Optimization and Economic Evaluation of Coal Fly Ash Reuse in New Synthetic Lightweight Aggregates

Christopher Swan[1], Drusilla Brown[2], Stephen Levine[3] and Jeffrey Zabel[4]

[1]Assistant Professor, Department of Civil and Environmental Engineering, Tufts University, Medford, MA 02155; [2]Associate Professor, Department of Economics, Tufts University, Medford, MA 02155; [3]Associate Professor, Department of Civil and Environmental Engineering, Tufts University, Medford, MA 02155; [4]Associate Professor, Department of Economics, Tufts University, Medford, MA 02155;

KEYWORDS: economic analysis, optimization, lightweight aggregate, coal fly ash, waste plastics, industrial ecology

INTRODUCTION

Industrial manufacturing can be simplified into a set of processes that directly or indirectly utilize material resources to create final products. Some examples include the use of coal by utility companies to produce electricity and the use of crude oil to form the basis of gasoline, heating oil and plastic containers. However, waste materials are inevitably produced in the manufacturing of the product (e.g., slag and fly ash are the wastes generated in the use of coal). These wastes must be handled and properly disposed, and many times, although this waste may be environmentally inert, it is discarded in landfills.

Such a strategy for final material management may be highly inefficient. As schematically diagramed in Fig.1, if industrial-related processes are seen as an ecosystem, the most efficient ecosystem is one which minimizes both the input of limited resources and the output of waste materials by optimizing the interaction of its various components; i.e., the material, manufacturing, and waste management processes. For example, if waste production can be reduced via recycling and reuse of post-manufacturing and post-consumer products, the ecosystem will become significantly more efficient and sustainable.

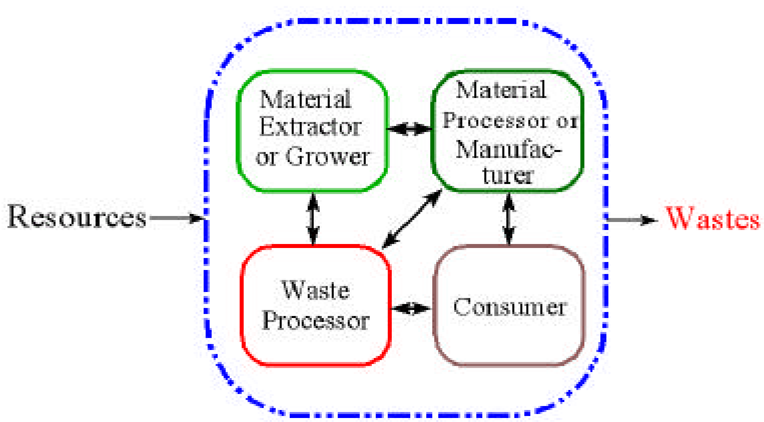

Figure 1 Industrial System [10]

Presently, the authors are conducting research on factors that effect the reuse/recycling of traditional waste products, specifically coal fly ash and recovered waste plastics. This research consists of two complimentary components. One component analyzes how changing a post-process material from a "waste" to a "resource" in the production of a new product (1) affects the local and global optimization of the manufacturing processes associated with both the original and new products, and (2) both creates new economic linkages associated with the production of the new products as well as modifies those linkages associated with the original products. Input/output models using computable general equilibrium techniques will be used in these analyses. The second component will apply these analyses to the production and use of a new, innovative synthetic aggregate that has been developed from two traditional waste materials; coal fly ash and recovered plastics. These research components are complimentary because the formulations developed in the first component will be verified by analyses conducted in the second component. This paper presents the rationale for this research.

The impact of this research will influence a number of disciplines. For the engineering profession, a tool for economic evaluation of new and innovative construction materials will be developed thus providing a stronger rationale for the use of alternative materials. For economics, this research will contribute to the understanding of the markets for recyclable materials and their impacts on the markets for competing virgin materials. In addition, the markets for the inputs of the production process that generate the waste materials (e.g. the market for coal in the case of fly ash) will be better understood. Successful research will also lead to better and stronger economic evaluation of recovered wastes in other engineered products/structures. On a broader scope, the model generated could further rationalize the trend towards general waste reuse necessary to create sustainable manufacturing processes by linking these processes to the national and international economic system.

RESEARCH RATIONALE

Economic System Aspects of Utilizing Waste Materials to Produce New Products

The converting of what was previously a waste material of an industrial process into an input to a new (or existing) product has several important features from an economic systems perspective [1]. This is true whether the material is to be recycled through the same process or reused in a new product. When waste materials from two different industries are combined into a new product, new manufacturing processes are developed, existing ones are modified, and as a result new linkages in the economic system are created. The importance of understanding how firms and industries interact has recently drawn increased attention from people across a wide range of disciplines and professions, both in industry and academia, and is now widely referred to by terms such as "industrial ecology" [7, 8, 10] and "industrial metabolism" [2].

