

CHAPTER 1

STATEMENT OF THE PROBLEM

1.1 Introduction

Pollution prevention¹ and the related issue of sustainable development are currently part of a policy debate. The EPA has its "Common Sense Initiative" with the goal of restructuring environmental protection on a cooperative, flexible approach focused on pollution prevention (EPA, 1994). A premise of EPA is that this approach will result in a cleaner environment at less cost. There seems to have been little detailed analysis done to support this assumption. Other important policy documents such as the "Technology for a Sustainable Future" report prepared under the guidance of the National Science Technology Council also make the assumption that a win-win situation can occur by re-focusing waste management to "pollution prevention, efficient resource use, and industrial ecology" (NSTC, 1994). Industrial Ecology draws an analogy between industrial systems and ecological systems. In an industrial ecosystem wastes are not just outputs to be prevented but "also a part of the industrial process product stream that is to be designed" (Frosch, 1992, p. 800).

The analysis of the effect of pollution prevention and environmental compliance for manufacturing systems has not been studied extensively. Furthermore, the measurement of productive efficiency has typically not included consideration of the environmental impacts of manufacturing. In the literature, the generation of pollution has been taken into account using a number of different analytical methods that are reviewed in Chapter 2. Assumptions underlying these methods are that:

¹ Pollution prevention is defined by the Pollution Prevention Act of 1990 and is restricted to source reduction. Source reduction refers to reduction of the amount of any hazardous substance, pollutant, or contaminant entering any waste stream or otherwise released into the environment (including fugitive emissions) prior to recycling, treatment, or disposal.

- Pollution controls are after-the-fact, end-of-pipe and do not explicitly take into account process and other changes that can reduce pollution (i.e., pollution prevention) and potentially improve productivity performance.
- Interactions with other systems are not taken into account. For example, from an environmental impact perspective it is more desirable to send a waste stream to a recycler than to land disposal.

The objective of this research is to develop a performance measurement modeling approach and to define performance metrics that potentially assess the environmental management system performance of manufacturing facilities.

The measurement of performance requires the definition of some reference. The metric of performance is then based on a difference between the reference and the system being evaluated. The proposed method for measuring environmental performance addresses three aspects of performance: productive efficiency, pollution prevention, and interaction with other production systems. Each of these aspects of performance is briefly discussed.

Productive efficiency is measured with a modification to an existing technique (Tulkens and Vanden Eeckaut, 1995) that provides more information on the performance of the current production plan. This measure is based only on inputs and product outputs and indicates how well the production plan is converting inputs to outputs. The less input required to produce a given output the better both from a productive efficiency perspective and an environmental performance perspective.

The possible relationship between production process changes (e.g., pollution prevention activities) and waste generation is taken into account by considering undesirable outputs (i.e., pollution) in production and by making a distinction between material and non-material inputs. Pollution prevention activities should reduce the quantity of the undesirable outputs and may also reduce the quantity of material inputs. By adding undesirable output quantities to the performance metric, environmental impacts are now also part of this performance metric. The distinction based on material vs. non-material inputs results in a

metric that is more focused on environmental performance. From an environmental impact perspective non-material inputs such as labor and capital are always preferred to material inputs. However, these can be important inputs from the perspective of productive efficiency. This is because capital spending, for example, may be used to reduce undesirable outputs which is an improvement in environmental performance. This occurs when capital is spent to implement end-of-pipe treatment to conform to environmental regulations. The performance metric without this non-material input will show an improvement in performance assuming all else being equal. This is because undesirable outputs are reduced (because of pollution controls) and product outputs and inputs are constant (since non-material inputs are excluded).

