CHAPTER 5
SUMMARY AND CONCLUSIONS

A production theory based method for evaluating the environmental performance and productive efficiency of manufacturing was developed and applied. Chapter 3 defines the method developed and Chapter 4 applies the method along with standard statistical and productive efficiency analyses. There are five main areas that this research addresses: approaches for achieving an industrial ecology; data collection and model specification; application of existing methods for the measurement of productive efficiency to operational data; development of a method based on the extension of existing methods; and application of the developed method to operational data. Each of these issues is discussed in the following sections. Finally, areas for additional research are reviewed.

5.1 Achieving an Industrial Ecology

Industrial Ecology is the context for this research. Industrial Ecology analogizes industrial systems to ecological systems. The complex-web of connections in ecological systems has evolved over time to essentially make use of all available energy and useful material. There is the need for "a coherent operational framework for examining potential long-term advantages and disadvantages of alternate webs of industrial changes and identifying the short-term bottlenecks that may emerge. These studies will provide the kind of information required both for public debate and decision making and for private calculations about requirements and opportunities. These debates, decisions, and calculations are necessary for the development of markets and as input to the various other social institutions that have a stake in industrial ecology" (Duchin, 1992, p. 851). This research is a contribution to the development of such an operational framework.

The research is focused on the evaluation of a single manufacturing system. The method for evaluating environmental performance accounts for both process changes such as pollution prevention as well as improvements in terms of greater integration with the industrial ecology. The developed method was specifically designed to work with the types of data that are available to a manufacturing facility.

This research did not have the data to directly address policy issues Based on the analysis of this single manufacturing facility the author believes it is fair to conclude that, given environmental regulations, pollution prevention can indeed also be cost effective. In other words, pollution prevention is often worthwhile because the alternative of end-of-pipe treatment and the concomitant paper work is so expensive. There are circumstances where improved productive efficiency also results in reductions in pollution. For example, the facility examined had a significant scrap production. Reducing this scrap production could very well have the effect of both improving productive efficiency and reducing pollution thereby improving environmental performance.

Environmental regulations can have a distorting effect on priorities. For example, reducing an input may reduce environmental impact more that reducing a regulated, undesirable output. Given incomplete information on environmental impacts, from a practical perspective, environmental regulation often must focus on pollution generation. This focus of environmental regulation means that efforts at pollution prevention also focus on reducing undesirable outputs. As a result, reductions or substitutions on inputs that may be environmentally desirable are often not addressed. In general, the creation of an industrial ecology is not encouraged by the current regulatory system.

5.2 Data Collection and Model Specification

While detailed data on inputs and outputs were obtained as part of this research the resulting data set was not ideal. To be applied, this method requires more detailed data as described below:

- *Product Output:* These data should typically be available. The data used in this research were accurate for product outputs.

- *Inputs to the Production Process:* These data should be available in some form. Ideally, these data would reflect actual use in the production process in terms quantity of use such as pounds, kilograms, gallons and so on. The data used in this research reflected inventory and were only indirectly related to actual production use. In addition, data were in terms of costs rather than quantity. Quantity measures are more meaningful in terms of environmental performance.

- *Undesirable Outputs:* Undesirable outputs are often only tracked though the requirements of the regulatory system and are not well integrated with other information systems. As a result, these data can be difficult to relate to actual production generation. These type of data were obtained in the research, but were quarterly and not directly related to production.

- *Labor Hours:* These data were available and should be available at other facilities.

- *Salary Hours:* These data were also available and should be available at other facilities.

- *Capital:* This information was part of the overhead accounts and was not part of the data set used. Details on capital investment and significant changes to the production process are required to do a complete analysis. For the system being analyzed there were no major changes to the production process over the time period for which data were collected.

The data for material inputs and outputs also needs to be of sufficient detail to perform a material balance. This allows a check to be made to ensure that all inputs and outputs are being appropriately considered. This can be especially critical when estimating undesirable outputs since this information is often obtained for regulatory purposes and may not relate well to the production process. The ordinal classification scheme used to assign relative environmental preference was based on the source of inputs and the destination of outputs. This information may not be readily available, but can often be obtained by contacting suppliers of materials and services.

