seven "hot spots" where economic gain is expected to be greatest.

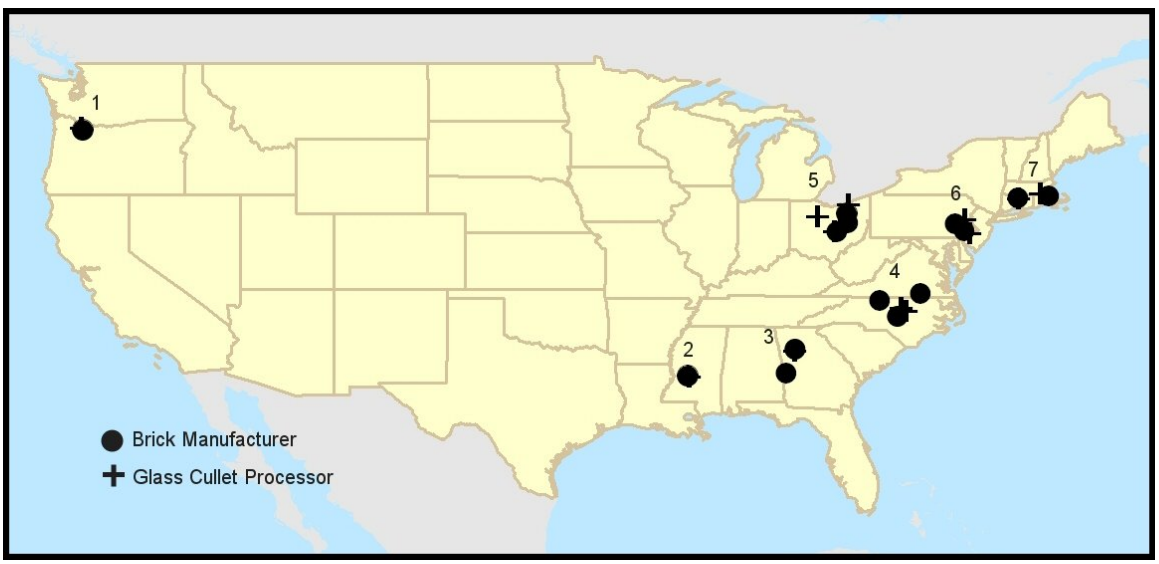

Figure 5.5 Map of Facilities with Expected Economic Gain Greater than $100,000 under EIA Future Natural Gas Pricing

Table 5.1 presents the facilities' names and locations for the seven areas.

#	Brick Plant Name	Glass Cullet Processor	Location	
5	Belden - Plant #2-9 Sugarcreek	Strategic Materials Inc.	Newark	OH
3	Boral - Atlanta Plant #7	Strategic Materials Inc.	Atlanta	GA
3	Boral - Columbus Plants (4)	Strategic Materials Inc.	Atlanta	GA
5	Bowerston Shale Company - Hanover Plant	Strategic Materials Inc.	Newark	OH
4	Brick & Tile Corp. of Lawrenceville - Plant 3	Strategic Materials Inc.	Durham	NC
5	General Clay Products Corp	Strategic Materials Inc.	Cleveland	OH
3	General Shale Brick – Atlanta - Plant #30	Strategic Materials Inc.	Atlanta	GA
4	General Shale Brick - Brickhaven #25	Container Recycling Alliance	Raleigh	NC
4	General Shale Brick - Moncure - Cape Fear Plant	Container Recycling Alliance	Raleigh	NC
5	Glen-Gery Corporation - Iberia Plant	Dlubak Glass	U. Sandusky	OH
6	Glen-Gery Corporation – Mid-Atlantic Plant	Todd Heller Recycling	Northampton	PA
1	Mutual Materials Co Inc	Strategic Materials Inc.	Portland	OR
4	Pine Hall Brick - Madison Face Brick Plants (2)	Strategic Materials Inc.	Durham	NC
7	Redland Brick Inc. - K-F Plant	Nutmeg Recycling	East Hartford	CT
6	The McAvoy Brick Company	Blue Mountain Recycling	Philadelphia	PA
7	The Stiles & Hart Brick Company	Container Recycling Alliance	Franklin	MA
4	Triangle Brick Company/Carpenter Plant	Container Recycling Alliance	Raleigh	NC
4	Triangle Brick Company/Merry Oaks Plant	Container Recycling Alliance	Raleigh	NC
2	Tri-State Brick and Tile Co Inc	Strategic Materials Inc.	Flowood	MS

Table 5.1 Locations of Highest Probable Economic Value in Adopting Life Cycle Change (Expected Value Greater than $100,000 in DOE EIA Low Price Case)

Using either future price predictions, the fact remains that if this technical innovation can make a net reduction on the environmental impact of brick manufacturing, the locations where that benefit is most likely to happen have been identified.

5.4. Sensitivity of Assumptions

The current analysis depends heavily on assumptions made about an entire industry that are unlikely to be true in all or even any specific cases. As is clear in Chapter 4, the future price of natural gas truly dominates the environmental impact that can be made by changing the life cycle of brick in specific cases. If the more widely ranging Binomial Pricing scenario is utilized, the value to the above facilities is dramatically increased and additionally, many more facilities may become interested in the technology. Other assumptions that were not considered as uncertain that affect the findings of this research are changes in the level of production for brick manufacturers across the country. This will serve to scale the benefits either up or down depending on the relative trend in production. A last assumption that can have a dramatic effect on the findings is how production is distributed amongst the industry members. In the absence of information regarding annual production for individual plant it is impossible to include this in any kind of analysis. As a substitute, industry wide production has been distributed evenly, but it is known that production can vary as much as 10 times the assumed value to one half the assumed value.

Given these qualifications, the value of the research is clear. The use of glass cullet is a life cycle change that warrants further investigation by brick manufacturers in the United States. Given the binomial case of natural gas pricing, the industry as a whole stands to benefit by anywhere from 0.5% of its profit to 1.0% of its revenue in a six year time frame and reduce its life cycle emissions from 0.5% to 0.7%. These are real gains that can be generated through market forces.

5.5. Conclusions

This work indicate that absent the cost of initializing the use of glass cullet (i.e. research costs and process modification) the value is most probably in excess of $25 million dollars in the binomial case prediction of future natural gas prices. Additionally, the technology can result in greater than 100,000 tons of carbon dioxide not released to the atmosphere (in the binomial case) over 6 years. Beyond these cumulative values, the analysis was able to identify exactly which facilities stand to gain the largest portion of economic gain. The analysis has identified the locations that should be the focus of efforts to disseminate information about this opportunity. This original work has not only validated claims about the economic benefits of glass cullet as a fluxing agent, but has also demonstrated the feasibility of using generally available information to search for "hot spots" that can have real economic gains through adoption of industrial symbiotic relationships across industries.

6. Discussion

6.1. Introduction

This chapter of the thesis discusses the participation of stakeholders in realizing the previously described environmental and economic benefits. After outlining this relationship, the chapter moves on to consider this approach as compared to past efforts to identify and initiate industrial symbiotic relationships. Finally, the chapter makes policy recommendations for this specific case and for the research approach in general.