The extent of interaction with other production systems is another important aspect of environmental performance. This is considered in the proposed method by evaluating input and output mixes in terms of environmental performance. The substitution of one input for another or one output for another may result in improvements in environmental performance. For example, an output that was sent for disposal but, instead, can be used as an input in another production process represents an improvement in environmental performance. Similarly, if an input that was formerly obtained by mining can instead be obtained by recycling then this is an improvement in environmental performance. Such changes in input and output mix will be neutral (i.e., are not judged to be either good or bad) in terms of the previously discussed performance metric that considers inputs, products, and undesirable outputs. These interactions among systems can be indirectly accounted for by studying the relative preference, in terms of environmental protection, among various input and output mixes. This requires that inputs and outputs are categorized according to their relative desirability from the perspective of environmental performance. From an environmental perspective, it is desirable to substitute less desirable outputs (e.g., discharge to the air or water) with a more desirable outputs (e.g., recycled output) and to substitute less desirable inputs (e.g., mined and refined ores) with more desirable inputs (e.g., scrap metal). The way in which inputs and outputs are categorized will vary depending upon the purpose of the metric and the system being evaluated.

1.2 The Problem Statement

This research proposes to define a measure of efficiency for a production system based on pairwise dominance criteria that account for pollution prevention and the interaction among production systems (e.g., recycling). This performance measure will be applied to data from a manufacturing facility to assess its environmental performance.

Subproblem 1: Define a metric of environmental performance that also considers productive efficiency.

Hypothesis 1: Improvements in environmental performance can also result in improvements in productive efficiency.

Subproblem 2: Define a metric of environmental performance that accounts for system interactions.

Hypothesis 2: There exists a metric of environmental performance that takes into account system interactions.

Subproblem 3: Implement and evaluate previously defined environmental performance metrics by assessing performance of an actual production system (e.g., a manufacturing system).

Hypothesis 3: The proposed measures of environmental performance provide useful information for decision making that can potentially lead to improvements in productive and environmental performance.

1.3 Summary of the Research Methodology

The proposed method is ultimately based on production theory and is described in Chapter 3. In production theory a function is used to designate optimal behavior associated with a particular production technology. For example, a function, $Q = f(\mathbf{x}, \mathbf{u})$, represents the combination of inputs ($x_1, \dots, x_i, \dots, x_I$) that can produce particular levels of outputs ($u_1, \dots, u_j, \dots, u_J$). Economic analyses often assume that all production systems are represented by this production function where productive inefficiency does not exist. Farrell (1957) introduced

the concept of defining a production function or frontier based on data using standard linear programming techniques. The production frontier defined in this way is a reference technology that represents the best performance actually achieved. Efficiency is measured by taking the distance of a particular production plan to the frontier. Any production plan on the production frontier is assigned an efficiency score of 1.0. By definition there can be no production plans that are not enveloped by the production frontier. Production plans that are inefficient, meaning not on the production frontier, are assigned an efficiency score of less than 1.0 (if inputs are being minimized) or greater than 1.0 (if outputs are being maximized). The actual efficiency value assigned is based on how far the production plan is from the production frontier.

There are many variations on how to compute the production frontier and the distance measures that are introduced with the linear programming approach of Farrell. This includes incorporating various constraints and accounting for various methods of defining distance. One of the most influential variations on the approach introduced by Farrell is by Charnes, Cooper, and Rhodes (1978). The formulation of the linear program by Charnes, Cooper, and Rhodes (CCR) restricts the radial measure to segments of the production plan defined by actual production plans that are closest to the production plan for which efficiency is being measured. This is the basis for Data Envelopment Analysis (DEA). Over the 20 plus years since the CCR paper there have been hundreds of papers published on variations and applications of this method.

Generally, DEA is applied to data from multiple facilities that are assumed to have similar technology. For example, one can compare the efficiency of bank branches, schools, power plants, and so on. When applied to manufacturing, DEA studies have generally treated the manufacturing facility as a “black box.” Applications of DEA at a less aggregated level within a manufacturing facility are few. Consideration of how data is used and interpreted is also rarely a part of DEA analyses. An exception is Girod and Triantis (1999).