Optimization of Manufacturing Processes

Products, with their resultant waste materials, are produced in ways so as to maximize the profits of the firms producing them. Production of a waste material results in costs incurred by the firm; as an example, solid wastes may have to be hauled away and put into appropriately designed landfills. All these costs are factored in when a firm designs and operates its production processes, and prices its products. Governments use fines and taxes to influence these production processes in ways intended to reduce pollution and hazardous wastes, and discourage or encourage the use of certain inputs.

Firms often have the option of selecting among a set of alternative production processes, all resulting in the same product, but each in turn generating different amounts and even types of waste materials. Costs associated with waste materials influence which option is selected. When a material ceases to be a waste and instead becomes the input to another product, whether the product is produced by the same or another firm, the material gains positive economic value. The result can involve more than increasing the profits of the firm due to utilization of the waste. It may also lead to the previous production process no longer being the optimal choice with the consequence that the firm may choose to switch to a newly optimal process. Issues of this type have long been the domain of Operations Research [11].

It is here that the critical issue of global versus local optimization arises. Large firms tend to have an array of products, and it is the profitability of that array, and not any one product alone, that determines the firm's profitability. Attempting to optimize the profit associated with each product without regard to the other products, is an example of local optimization. If the various production processes in no way interact, then local optimization for each product would result in global optimization over the array of products. When the production processes do interact such as often results from scale factors in purchases or common use of equipment and labor, that is, when the array of products constitute a true system, global optimization ceases to be this summation of the various local optimizations. This principle is well represented in other business arenas; e.g., sales of specified products by retailers may result in those products being sold at close to or even below cost with the intent of getting customers into the store, and thus increasing sales and more importantly profits overall. When a potential new product is to be produced from what was once waste material of other production processes, those processes interact in a profound manner. Deciding on the profitability of the new product may require re-examination of how the existing products are produced.

Optimization at the level of profitability of the firm is itself not the broadest outlook that can be taken. What is best for society as a whole may play a critical role, and is often enforced through laws, regulations, legal decrees, and other political and social avenues. Creation of waste, especially hazardous wastes, is often seen as generating societal costs even when individual firms are not held accountable. Concepts of environmental "accounting", such as taxes and tradeable permits, seek to incorporate costs of these types into the economic decision making process [9], and in doing so redefine the characteristics of the global optimum.

MODIFICATION OF ECONOMIC LINKAGES

The conversion of waste materials into either products or useful materials sold to other firms results in structural changes in the economy [15]. New linkages may be created between industries when what were waste materials now flow from one industry to another. New products also result in either new inter-industry linkages, if they are intermediate goods, or new linkages to the consumer sector, if they are final goods. Linkages may be weakened or even broken, as occurs in reduced flows to landfills. It is not only the change in the firm's outputs that must be accounted for. As noted in the previous section on optimization, the utilization of products that were previously waste materials can lead to changes in production processes and therefore to changes in the firm's inputs.

Input-output analysis considers the flow of goods and services within an economy and allows for the determination of the indirect as well as direct requirements of the production process [14]. As an example, coal is a direct requirement or a direct input to the electric power industry. But in order to operate, the coal industry must first purchase the coal mining equipment, so this equipment is an indirect requirement or indirect input to the electric power industry. Coal mining equipment, in turn, requires steel in its production, and that industry is dependent on the mining of iron ore, and so on. In this way the totality of economic activity required to produce electric power is accounted for. In a similar fashion, we can account for the totality of economic activity that requires, directly or indirectly, the output of the electric power industry [5]. With this in mind, we see that changes in inputs and outputs of firms resulting from the conversion of a waste material to a product reverberate through the economic system as a whole. From the perspective of the society at large, it is this total economic impact that is of primary interest.

Application of Economic Analysis and Optimization to a New Product

In this project we consider the reuse of two major waste products of American industry, coal fly ash and waste plastics. Fly ash represents the fine, dust-sized residue from coal combustion as well as from the incineration of other wastes such as municipal solid wastes (MSW). In coal combustion, light ash particles (fly ash) are suspended in exhaust gases that exit through smoke stacks. Annual coal consumption in the US is approximately one billion tons leading to approximately 50 million tons of fly ash. This makes coal ash the fifth most abundantly produced material in the US after crushed stone and gravel, raw steel and Portland cement. However, only 10% of this fly ash, that with low carbon content, is suitable for reuse, typically as an alternative pozzolan in concrete. Very small quantities are also used in other areas of construction such as for flowable and/or structural fill, as filler in asphalt, as road base material, and in environmental waste stabilization. Unused fly ash is usually land disposed with more than 950 million tons of this material have been sent to landfills throughout the United States since 1965 [6].