A week or day is a preferred time frame for data. This provides sufficiency detail with enough currency to allow identification of problems and potential improvements in a production process. Data for times periods of less than a day will tend to be subject to so much variation that conclusions concerning productive efficiency or environmental performance will be difficult to make. Monthly data is also a possibility, but since months differ in length there would have to be an adjustment made to have comparisons on a common time frame. Yearly data is not particularly useful from an operational perspective. Manufacturing information systems are rarely stable over long periods of time making it highly unlikely that long term yearly data are available at the level of detail that is desirable. Yearly data is also highly aggregated making it difficult to relate results to production. However, such data over an extended period of time, if it were available, could be usefully analyzed to address the policy issue of pollution prevention and its impact on productive efficiency.

Unfortunately, the method developed, while an improvement in terms of the number of inputs and outputs that may be analyzed compared to DEA based methods, is still limited. If more than about 15 inputs are part of the production process then some selection method will be required to reduce the number of inputs. A Pareto analysis was performed as part of this research to select 14 inputs (from 95) that represent the largest inputs. The remaining inputs were aggregated into a single 15^{th} input. In some cases selecting inputs that are known to more strongly affect the production output may be preferred. This information can be obtained by performing standard statistical regression and correlation analyses and by discussions with facility personnel as data collection is occurring.

Assessing operational performance also requires timely information. This means that there must be some routine method for gathering the appropriate data for analysis. The data set that was generated required information from both automated and manual systems. Obtaining these data and creating the data set was a labor intensive process requiring many days. Few manufacturing facilities have the kind of integrated information systems required to quickly accumulate the data needed to apply this method. However, the trend in towards such integration so that more effective use of large amounts of plant data is becoming a more realistic goal.

5.3 Application of Existing Methods

This research applied various methods for the measurement of productive efficiency to detailed operational data. A complete consideration of the many variations on techniques for the measurement of productive efficiency was not performed. However, some general conclusions can be made concerning methods for the measurement of productive efficiency.

Existing methods have two main drawbacks in terms of application to operational data. The original development of methods of productive efficiency was focused on evaluating the relative productive efficiency of similar facilities. For example, bank branches, power plants, and so on. The methods were not originally intended for the application to time series data from a single facility. While there are examples of applications to time series data from a single facility the model specification issues associated with this application have not been fully addressed.

The second drawback is the limited number of inputs and outputs that may be specified. In the data set used (18 inputs, three undesirable outputs, and one product output) the standard methods simply assign all production plans an efficiency score of 1.0 (meaning the production plan is as technically efficient as possible). So, no information on relative performance is provided. Inputs were aggregated to produce a data set for which results were obtained with the standard methods. However, aggregated data makes it substantially more difficult if not impossible to relate results back to events in the production process. Even with this reduced data set the standard methods often assigned an efficiency score of 1.0 to a production plan.

The analysis of slacks produced by the linear programming procedure does provide more data. However, with the highly aggregated inputs that must be used it is not clear what these slacks actually imply in terms of decision making. Also, different assumptions for the Data Envelopment Analysis formulation produced different relative efficiency scores. As a result, the conclusions drawn concerning performance depend on the type of model used. Research into how to determine correct model assumptions and how the results for these different linear programming formations relate to each other and the modeling assumptions is not complete. These results do not seem reliable for making operational decisions.

5.4 Developed Method

The existing Benchmark Correspondence method described in Chapter 2 was taken as the starting point for the development of the method for this research. The Benchmark Correspondence method was chosen rather than other methods for the measurement of productive efficiency because:

- *Only actual data were used as the basis for measurement:* Performance measures, as opposed to predictive measures, are more appropriately based on actual data rather than mathematical representations.

- *More inputs and outputs may be specified:* More inputs and outputs may be specified for the production system being evaluated than with many other approaches for measuring productive efficiency. As a result, less aggregation of inputs and outputs are required which allows results to be more readily related back to changes in the production process.

The developed method is produced with three extensions to the Benchmark Correspondence model that are more fully described in Chapter 3. These extensions are:

- *More Information is Generated:* The proposed method, through a change in the solution algorithm, uses the current production plan as the reference against which previous production plans are assigned to sets. This generates more detailed information on the performance of the production plan at time t than is the case with the Benchmark Correspondence method.

- *Undesirable outputs are considered:* The dominance criteria for the Benchmark Correspondence method are expanded to include undesirable outputs. This allows the affect on the generation of pollution to be considered along with productive efficiency.

- *Changes in input and output mix are considered:* Environmental performance may also be improved by changes in input or output mix. A method of detecting some changes in input and output mix that are improvements in environmental performance is added to the dominance criteria.