A recent paper by Tulkens and Vanden Eeckaut (1995) does away with the concept of a frontier altogether and is instead based on the pair-wise comparison of production plans with an application to time series data. Their method is called Benchmark Correspondence and is the starting point for the proposed method. There are a number of reasons why the Benchmark Correspondence approach is chosen as the basis for this research. First, the approach does not require any assumptions about the existence of a production frontier. The use of actual data makes Benchmark Correspondence a more appropriate technique for the performance evaluation of a single manufacturing facility since the comparison to actual production plans is what is of interest. On the other hand, performance measurements that are based on the definition of a best practice frontier (as is the case with DEA) are composed of production plans that are not necessarily observed in reality and are dependent on the assumptions made concerning the definition of the frontier. Second, the nature of the data set being evaluated also makes the Benchmark Correspondence method a more reasonable choice. Standard methods like DEA only produce meaningful results when there are a relatively small number of inputs and outputs. The data set being used has too many inputs and outputs for the DEA method to be applied. In contrast, no limit on the number of inputs and outputs is required for the Benchmark Correspondence approach. This is because the method evaluates performance based on the direct comparison to actual production plans. However, it is noted that the actual data being used in this research does present problems and issues regardless of the method being used. These data issues are discussed in Chapter 4.

The definition of pairwise dominance used in the Benchmark Correspondence method, which is the starting point for the proposed method, is defined below (Tulkens and Vanden Eeckaut, 1995).

- Definition. (1) $(\mathbf{x}', \mathbf{u}')$ dominates (\mathbf{x}, \mathbf{u}) in inputs if both $\mathbf{u}' \geq \mathbf{u}$ and $\mathbf{x}' \leq \mathbf{x}$.
- (2) $(\mathbf{x}', \mathbf{u}')$ dominates (\mathbf{x}, \mathbf{u}) in outputs if both $\mathbf{u}' \geq \mathbf{u}$ and $\mathbf{x}' \leq \mathbf{x}$.
- (3) $(\mathbf{x}', \mathbf{u}')$ dominates (\mathbf{x}, \mathbf{u}) if either (1) or (2) holds or both.

The term, \mathbf{x} , is an I-dimensional vector of the inputs $(x_1, \dots, x_i, \dots, x_I)$ and the term, \mathbf{u} , is the J-dimensional vector of the outputs $(u_1, \dots, u_j, \dots, u_J)$. The comparison is made between the elements of the input and output vectors of two production plans with one being designated as $(\mathbf{x}', \mathbf{u}')$ and the other as (\mathbf{x}, \mathbf{u}) . The terms $\underline{\geq}$ and $\underline{\leq}$ mean greater than or equal to the reference and less than or equal to the reference, respectively. The terms \geq and \leq mean greater than or equal to with at least one element in the vector greater than the reference; and less than or equal to with at least one element in the vector less than the reference, respectively.

The definition of pairwise dominance requires that for a production plan to dominate another its inputs must be less than or equal to the other and its outputs must be greater than or equal to the other with at least one input being less or one output being greater than the corresponding element of the other production plan. This definition of dominance is similar to one provided by Koopmans (1951, p. 460) where a production plan would be considered efficient “if there is no other attainable set of commodity flows in which all flows are at least as large as the corresponding flows in the original set, while at least one is actually larger.”

The definition of dominance is applied by Tulkens and Vanden Eeckaut (1995) to partition production plans into one of three sets: dominating, dominated, and dominance indifferent. The first observation in a time series of data is always placed in the dominance indifferent set. Then, each production plan in a time series is compared to all previous production plans that were determined to be dominance indifferent. If a production plan is neither dominated or dominating it is added to the set of production plans that are dominance indifferent. If a production plan is placed into the dominating or dominated set then a distance measure is calculated to evaluate that production plan's relative performance. Various approaches (e.g., maximum, minimum) may be used to select the particular production plan from the dominance indifferent set to which the distance of production plans in the dominating and dominated sets are measured.

This research modifies the Benchmark Correspondence approach so as to incorporate the measurement of environmental performance and to be more applicable to non-aggregated, manufacturing data. There are three modifications to the Benchmark Correspondence approach in this research methodology. First, in the proposed method, at each time t in the time series of production plans all previous production plans are partitioned into dominating, dominated, and dominance indifferent sets with the production plan at time t as the reference.

This proposed method has the advantage of providing more information on how a current production plan compares to previous production plans. The Benchmark Correspondence method only allows calculation of performance measures when a production plan falls into a dominating or dominated set compared to *all* previous production plans defined to be dominance indifferent. The proposed method will calculate a performance measure anytime a production plan before time t either dominates or is dominated by the production plan at time t . Given the application of this method to operational level data the current performance is of primary interest.