Approximately 29 million tons of plastics are generated annually for use in the US with close to half of this amount entering the MSW stream [13]. High density polyethylene (HDPE) is a very common plastic used in making containers such as milk jugs, shampoo bottles, soft drink bottles, and other containers. However, only 25% of HDPE is recycled, and, worse still, only 1 to 2 percent of all plastics produced are recycled. This low recycling rate is partially due to the fact that various plastics produced each have different physical and thermal properties. Consequently, mixing of different plastics often will result in a product that exhibits physical and structural behavior inferior to its parent materials.

Successful reuse of the fly ash and plastics would impact on a number of industries. First, of course, is the coal-burning power industry, to which the reuse of fly ash would provide a new source of revenue while eliminating previous expenses associated with its disposal. In addition, coal is but one of the major inputs to the electric power production industry competing with oil, nuclear, solar, wind, and water. Any development which turns fly ash into a source of profit for the power industry could have a major impact on the coal-based fraction of electricity generation, and therefore on the other fuels as well. This in turn would affect levels of production and employment in the coal mining industry, in those industries that build equipment for coal mining, and in the shipment of coal (a major source of revenue to the railroad industry). Further illustrating the systems nature of such an outcome, increased coal utilization presents major issues with regard to air quality, and thus might demand improved equipment and policies to protect the public and the environment (e.g., the current debate on minimum particulate-size and SO_2 emission levels for the new Clean Air Act Amendments).

Plastic and plastic recycling industries may also be effected by the new use of their post-consumer waste. As noted above, there are a number of linkages associated with the production and use of coal. One could develop a similar set of linkages for plastics involving petroleum companies which supply the raw materials for plastics, the consumers (individuals and firms) which use plastics, and the recycling and disposal facilities which collect waste plastics. The construction industry, for which the aggregate would become a new input, would also be affected, as would all those industries which produce products for which the new material would be a competitor. Therefore, there would also need to be an analysis of the production and use of lightweight aggregate in construction and other industries.

Development of a Synthetic Aggregate

Current research is focusing on a new product; synthetic lightweight aggregates developed from the co-extrusion of coal fly ash and recovered waste plastics [12]. An extrusion process was used to mix the two raw materials and thus create a more thorough mixing of the HDPE with the inert coal fly ash. This extrusion process leads to five aggregate mixtures with different fly ash-to-plastic ratios, ranging from 25% fly ash to 75% HDPE to 80% fly ash to 20% HDPE (by weight). These mixtures were created by simultaneously feeding the extruder the individual components, then allowing the resulting extruded mixture to cool. These mixtures were then "granulated" to create a lightweight (specific gravities of 1.64 or less), uniformly-sized (average diameter of 0.25 inches), angular aggregate.

The five new synthetic aggregates were incorporated into concrete specimens (2-inch cubes) which were tested for unit weight and compressive strength. Control specimens were also made using normal-weight, natural aggregate for comparison. Subsequent analysis of the test results illustrated a number of beneficial characteristics to concrete behavior provided by the new aggregate; namely,

1) The synthetic aggregates created lightweight concretes (unit weights less than 1.84 g/cc), a structurally and economically beneficial product.
2) With respect to stress-strain-strength behavior, the average maximum strength (Q_p) of the lightweight concretes, while lower than the average strength of the control specimens, is comparable to that of concrete composed of natural, lightweight aggregates [16]. In addition, the lightweight concretes exhibited a ductile behavior; i.e., a significant load-carrying capacity of the concrete at relatively large strains. This attribute has not been noted in other concrete mixtures.

These preliminary engineering test results indicate that these new aggregates may be useful as lightweight aggregate in concrete. These aggregates may also be useful in cold-mix asphalt or as lightweight fill.

FUTURE RESEARCH EFFORTS

Future research efforts will examine how economic linkages, and therefore economic impacts, change due to the re-categorization of a waste as a resource to be used in the production of an existing or new product. We will analyze both the direct and indirect economic impacts and investigate the role played by changes resulting from the optimization of production activities associated with both existing products and those newly derived from the waste. These analyses will focus on the reuse of coal fly ash and recovered plastics in the production of new SLAs. Specific tasks are summarized below.

Task 1. Examination of the existing economic and optimization structure of three industries; coal, plastic, and lightweight aggregate. This task will show the other components of the "global ecosystem"; e.g., manufacturing processes that lead to an increase or decrease in produced wastes and may influence existing economic and optimization structures of the three industries.

Task 2. Examination of the production and potential use of the recently developed, synthetic aggregates. This analysis will include an estimation of costs associated with the procurement of raw input materials (fly ash and recovered plastics) and production equipment, operation and maintenance, labor, and product marketing. Economic examination of aggregates developed from the continued, but separate, research efforts will be performed as new aggregates and or methodologies of aggregate production are proven technically viable.