6.2. Overcoming Cost

Through this analysis, the most promising locations for the establishment of inter industry links have been identified. While multiple possible locations have been identified under future gas pricing scenarios, few of these locations have an average economic benefit that is substantially beyond the cost of research needed to allow for implementation of the change. Looking at the list of facilities, an interesting phenomen is present. There are multiple areas that have multiple brick manufacturers within a feasible distance. These cullet suppliers are stakeholders as well and they stand to gain economically as well as the brick manufacturers. Therefore it is reasonable to assume that they would be willing to participate financially in a research program to eliminate the uncertainties involved in the level of available benefit in the symbiotic relationship. Establishing these contacts is the critical next stage of this work.

6.3. Is It An Industrial Symbiosis Precursor?

Before comparing this approach to other approaches, it is important to determine whether or not the relationship being described is actually an Industrial Symbiosis Precursor. If processed glass cullet is an available material and the result of brick manufacturers utilizing glass cullet is simply a new use for an industrial product, there is no mutually beneficial relationship. Considering only glass cullet processors and brick manufacturers, this is a reasonable description of the system in consideration. However, if the processor is thought of as a contact point and one considers the brick industry and the glass packaging industry, one begins to see the symbiotic nature of the relationship.

Glass packaging is recycled at a rate of approximately 25% of the 10-12 million tons created each year. Nearly all of this recycled glass is already allocated within the glass industry. If all of the brick manufacturers that stood to gain financially began purchasing glass cullet, it would lead to a new demand for high value processed glass cullet on the order of 600,000 tons a year. Assuming the recycling infrastructure can handle increased throughput this would increase the national recycling rate to 30%. Thus it is indeed an Industrial Symbiosis Precursor from an environmental perspective in that the brick industry system benefits from improved resource efficiency and the glass container industry system benefits from reduced waste generation.

6.4. The Research Approach as a General Method

The case study has found a potential model for Industrial Ecology. Previously discussed approachs (eco-industrial parks and region-based studies) have found limited success in actually initiating increased sustainability. The former has struggled from the limitations of central planning as described by Heeres (2004) and Desrochers (2004) and the latter has struggled from both a lack of motivating incentives and the absence of an agent to promote the vision of Industrial Symbiosis, as chronicled by Kincaid and Overcash (2001). The current approach is an advance over previous efforts in multiple ways.

While both EIP's and the regional study have the advantage of field testing, through the dissemination of the results, the current research will also be field tested. If all three approaches are considered as a method to search for and quantify industrial linkages, the findings of studies conducted in a similar manner to this study create advantages that cannot all be gained in the EIP or regional approach. Those advantages are:

1. **Focus on the entire industrial sphere (both existing and emerging)**

The EIP approach to generating Industrial Symbiosis focuses only on facilities that are new. This speaks to only a small portion of total environmental impact from industry. Both regional approaches and the current industry approach focus on existing industry, therefore the time horizon for these approaches to have substantial effects is effectively shorter.

2. **Incremental development of larger Industrial Ecology**

Conceptually, this approach and the regional approach allow for an evolutionary development of a sustainable industrial ecosystem. In fact, this approach much more closely matches a natural ecosystem's evolution. This is in comparison to the EIP approach that is more of a step-wise approach to achieving sustainable development.

3. **Identification of agents for initiation**

As Jackson and Clift (1998) have described, a major issue limiting the adoption of industrial ecological thinking is the idea of "agency." Who will act to establish linkages across industries? In this case with such clear economic benefit for both partners in the potential link, the agents are the firms themselves and they have been identified.

4. Development of measurable incentive to investigate relationship

Closely related to the idea of an agent to actuate a change in industry is the idea of motivation for the agent. This speaks directly to the idea that both Desrochers (2004) when he says “market mechanisms” and Esty and Porter (1998) drive at commenting on the “competitive advantage” of industrial ecological thinking. At the firm level, the only motivation to adopt more sustainable practices must be profit. This analysis identifies what the economic benefit would be to the participants in the link.

5. Concentration of technical expertise

In this approach, it was only necessary to focus on one industry and a small set of related technical matters. This made the analysis manageable for a single person with a single area of expertise. This is an improvement over the regional approach where many forms of expertise would be required to accurately understand the subtleties of any potential industrial symbiotic relationships.

The limitations of this approach are centered completely around available information. While these are substantial obstacles, they are rapidly being reduced by the rapid growth in available information. In the case of locations of different types of facilities resources like the EPA’s Envirofacts Data Warehouse provides location information for all facilities that are regulated by the EPA in the United States. This information combined with powerful tools like geographic information systems and life cycle analysis databases drastically increases the ease of this type of analysis. In summation, this approach only provides information, but it provides information that is of interest to the people who would adopt any life cycle change that might lead to increased sustainability.

6.5. Policy Recommendations

There are really two areas of recommendation regarding policy. The first relates specifically to this case of brick manufacturing and the use of glass cullet as a fluxing agent. The results of this analysis indicate that there are clear environmental benefits to the use of glass cullet as a fluxing agent. There are also clear economic benefits beyond the cost of determining certain technical parameters. Depending on the future price of natural gas, regulation that placed a cost on the emission of carbon dioxide may serve to increase the use of this technology. So a carbon tax or cap and trade systems may be effective, but in this case, the greatest cost is in the research necessary to establish optimal mix designs and what the actual energy savings might be. It is in facing this cost that a policy might be most helpful. Something as simple as a research grant from the National Science Foundation or the Environmental Protection Agency in partnership with brick manufacturers and glass cullet producers (both of whom have an economic stake in the results of the research) is most likely to lead to a realization of environmental benefit in this case.

The second area of policy recommendations speaks to the competitive advantage that the United States has in its information. From Census reporting in the annual survey of manufacturers to geographic and waste material information collected by the EPA, the US industry has the potential to benefit economically from all this information. This research is a strong example of such advantage. Imagine an online tool that allows a firm to input its raw materials and quickly determine if there is a facility somewhere in their vicinity that produces the same product as waste. This model of the world is not as ridiculous as it might seem. Online tools like Google Earth or Virtual Earth by Microsoft are capabilities that already exist. As these tools become more common place it is only necessary to disseminate the evaluation methods like those used in this thesis to identify the most fertile areas for increasing sustainability through Industrial Ecology.

6.6. Conclusions

This chapter has discussed the stakeholder relationships and how potential benefits might be achieved. The second section provided a clarification on the use of the term Industrial Symbiosis in this particular case. Finally, this chapter has described the advantages of this method over other approaches to create industrial symbiotic relationships and concludes by indicating what policy recommendations might be made to promote both this individual opportunity for increased sustainability and in general through Industrial Ecology.