5.5 Application of the Developed Method

The application of the developed model is also an extension of existing approaches. The Benchmark Correspondence method uses dominance to assign production plans to sets. The proposed method applies several dominance criteria to partition production plans into various sets. The memberships in these sets have different meanings in terms of productive efficiency and environmental performance. Once production plans are assigned to sets then distance measures for inputs, outputs, and undesirable outputs are calculated. Also, an average distance to a set of production plans (also for inputs, outputs, and undesirable outputs) is calculated. The explicit separation of these three components and the average distance measure are extensions of existing methods. Since distance is calculated directly the data is normalized. This is also not a typical approach for the measurement of productive efficiency. Counts of set memberships are also used to provide an overview perspective of the data as has been done in other work. The application is more fully described in Chapter 4, Section 4.6. Model specification issues were also dealt with to a greater extent than is typical for productivity analysis and provided useful insights into the method and possible applications.

Programs were developed in MATHEMATICA (refer to Appendix D) as part of the research for the Benchmark Correspondence method and the proposed method. The Benchmark Correspondence method placed all production plans evaluated into the dominance indifferent set and, therefore, produced no information for decision making. The proposed method did generate data that could be used for decision making. However, the proposed method was also not ideal for the data set. The requirements for membership in the sets TE and TI were so demanding that no production plans were placed in these sets. Production plans were placed in the sets D_d, ,D_g , D_i, TU, SE, and SI. The proposed method does generate more information concerning changes at the operational level than did the standard methods. Data on inputs and outputs were sufficiently detailed so that results can potentially be linked to what is going on at the production level. MATHEMATICA is not the ideal choice of a programming language for this application. Visual Basic, perhaps in combination with the database software Microsoft Access®, would have been a better application.

5.6 Research Issues

There are a number of research issues to be addressed before the developed method would be a fully appropriate approach for the measurement of environmental performance. These are each discussed below:

Model Specification: There are many data issues that would be useful areas of research to include: treatment of outliers, consideration of data error, consideration of incomplete data, normalization procedures, and specification of appropriate inputs and outputs

Combine the Developed Method with Standard Methods: The developed method, along with other analysis such as that described by Seaver and Triantis (1995), may be used to select production plans for inclusion in standard DEA analyses.

Evaluating Production Plans based on Set Memberships: The general approach of "sifting" data based on various filters to assign observations to sets seems to have potential applicability to the analysis of large data sets with messy data. Given membership in particular sets, with particular properties, metrics can be calculated to provide quantitative performance information. The more information that is available on the relative environmental desirability of production plans the more detailed the analysis possible. For example, there are a number of methods for quantifying environmental impacts such as life cycle cost analysis as described in Section 2.1. While these methods may not yet be up to the task of precisely defining relative environmental impacts they may be applied to estimate weights for inputs and outputs. One input may be twice as desirable (weight of 2 multiplied by the input) as another (weight of 1 multiplied by the input). Or, a range may be specified such as 2 to 4 times more desirable upon which sensitivity analyses may be performed. Such weights could directly substitute for the price of an input or output allowing methods of estimating allocative efficiency (how well a production system is reducing costs) as defined by Farrell (1957) to be used.

Distance Measures: Only two distance measures were applied in this research. There are many other possibilities. Tulkens (1993a) addresses this issue for frontier free methods. Additional work on the possible distance measures, their meaning in the measurement of performance, and their application would be useful.

Relationship to Other Methods: There are many models and methods for the measurement of productive efficiency. An understanding of how these methods relate to each other, the appropriate circumstances for applying these methods, and the interpretation of results is far from complete. In the area of environmental performance Tyteca (1995, 1996) addresses this issue.

Visualization of Data and Results: The results of analyses using methods for the measurement of productive efficiency often do not have very clear intuitive interpretations. One way of making results from productive efficiency analysis more accessible to decision makers and more applicable is to allow results to be visualized and to also allow interaction to perform, for example, sensitivity analyses. Some work in this area has been done for DEA methods by Belton and Vickers (1993).

Integration with Information Systems: With the increasing computerization and integration of data gathering and reporting systems in manufacturing and other industries, there is a need for methods of sifting and analyzing this data. The theory and methods of productive efficiency do have the potential to be usefully applied to these large data sets. In combination with appropriate data treatment and reporting methods, such as visualization techniques, approaches of measuring productive efficiency can provide information useful to decision makers.