The second modification is that undesirable outputs are added to the pairwise dominance criteria. As a result, for a production plan to be considered an improvement in environmental performance relative to a reference production plan, these undesirable outputs must not increase.

Third, changes in input and output mixes are evaluated. This is an indirect measure of the level of interaction among systems. Both inputs and outputs are classified by their relative environmental desirability. These changes in input and output mix are neutral in terms of productive efficiency (assuming input substitutions do not adversely affect the production process). This is because categorizations are based on factors that are not relevant to the performance of the production process. One possible categorization may be based on the origin of inputs and the destination of outputs that do not necessarily affect

productive efficiency. If an output is sent to another production system for recycling rather than being sent to disposal, this is an improvement in the output mix in terms of environmental performance. If scrap steel is used as an input rather than iron ore, this is an improvement in the input mix in terms of environmental performance.

The metrics that are applied are not typical for the Benchmark Correspondence method. These are the Euclidean Distance, Average Euclidean Distance, and set counts. The Euclidean Distance is simply the shortest distance between two production plans. The Average Euclidean Distance is the average distance obtained for a production plan to all of the production plans in a set. Counts of memberships in different sets provide summary information concerning environmental performance and trends.

There are many issues associated with the model specification that are addressed in the research. Methods for the measurement of productive efficiency are usually applied to highly aggregated data obtained from government statistical agencies. Model specification is typically not dealt with at all in literature associated with the measurement of productive efficiency. This research applies the proposed and standard techniques to detailed operational level manufacturing data obtained from a participating facility to be called Manufacture, Inc. The analysis performed on the data is discussed in the next section.

1.4 Application of the Proposed Method and Standard Methods

As noted by Seaver and Triantis “[g]iven that most data used for production studies has not been accumulated for such purposes, it is important that data and modeling issues such as, outliers, collinearity, measurement errors, aggregation, input/output specification and others are studied carefully given their impact on efficiency performance measurement” (p.1, 1991). Rather than performing a completely theoretical study or using existing data sets, the proposed method is applied to data obtained from a printed circuit board manufacturing facility to be called Manufacture Inc. The data obtained from Manufacture Inc. is less than ideal which is typical of real data. Analysis of the data, described in

Chapter 4, was performed to create data sets appropriate for the application of the proposed method as well as standard methods.

The use of real data provided significant insights that are incorporated into this research. In addition, a significant amount of work was performed for Manufacture Inc. in exchange for their assistance in obtaining data. This included analysis of water use, cost of water (twice the cost charged by the water authority when on-site treatment costs were considered), bottleneck identification (process is well-balanced and no major bottlenecks were identified), and an initial effort to apply Activity Based Cost Accounting (accounting department was working on this anyway, but the work performed by the author provided some useful insights) (Otis, 1997, 1997a, 1997b). This work was helpful in understanding the limitations of the data and the results of the analyses reported in Chapter 4.

Although not a modification to the Benchmark Correspondence method, in the specification of the model the data was normalized. This normalization procedure was necessary to remove the bias associated with the units of measurement. So, the data that was used is without units after the normalization procedure. Note that more standard methods for the measurement of productive efficiency (like DEA) use a metric that is derived from ratios of the same inputs and outputs. As a result, the distance measure is unitless. If distance is to be directly measured (as in the proposed method), the issue of bias related to units of measurement becomes an issue.

Standard statistical analysis are applied to determine how inputs and outputs are related. Standard methods such as DEA (Charnes, Cooper, Rhodes, 1978) (Banker, Charnes and Cooper, 1984), FDH (Deprins, Simar and Tulkens, 1984), and Benchmark Correspondence (Tulkens and Vanden Eeckaut, 1995) are also applied to the data to provide a standard of comparison for the proposed method. The proposed method is then applied to the data. Computer programs were developed in the language MATHEMATICA to implement both the Benchmark Correspondence method and the proposed method.

It is shown that the proposed method does indeed provide more informative results concerning plant performance at the operational level than do standard methods. For example, since inputs are not as aggregated as they are required to be for standard DEA analyses particular plant inputs can sometimes be identified as the source of particular performance results. There are a number of research issues yet to be resolved. Conclusions and possible additional research are discussed in Chapter 5.