7. Conclusion

7.1. Introduction

Sustainable development and growth is the most difficult and most important challenge that humanity faces today. On a planet with limited resources, how can the current generation meet its needs without depleting future possibilities? The field of Industrial Ecology has emerged as one approach to conceptualize real sustainability and determine what steps might be appropriate for achieving this goal. The useful tools of life cycle assessment and material flow analysis have lead to a rapidly growing knowledge of the industrial system that consumes the limited resources of Earth. Having found opportunities to increase sustainability through research in areas like Industrial Symbiosis, the question posed by Jackson and Clift (1998) remains. How can the stakeholders who must act to achieve potential gains be identified and how can they be motivated?

This thesis has presented a method for identifying potential gains through geographic information systems, life cycle assessment, and financial analysis tools. Using the brick industry and the glass packaging industry as a case study for this approach, the research demonstrated measurable economic gains that might be recognized for adopting a life cycle change that benefits the environment as well. In the case of brick manufacturing the expected value of adopting environmentally preferable options can be as high as $40 million. Not only has this thesis presented the cumulative benefit of this information, it has identified where this value is most likely to accrue. In essence, the approach has taken 200 potential locations for Precursors and determined the 20 locations that have the greatest economic incentive to adopt the life cycle change.

Given this identification and the conclusion that Esty and Porter (1998) make regarding economic incentive being the motivation for companies to adopt product life cycle changes, the method has provided new information to help realize increased sustainability through Industrial Ecology.

7.2. Findings

This thesis leads to two categories of conclusions. The first category speaks to the specific case study in brick manufacturing.

- The use of cullet as a fluxing agent in the United States will generate environmental benefits when considered in the context of changes to the life cycle of brick.
- The disincentive to adopt this life cycle change is the initial cost of a research program to determine optimal design and optimal performance.
- Depending on the future price of natural gas, the use of glass cullet in brick manufacturing can generate economic benefits for facilities that invest in the research to determine optimal conditions.
- The adoption of this life cycle change is an example of an Industrial Symbiosis Precursor.
- Due to the symbiotic nature of the benefits, both stakeholder groups (brick manufacturers and glass cullet processors) have strong incentives to invest in the necessary research.
- The findings of this research indicate the approximate value of the research to the brick industry to be on the order of $30 million.

The second category of conclusions speaks more generally to all industry.

- The various regulatory and data collection agencies in the United States represent a largely untapped resource for researchers and industry in efforts to increase resource efficiency.
- As was found in the case of brick manufacturers, this information may uncover not only environmentally preferable options, but economically preferable options.
- Economically preferable options have agents for activity and motivations for these agents.
- Given the potential for finding economic advantages, this type of research with the available information represents a competitive advantage for domestic industry.
- The approach taken in this thesis may be repeatable for many other types of industry and potential symbiotic relationships.

7.3. Future Work

The future work necessary for the concepts and ideas presented in this thesis are again divided into two categories based on the case study and the scaling up of the approach to other potential Industrial Symbioses. Within the specifics of the brick manufacturing industry, the findings of this research can be greatly enhanced with information that is proprietary to the industry itself. As such, these findings must be communicated to the Brick Industry Association for consideration and internal verification and modification of the findings. Regardless of refined analysis, the findings of this thesis indicate that research should be conducted to evaluate the use glass cullet as a fluxing agent at specific locations in the United States. Lastly, an equity analysis of the benefits from research will aid in determining how much incentive glass cullet processors have in funding and participating in research of this potential industrial symbiotic relationship.

Again speaking generally about all industry, it is important that more case studies be conducted to determine whether the types of results found in this study are possible in other industrial contexts. It must be determined whether the findings of this study are an exception due to the simplicity of manufacturing or if it is part of a larger general rule of applicability. If that is indeed the case then real discussion and consideration is needed to answer the question of whether increasing the ease of accessibility of this type of research should be part of national efforts to increase sustainability. One such example might be incorporation of the kind of research described in this thesis with the National Renewable Energy Laboratory's US Life Cycle Inventory Database project. If this were to occur it would help US firms to gain the competitive advantage from the prevalence of information. In addition the environment would benefit from improved resource efficiency.

7.4. Conclusion

This thesis has found a way to identify actors for change to increase sustainability in industry. In addition to identifying these actors, this thesis provides analysis that describes motivations for these actors. The presence of this information helps to motivate the market mechanisms that will motivate Industrial Symbiosis across an entire economy. As a result of this Industrial Symbiosis, there can be dramatic increases in the sustainability of production and development.

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Appendix A: Cost Model

The cost model used for analysis is derived from industry data available from the Annual Survey of Manufacturers (Annual Survey of Manufacturers: Statistics for Industry Groups and Industries 1990-2005)and the Services Annual Survey (Service Annual Survey 2005) for freight costs. Additionally, process data available from the various life cycle studies cited in Chapter 2 has been used to determine such things as energy consumption. All data is based on 2005 information with the exception of the current price of natural gas which is based on the average 2006 price (Energy Information Agency: Natural Gas Navigator 2007).

As was mentioned in Chapter 4, the costs faced by a typical brick manufacturer are modeled from industry wide statistics. It is unlikely that the cost values used in this model match those of any individual plant. However, they serve as a good representation of a “typical producer.” The cost of freight is simply the total revenue for the industry in 2005 divided by the total miles traveled. Again, it is unlikely that this will represent any individual case perfectly, but does serve as reference point for how much manufacturers can expect to pay for freight transport of materials.

Lastly, and perhaps most importantly, the cost model assumes an efficient brick manufacturer who has well maintained processes and uses natural gas as fuel source. Once again this does not capture all of the various manufacturing scenarios that exist in the US, but well over 90% of plants use natural gas. Generally the cost model represents the “typical producer” as opposed to a specific producers costs and manufacturing techniques.

Constants		
Mass SBE	1.8	kg
convert cu m to cu ft	35.315	cu ft/cu m
Specifics		
Energy Savings	20%	%
Transport Distance	200	km
MATERIAL		
Material Cost	$45.33	$/ton finished product
LABOR		
Labor Cost	26.61	$/ton finished brick
CAPITAL		
Capital Cost	7.28	$/ton finished brick
NON FUEL ENERGY		
Electricity	3.54	$/ton finished brick
FUEL (Natural Gas)		
Cu. Ft/SBE	2.46	Cu ft
Price	$7.89	$/1,000 cu ft
Energy	39	MJ/cu m
Emission from NG	0.05	kg/1MJ of NG
Cullet		
% SBE	5%	%
Price	$100.00	$/ton
FREIGHT (Freight Cost)		
Freight Cost	$1.42	$/KM
Truck Size	16	tons
Per KM Price (Freight)	$0.09	$/tKM
Carbon Tax		
Emission Cost	$0.00	$/ton Carbon
Base Cost		
	$0.08159	Material Cost $/SBE
	$0.04790	Labor Cost $/SBE
	$0.01310	Capital Cost $/SBE
	$0.00637	Electricity Cost $/SBE
	$0.01946	Fuel Cost $/SBE
	$0.16843	Cost $/SBE
GHG Tax		
	$0.00000	Carbon Tax Savings $/SBE
	$0.16843	Cost $/SBE with Carbon Tax
Life Cycle Change		
	$0.00900	Cost of Cullet $/SBE
	$0.00160	Freight Cost (Cullet)/SBE
	$0.00389	Energy Savings $/SBE
	$0.00408	Material Savings $/SBE
	$0.17093	Cost $/SBE with Life Cycle Change

Figure A.1 Sample Cost Model Calculation

Appendix B: Model Life Cycle

The life cycle utilized in this study was compiled by Kellenberger et al as a part of the Swiss Life Cycle Inventories EcoInvent 2000 Database (Kellenberger 2003). The metadata provided within the SimaPro 6.0 software indicates that the sampling for this life cycle was conducted at 12 brick manufacturing plants in Germany, Austria, and Switzerland. In applying this life cycle to US manufacturers it is important to mention where this life cycle diverges from data available regarding US producers.