Task 3. Collection of information on other possible recycling/reuse strategies for the two waste materials and potential changes in the manufacturing processes that lead to these wastes. We will focus on the markets for fly ash and recycled plastic. Our goal is to determine the prices for these materials so that the economic viability of the SLAs can be determined. This information will allow for analyses of how changes in design and production practices will effect current economic and optimization structures.

Task 4. Development of computable general equilibrium models (CGE's) which can incorporate structural changes in linked-industries. Input-output (I/O) models provide a traditional tool for analyzing the economic impacts due to technological changes [17]. Impacts due to structural changes, such as the creation of new linkages or the modifications of existing linkages, as well as impacts due to changes in product demand can be evaluated. At the same time, the simplicity of the linear production function that forms the basis of the traditional model limits its ability to model the truly dynamic economic behavior resulting from significant technological innovations. In recent years, spurred by these limitations and the increased power and reduced cost of computational analyses, development of computable general equilibrium models (CGE's) has accelerated [3, 4, 18]. The CGE methodology overcomes some of the inherent limitations of the I/O approach by allowing for realistic and important features to be evaluated such as product substitutions, resource constraints, returns to scale and price elasticities, and more generally thorough consideration of the efforts of economic agents, such as firms, to optimize their own economic performance. We will develop a model incorporating these useful features of CGE's as well as other appropriate techniques for evaluating the economic impact of technological innovations arising from the utilization of waste, and then apply this model to the production and use of new synthetic lightweight aggregates.

ACKNOWLEGEMENTS
This research is funded by a grant from the National Science Foundations (Grant No. BES-9814551) and Lucent Technologies Foundations.

REFERENCES

1. Allen, D. T. and Behmanesh, B.(1994), "Wastes as Raw Materials", The Greening of Industrial Ecosystems, Washington, DC: National Academy Press, pp.69-89.
2. Ayres, R. U. (1994), "Industrial Metabolism: Theory and Practice", The Greening of Industrial Ecosystems, Washington, DC: National Academy Press, pp. 23-37.
3. Bandara, J. S. (1991), "Computable General Equilibrium Models for Development of Policy Analysis in LDC's", Journal of Economic Surveys, 5, pp, 1-69.
4. Bergman, L. (1982), "A System of Computable General Equilibrium Models for a Small Open Economy", Mathematical Modeling, 3, pp. 421-435.
5. Boustead, I. and Hancock, G. F. (1979), Handbook of Industrial Energy Analysis, Chichester, UK: Ellis Horwood Ltd.
6. ACoal Combustion Byproduct (CCB), Production & Use : 1966 - 1993, Report for Coal-Burning Electric Utilities in the United States@, American Coal Ash Association.
7. Duchin, F. (1994), "Input-Output Analysis and Industrial Ecology", The Greening of Industrial Ecosystems, Washington, DC: National Academy Press, pp.61-68.
8. Ehrenfeld, J. R. (1994), "Industrial Ecology and Design for Environment", The Greening of Industrial Ecosystems, Washington, DC: National Academy Press, pp.228-240.
9. Environmental Protection Agency (1995), An Introduction to Environmental Accounting as a Business Management Tool: Key Concepts and Terms EPA 742-R-95-001,Office of Pollution Prevention and Toxics.
10. Graedel, T.E., B.R. Allenby and P.B. Linhart (1993), "Implementing Industrial Ecology", IEEE Technology and Society Magazine, Spring 1993, pp. 18-26.
11. Hillier, F. S. and Lieberman, G. J. (1995), Introduction to Operations Research, New York: McGraw-Hill.
12. Kashi, M., Swan, C., Holmstrom, O., and Malloy, R. (1999) "Innovative, Lightweight Synthetic Aggregates Developed from Coal Fly Ash", 13th International Symposium on Management and Use of Coal Combustion Products, January 1999, Vol. 1, pp. 5-1 through 5-14.
13. Kreith, F., Handbook of Solid Waste Management. Chapter 3. McGraw-Hill, 1994,336p.
14. Leontief, W. (1951), The Structure of the American Economy, 2nd ed., New York: Oxford University Press.
15. Leontief, W. (1970),"Environmental Repercussions and the Economic Structure: An Input-Output Approach", The Review of Economics and Statistics, Vol 52, pp.262-271.
16. Mindess, S. and Young, J.F. (1981) Concrete. Prentice-Hall, Inc. Englewood Cliffs, NJ. 671p.
17. Rose, A. (1984), "Technological Change and Input-Output Analysis: An Appraisal", Socio-Economic Planning Sciences, 18.5, pp. 305-318.
18. Shoven, J. B. and Whalley, J. (1992), Applying General Equilibrium, New York: Cambridge University Press.