The EcoInvent life cycle (LC) reports consumption of 2.23 MJ (equivalent to 4.43 ft^3) of natural gas per kilogram of finished brick. According to the Brick Industry Association this is equivalent to the most efficient and large plants in the US. Domestic plants can range from 4 ft^3 to 6.75 ft^3 per SBE (*Profile of Brick Manufacturing* 2001). Similarly, the life cycle assumes the use of natural gas as the fuel for firing. This is true for approximately 90% of brick manufacturers in the US (*Profile of Brick Manufacturing* 2001). The only other difference is that the EcoInvent LC considers substantially less water consumption than the Athena Institute study of brick manufacturing in Canada (Venta 1998).

SimaPro 6.0	Process	Date:	5/2/2007	Time:	4:16:03 PM
Process					
Category type	Material				
Process identifier	EIN_UNIT0656770049 1				
Type	Unit process				
Name	brick, at plant				
Time period	Unspecified				
Geography	Unspecified				
Technology	Unspecified				
Representative ness	Unspecified				
Multiple output allocation	Unspecified				
Substitution allocation	Unspecified				
Cut off rules	Unspecified				
Capital goods	Unspecified				
Boundary with nature	Unspecified				
Infrastructure	No				
Date	8/19/2005				
Record	Data entry by: Daniel Kellenberger				
	Telephone: 0041 44 823 48 66; E-mail: empa.du@ecoinvent.ch ; Company: EMPA-DU; Country: CH				
Generator	Generator/publicator: Daniel Kellenberger				

	Telephone: 0041 44 823 48 66; E-mail: empa.du@ecoinvent.ch ; Company: EMPA-DU; Country: CH				
Literature references	Life Cycle Inventories of Building Products/2003/Kellenberger D.				
	Data has been published entirely in				
	Copyright: true				
Collection method	Sampling procedure: The data relates to 12 brick production plants in Germany, Austria and Switzerland; The estimation of infrastructure relates to one company in Switzerland (Ziegelei Gasser AG in Rapperswil BE),				
Data treatment	Extrapolations: See geography				
Verification	Proof reading validation: passed				
	Validator: Roberto Dones				
	Telephone: 0041 56 310 2007; E-mail: psi@ecoinvent.ch; Company: PSI; Country: CH				
Comment	Translated name: Backstein, ab Werk				
	Included processes: includes first ginding process, wet process (includes second ginding, mixing and plastifying), storage, forming (extruding molding method) and cutting, drying, firing, loading, packing and storage				

	Remark: not included: charge of the wastewater and solid waste, it's assumed that the waste heat is totale reused for drying, no hard coal coke is used within these 12 plants; Geography: certain exchanges are proxies (CH for RER), specially for the petrol consumption the proxy "operation, passenger car" has been used; data stem from Switzerland, Germany and Austria				
	Technology: Mix of different technologies (different firing fuels) in A, D, CH.				
	Version: 1.2				
	Synonyms: Ziegel, clay, Ton				
	Energy values: Undefined				
	Production volume: unknown				
Allocation rules					
System description	Ecoinvent				
Products					
Brick, at plant/RER U	1	kg	100 %	Brick	Construction\Bricks
					Europe
Avoided products					
Resources					
Water, well, in ground	in water	7E-05	m3	(5,5,3,3,1,5);	

Materials/fuels					
Lubricating oil, at plant/RER U	0.0000132	kg	(5,5,3,3,1,5);		
Clay, at mine/CH U	1.35	kg	(5,5,3,3,1,5);		
Mine, clay/CH/I U	2E-10	p	(3,5,5,1,3,5);		
Sand, at mine/CH U	0.0147	kg	(5,5,3,3,1,5);		
Limestone, crushed, for mill/CH U	0.000396	kg	(5,5,3,3,1,5);		
Limestone, milled, packed, at plant/CH U	0.0239	kg	(5,5,3,3,1,5);		
Diesel, burned in building machine/GLO U	0.0297	MJ	(5,5,3,3,1,5);		
Electricity, medium voltage, production UCTE, at grid/UCTE U	0.0394	kWh	(5,5,3,3,1,5);		
Pulverised lignite, at plant/DE U	0.0245	MJ	(5,5,3,3,1,5);		
Steel, low-alloyed, at plant/RER U	0.0000306	kg	(5,5,3,3,1,5);		
Sheet rolling, chromium steel/RER U	0.000000157	kg	(5,5,3,3,1,5);		
Sheet rolling, steel/RER U	0.0000157	kg	(5,5,3,3,1,5);		
Natural gas, high pressure, at consumer/RER U	1.24	MJ	(5,5,3,3,1,5);		
Heavy fuel oil, at regional storage/RER U	0.000381	kg	(5,5,3,3,1,5);		
Light fuel oil, at regional storage/RER U	0.00541	kg	(5,5,3,3,1,5);		
Polyethylene, HDPE, granulate, at plant/RER U	0.000000858	kg	(5,5,3,3,1,5);		

Polystyrene, expandable, at plant/RER U	0.000352	kg	(5,5,3,3,1,5);	
Packaging film, LDPE, at plant/RER U	0.000542	kg	(5,5,3,3,1,5);	
Transport, lorry 28t/CH U	0.00468	tkm	(5,5,3,3,1,5);	
Transport, lorry 40t/CH U	0.014	tkm	(5,5,3,3,1,5);	
Transport, passenger car/RER U	0.0166	personkm	(5,5,3,3,1,5);	
Transport, freight, rail/RER U	0.00009	tkm	(5,5,3,3,1,5);	
Tap water, at user/RER U	0.0272	kg	(5,5,3,3,1,5);	
Wood chips, mixed, from industry, u=40%, at plant/RER U	0.000053	m3	(5,5,3,3,1,5);	
EUR-flat pallet/RER U	0.0000161	p	(5,5,3,3,1,5);	
Electricity/heat				
Emissions to air				
Benzene	0.00000296	kg	(5,5,3,3,1,5);	
Carbon dioxide, fossil	0.18	kg	(5,5,3,3,1,5);	
Carbon monoxide, fossil	0.000391	kg	(5,5,3,3,1,5);	
Formaldehyde	0.0000164	kg	(5,5,3,3,1,5);	
Heat, waste	0.142	MJ		
Hydrogen chloride	0.0000122	kg	(5,5,3,3,1,5);	
Hydrogen fluoride	0.0000106	kg	(5,5,3,3,1,5);	
Nitrogen oxides	0.00026	kg	(5,5,3,3,1,5);	
NMVOC, non-methane volatile organic	0.0000763	kg	(5,5,3,3,1,5);	

compounds, unspecified origin					
Particulates, < 2.5 um	0.000014	kg	(5,5,3,3,1,5);		
Particulates, > 10 um	0.00000468	kg	(5,5,3,3,1,5);		
Phenol	0.00000013	kg	(5,5,3,3,1,5);		
Sulfur dioxide	0.0000998	kg	(5,5,3,3,1,5);		
Emissions to water					
Emissions to soil					
Final waste flows					
Non material emission					
Social issues					
Economic issues					
Waste to treatment					

Table B.1 Life Cycle Assessment for "Brick"(Kellenberger 2003; SimaPro 6.0 2006)

This is the modified life cycle made for assessing the use of glass cullet as a fluxing agent.

SimaPro 6.0	Product stage	Date:	5/15/2007	Time:	3:43:55 PM		
Assembly:							
Name							
Variability Brick							

Materials/Assemblies	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Brick, at plant/RER U	1	kg	Undefined				
Glass, cullets, sorted, at sorting plant/RER U	0.1	kg	Undefined				
Clay, at mine/CH U	-0.1	kg	Undefined				
Mine, clay/CH/I U	2E-11	p	Undefined				
Processes	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Crushing, rock/RER U	0.1	kg	Undefined				
Transport, lorry 16t/CH U	0.1	tkm	Undefined				
Heat, natural gas, at industrial furnace >100kW/RER U	-0.2604	MJ	Undefined				

Table B.2 Life Cycle of Utilizing Glass Cullet as Fluxing Agent (SimaPro 6.0 2006)

Appendix C: Monte Carlo Simulation

1. Introduction

The economic results presented in this thesis are developed through a Monte Carlo simulation of the entire brick manufacturing industry through the cost model presented in Appendix A. The environmental benefits presented in the thesis are developed through the modified life cycle of brick presented in Appendix B. In these calculations there are 4 uncertainties. They are:

1. Transportation distance between cullet processor and brick manufacturer
2. Price of processed glass cullet
3. Actual energy savings realized at individual brick manufacturers
4. Future price of natural gas

In Appendix C, each of these uncertainties are discussed in detail and the chosen stochastic model of probable values is described and defended. After describing the uncertainties, the following section describes the method of determining what the probable benefits might be. Finally detailed results of this analysis are presented.

2. Uncertainty Sources and Distributions

Table C.1 lists the unknowns that dictate how much of the 20% energy savings that Smith described can be realized by the US brick industry. The table also describes how these unknowns are modeled within this thesis and the sources of information used to identify appropriate values. Armed with this information, the benefits can be quantified.

Variable	Model Relationship	Source of Information
Transportat	Utilizing GIS and road network	Envirofacts Data

ion Distance	analysis tools, the road travel distance between the relevant facilities can be determined	Warehouse (online database of all EPA regulated facilities) (Envirofacts Data Warehouse US Environmental Protection Agency 2007)
Site Specific Energy Savings	No empiric relationship between raw material chemistry and energy savings is known, but a general inverse correlation between natural fluxing agents (alkalis: ex. Sodium, Potassium, Calcium, and Magnesium) is chemically sound since basic salts in the soil will tend to increase the pH of the soil	Soils data available from United States Department of Agriculture Natural Resources Conservation Service (USDA Natural Resources Conservation Service: Soil Data Mart 2005)
Cost of Natural Gas	Natural Gas Prices have varied over time and three considerations of future prices are made: the low price prediction made by the US Department of Energy: Energy Information Agency (DOE EIA), the high price prediction of the DOE EIA, and lastly a binomial expansion of historic growth trends	Predictions and historic data available from DOE EIA (Energy Information Agency: Natural Gas Navigator 2007; DOE Energy Information Agency: Annual Energy Outlook 2007 with Projections to 2030 2007)
Cost of Glass Cullet	The cost of processed glass cullet is not a monitored economic statistic, but major suppliers provide an approximate range of prices across the country	Supplied by industry representatives (Dudak 2007; Poole 2007)
Cost of Emissions	At present, GHG regulation may take on any of many proposed forms, in the absence of an official cap and trade system, the price of carbon credits on the Chicago Climate Exchange	Chicago Climate Exchange (Chicago Climate Exchange CCX 2007)

Table C.1 Variables Involved in Analysis of Value of Glass Cullet as Fluxing Agent

2.1. Transportation Distance

The required transportation distance between a glass cullet processor and a brick manufacturer was unknown prior to analysis, but it is not variable. There is a single finite transport distance that exists between the two facilities. It is only necessary to locate the facilities and then determine the amount of road distance a truck would have to travel between one point and another.

To accomplish this, the facility street addresses were collected from the Brick Industry Association's website (BIA Member Directory 2007) which has a database of manufacturing facilities and the Glass Packaging Institute's (Glass Packaging Institute: Recycling News 2007) website which has a database of cullet processors. These locations were cross-referenced with the locations of these facilities found in the EPA Envirofacts Data Warehouse (Envirofacts Data Warehouse US Environmental Protection Agency 2007). Then using ArcGIS (a geographic information system software package), these street addresses were "geocoded" to physical locations. Then using network analyst tools, the minimum road travel distance was calculated. The results of these calculations were compared to travel distances described by Mapquest.com. In the case of discrepancies, visual inspection was used to determine which distance was correct and that value was used in the simulation. In this way, uncertainty about actual travel distances for individual plants was eliminated.

2.2. Price of Processed Glass Cullet

The cost of acquiring cullet is an unknown and variable value in this analysis. There are no facilities that produce the required particle size of cullet in large quantities at this time. A comparable product is produced by most cullet processors for use by manufacturers of fiberglass. Through contacting the facilities that supply this material it was determined that the price of an appropriate product for brick manufacturers would range in price from $60 to $100 per ton of material (Dudak 2007; Poole 2007). Without any further information available, it was decided to model the range of prices as a discrete distribution with values of $60, $70, $80, $90, and $100. All of the values have a probability of 20%. In addition to this cost, the transportation cost was determined by using a constant freight cost and the same transportation distances that were calculated previously.

2.3. Actual Energy Savings Realized at Specific Plants

There is no empiric relationship that can be developed to predict the benefits of using a non-natural fluxing agent in a specific source of clay raw material. Testing must be conducted for each source and the mix design must be optimized. While no relationship can be developed, a good measure of the effect of the non-natural fluxing agent is the presence of natural fluxing agents in the clay. Minerals that are natural fluxing agents include sodium, potassium, calcium and magnesium (Worrall 1975). The presence of these alkali's serves to drive up the pH of the clay. Therefore, a region with soil pH's that are generally low will tend to have a lesser presence of natural fluxing agents in the clay. Using this fact and national soil survey data available from the United States Department of Agriculture, all of the brick manufacturing locations were divided up into three categories, those with: ambient soil pH of less than 6.0, ambient soil pH between 6.0 and 7.25, and ambient soil pH greater than 7.25.

The lowest pH soils are most likely to benefit from unnatural fluxing agents so the associated energy savings with this range was considered to be uniformly distributed with bounds 15% and 25%. The middle group is likely to see some benefit, but not the greatest benefit. The associated energy savings was considered to be uniformly distributed with bound 5% and 15%. Finally, the group with the highest pH is least likely to benefit from the unnatural fluxing agent and the associated energy savings was considered to be uniformly distributed between 0% and 5%.

2.4. Future Price of Natural Gas

The future price of natural gas is truly a driving cost for the brick industry and for the assessment of a life cycle change that reduces consumption of natural gas. Natural gas prices have ranged dramatically in the last 5 years, but a general trend exists if one considers the nominal price of natural gas delivered to industry since 1967 (see Figure C.1).

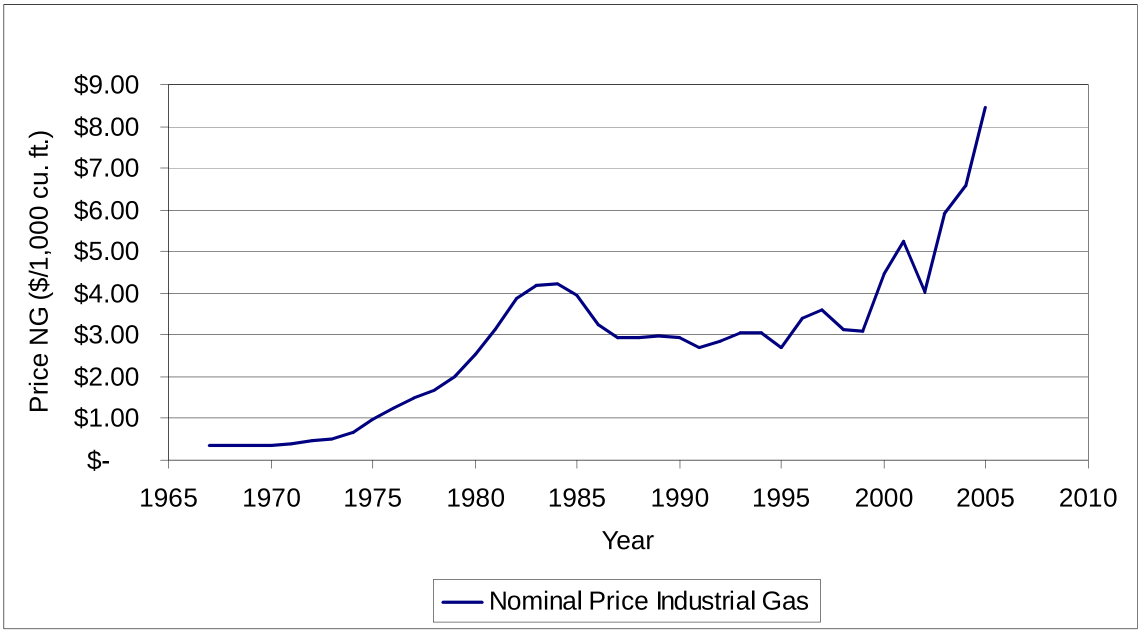


Figure C.1 Historical Natural Gas Prices (Average Price of Natural Gas Delivered to US Consumers, 1967-2000 2000; Energy Information Agency: Natural Gas Navigator 2007)

Given this historical data one way to predict future prices is consider past growth as an indicator of future growth. Based on the above data, exponential growth matches this pattern with a coefficient of determination value of .7555. In this case the growth can be expected to increase at a rate of 7% annually. Assuming that the distribution of future natural gas prices is lognormal and that the growth follows Geometric Brownian motion, and with knowledge that the year end price in 2006 was $7.89/1,000 cubic feet, one can develop a binomial lattice to model future natural gas prices (for details on the binomial lattice see Real Options: A Practicioner's Guide by Copeland and Antikarov and "Option Pricing: A Simplified Approach" by Cox et. al. published in the Journal of Financial Economics 1979).

To calculate outcomes from a binomial lattice, three values are needed: u (the expected increase should the price rise), d (the expected decrease should the price drop), and p (the probability that the price will rise). Using knowledge that the standard deviation of historical data is approximately 15% of the 2006 year end price, these values can be determined with the following equations:

$$u = e^{\sigma\sqrt{\Delta t}} = e^{0.198\sqrt{1}} = 1.161$$
$$d = e^{-\sigma\sqrt{\Delta t}} = e^{-0.198\sqrt{1}} = 0.861$$
$$p = 0.5 + 0.5(\frac{v}{\sigma})\sqrt{\Delta t} = 0.5 + 0.5(\frac{0.07}{0.150})\sqrt{1} = .734$$

Figure C.2 Determination of u,d,p for Binomial Lattice Calculation

Figure C.3 presents a binomial lattice for future gas prices delivered to industry. The first lattice presents the price of natural gas in a given year and the matching cell in the subsequent lattice presents the probability of that price occurring in that year.

u	1.161
d	0.861
p	0.734
p Start	1
Value Start	$ 7.89

Year						
2006	2007	2008	2009	2010	2011	2012
OUTCOME LATTICE						
$7.89	$9.16	$10.64	$12.35	$14.34	$16.64	$19.32
	$6.79	$7.89	$9.16	$10.63	$12.34	$14.33
		$5.85	$6.79	$7.88	$9.15	$10.63
			$5.04	$5.85	$6.79	$7.88
				$4.34	$5.03	$5.84
					$3.73	$4.33
						$3.21
PROBABILITY LATTICE						
1.00	0.73	0.54	0.40	0.29	0.21	0.16
	0.27	0.39	0.43	0.42	0.39	0.34
		0.07	0.16	0.23	0.28	0.31
			0.02	0.06	0.10	0.15
				0.01	0.02	0.04
					0.00	0.01
						0.00
Sum of Probability						
1.00	1.00	1.00	1.00	1.00	1.00	1.00

Figure C.3 Binomial Lattice of Future Natural Gas Prices Delivered to Industry

This binomial lattice provides a range of outcomes and their likelihoods. It can be argued that this stochastic approach may be preferred to deterministic predictions of future prices.

In addition to the relatively blind prediction that has been presented, the Department of Energy releases future expectations of natural gas prices through the Energy Information Agency. This information takes a deterministic approach to the future prices of natural gas. Table C.2 graphs the DOE Low and High future price forecasts over the same 6 year time period.

Year	High	Low
2006	$7.68	$7.67
2007	$7.68	$7.35
2008	$7.85	$7.20
2009	$7.50	$6.46
2010	$7.24	$6.00
2011	$7.09	$5.59
2012	$6.72	$5.27

Table C.2 DOE EIA Predictions of Future Natural Gas Prices (DOE Energy Information Agency: Annual Energy Outlook 2007 with Projections to 2030 2007)

Looking at these two methods for prediction it is clear that they overlap, but that the DOE considers the trend of future prices to be negative while history indicates otherwise. Figure C. 4 shows the differing predictions.

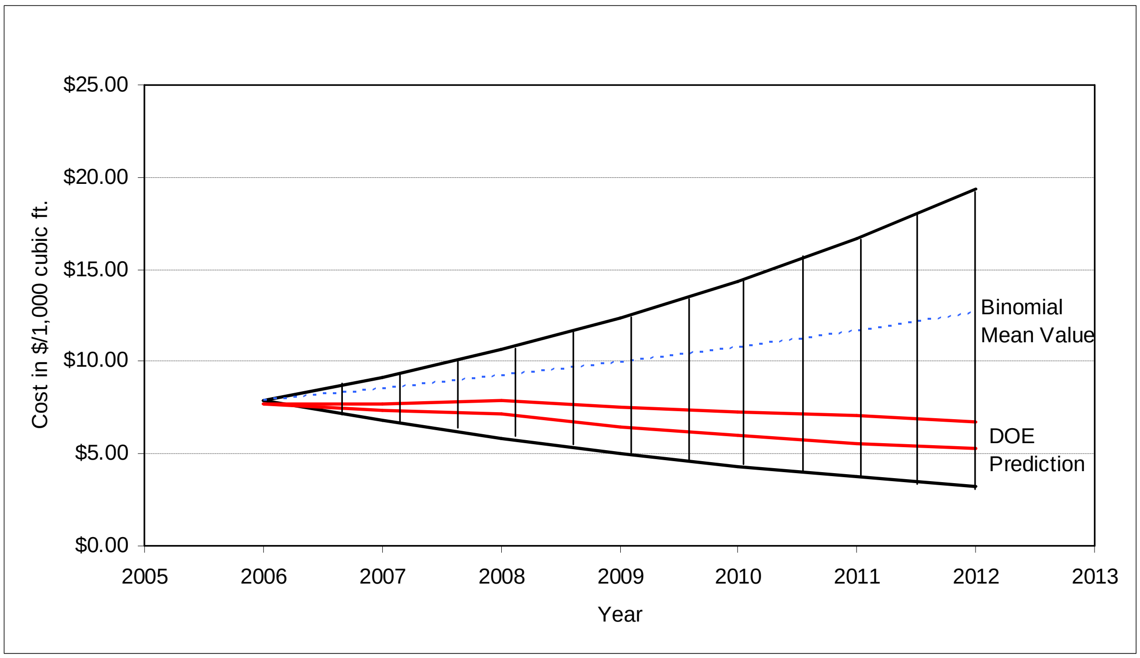


Figure C.4 Comparison of Future Natural Gas Price Projections

Both predictions of future natural gas prices are used to run through a Monte Carlo simulation of what the value of the life cycle change might be to the industry.

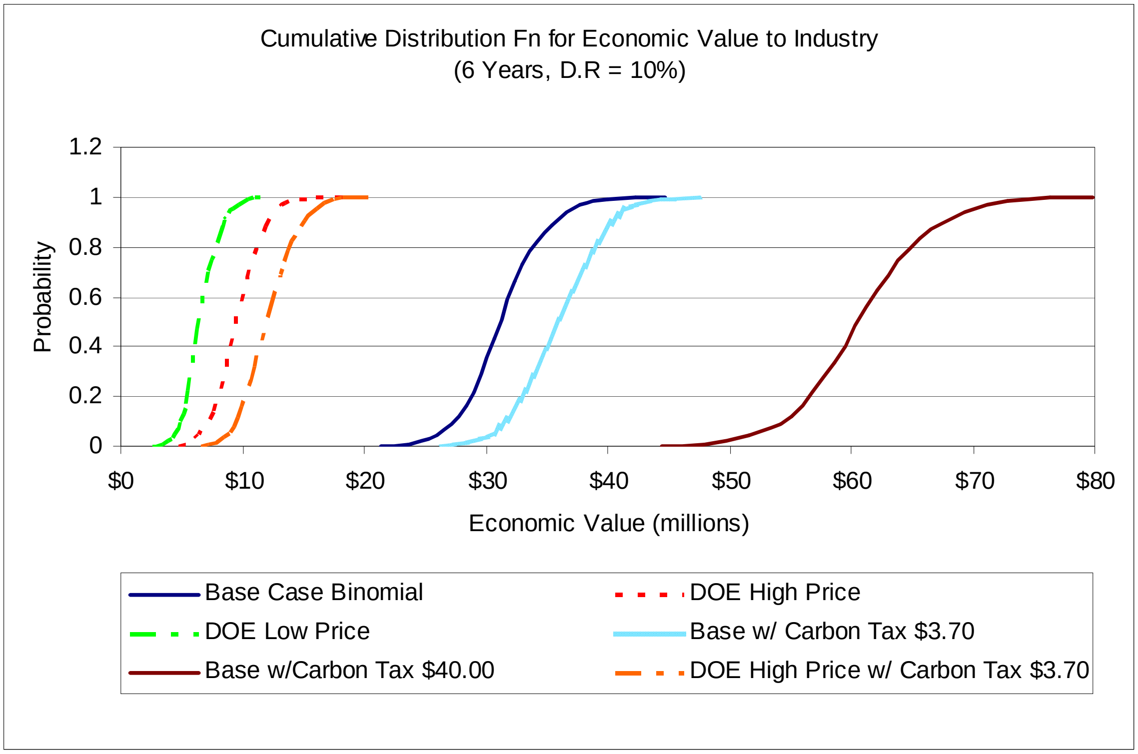
3. Monte Carlo Simulation

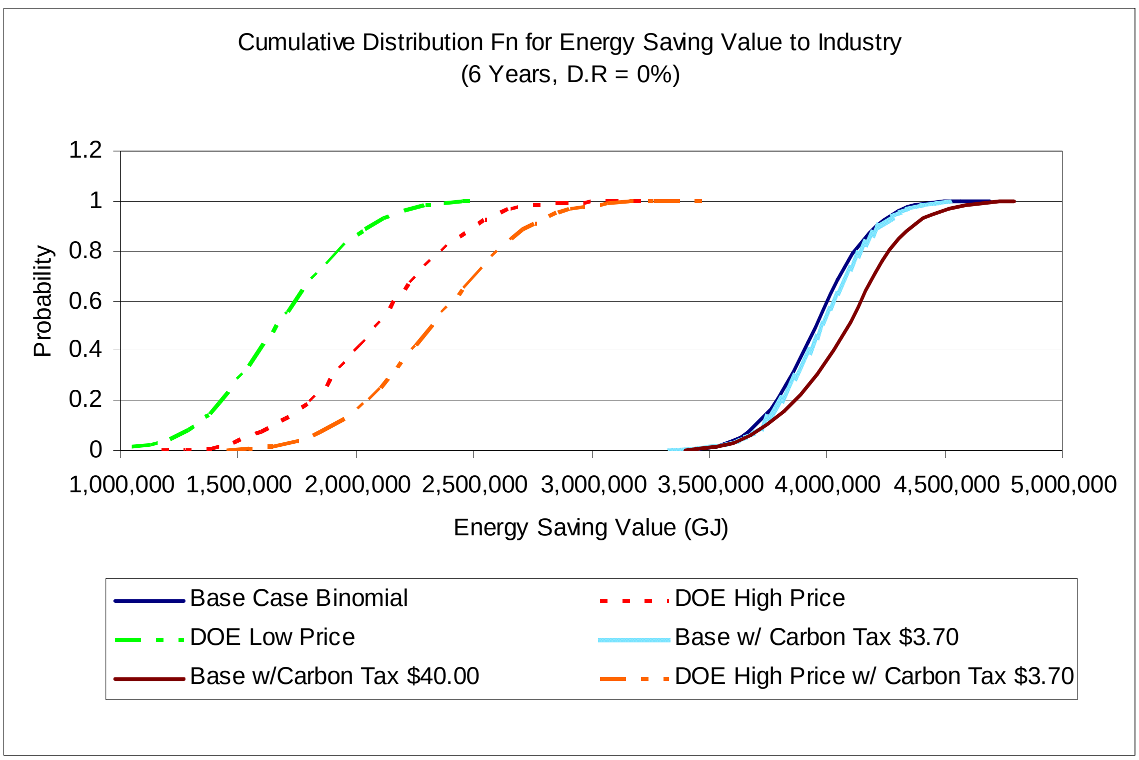
The specific situation of each brick manufacturing location was considered in the cost model (Appendix A) for each year and potential outcome for both the binomial case and the DOE prediction case. The decision maker at each plant was assumed to be a rational decision maker whose only decision criterion was maximizing annual profit for their particular facility. If the expected value of using glass cullet is positive then the decision maker would choose to use the glass cullet. If the expected value is negative then the decision maker will choose not to use glass cullet. Based on these results for each facility the economic benefit and environmental that might be gained in a potential outcome can be determined.

This process is repeated for each facility and then it is repeated 1,000 times for the entire industry. The repetition of these calculations while varying the uncertainties through the use of random variable generation is known as a Monte Carlo simulation. Using a Monte Carlo approach gives the potential outcomes and the likelihood of these outcomes within the ranges assigned to the uncertain values. This information is often best viewed as a cumulative distribution graph.

4. Results

The results presented in Figure C.5 indicate 5 different scenarios. These are the binomial lattice price prediction, DOE high and low price predictions, the application of a $3.70/ton carbon emission tax applied to both the DOE high price prediction and the binomial lattice price prediction, and finally a $40.00/ton carbon emission tax applied to the binomial case. In Figure C.5 the results based on economic benefit, energy savings and emissions avoided are presented.


Cumulative Distribution Fn for Economic Value to Industry
(6 Years, D.R = 10%)
Probability
1.2
1
0.8
0.6
0.4
0.2
0
$0
$10
$20
$30
$40
$50
$60
$70
$80
Economic Value (millions)
Base Case Binomial
DOE High Price
DOE Low Price
Base w/ Carbon Tax $3.70
Base w/Carbon Tax $40.00
DOE High Price w/ Carbon Tax $3.70


Cumulative Distribution Fn for Energy Saving Value to Industry
(6 Years, D.R = 0%)
Probability
1.2
1
0.8
0.6
0.4
0.2
0
1,000,000
1,500,000
2,000,000
2,500,000
3,000,000
3,500,000
4,000,000
4,500,000
5,000,000
Energy Saving Value (GJ)
Base Case Binomial
DOE High Price
DOE Low Price
Base w/ Carbon Tax $3.70
Base w/Carbon Tax $40.00
DOE High Price w/ Carbon Tax $3.70

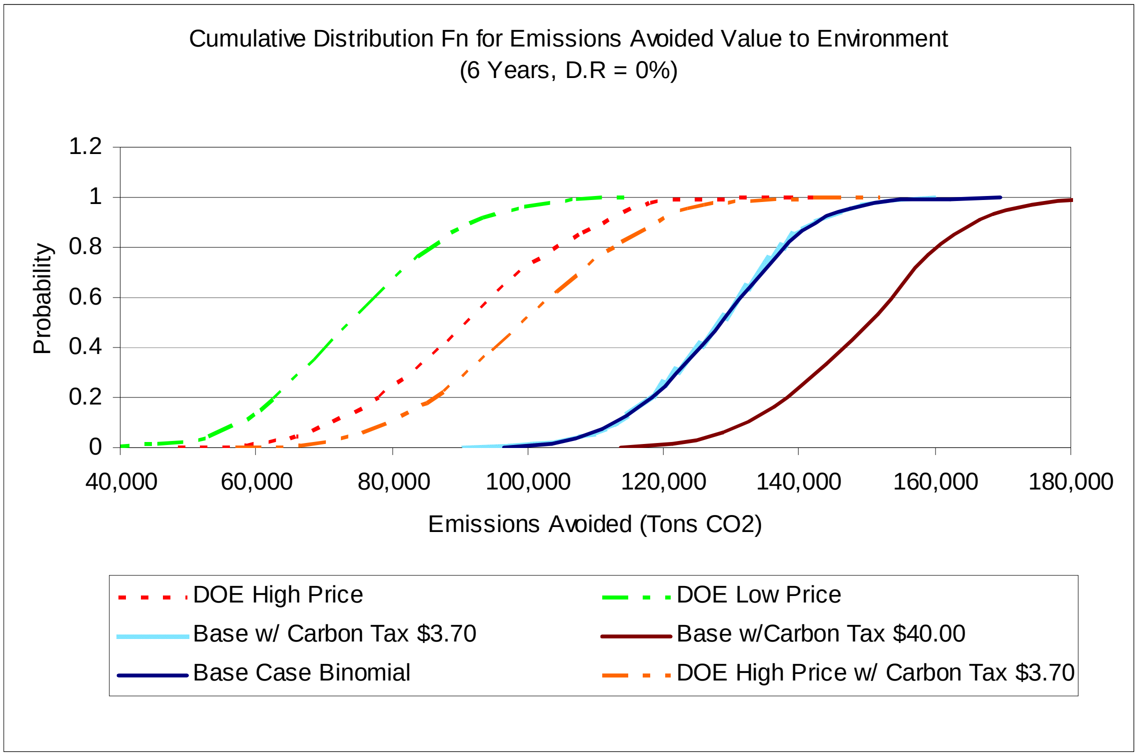


Figure C.5 Results of Monte Carlo Analysis for Various Results of Interest