To the Graduate Council:

I am submitting herewith a thesis written by Todd Mitchell Thomas entitled "Analysis of the Characteristics and Interrelationships of Industrial Energy Consumption and Waste Generation for Selected Tennessee Industries." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Engineering Science.

Dr. Richard J. Jendrucko, Major Professor

We have read the thesis
and recommend its acceptance:

Accepted for the Council:

Associate Vice Chancellor
and Dean of the Graduate School

Analysis of the Characteristics and Interrelationships of Industrial Energy Consumption and Waste Generation for Selected Tennessee Industries

A Thesis Presented
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ABSTRACT

This study focused on determining the characteristics and interrelationships among selected manufacturing facility parameters and production efficiency as measured by energy usage and hazardous waste generation. The types and quantities of hazardous waste generated for facilities in Standard Industrial Classifications 34, 36, and 37 were obtained from the 1991 Tennessee Annual Hazardous Waste Report (THWR). Energy consumption rates and facility characteristics for the same plants were collected with a direct-mail survey.

Characterization of the survey data using the JMP 3.02 Statistical Software Package revealed that most respondents were medium-sized companies with only one reportable hazardous waste stream. Furthermore, the waste quantities generated tended to correlate with the specific processes used in the plant. Among companies in the targeted SIC categories, most waste was produced from operations involving either metal-plating, solvent-based painting, and parts cleaning. As a result, the study determined the prevalent waste types to be corrosive or ignitable in character.

An initial investigation into the relationship between energy usage and waste generation was also performed using globalized data from the 1988 Manufacturing Energy Consumption Survey and the 1988 Toxic Release Inventory. The results demonstrated an overall proportional relationship between energy usage and waste generation.

Finally, analysis of combined data from the 1991 THWR and direct-mail survey revealed that hazardous waste production was unrelated to the quantity and type of energy used. But, when the quantity of hazardous waste generated was normalized with facility size, a significant relationship with energy usage was found.

These results confirm the overall importance of considering the linkages between industrial energy use and waste generation. Such relationships may be useful in designing industrial processes for improving manufacturing efficiency.

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1. INTRODUCTION

The rapidly developing "global environment" has created an unprecedented level of competitiveness in business. To gain an advantage, manufacturers of durable goods have tried to improve both product quality and production efficiency. Increasing quality directly relates to customer satisfaction, while increasing production efficiency relates to process optimization. Both are required to maximize profits.

Companies in the United States have tried various methods to improve efficiency. Examples include: downsizing and retraining of the labor force, product redesign and process automation, and just-in-time production scheduling and total quality management. However, both the Federal government and private industry are beginning to consider the influence on production of two specific and significant efficiency measures, namely energy consumption and waste generation.

In order to promote production efficiency improvements and to conserve natural resources, the Federal government supports outreach services to help manufacturers conserve energy and reduce waste. Until recently, the Environmental Protection Agency (EPA) funded a university-based Waste Minimization and Assessment Center program to help manufacturers improve production efficiency through reducing the generation rates of both hazardous and non-hazardous waste. Similarly, the Department of Energy (DOE) supports the eighteen year-old Energy Analysis and Diagnostic Center program to assist manufacturers in lowering energy requirements for production.

Unfortunately, employing either energy usage and waste generation as an efficiency measure is not straightforward. Many difficult-to-quantify factors influence each measure. Energy consumption for a manufacturing facility depends upon a variety of parameters such as: the number and age of process equipment, production operating hours and capacity. Likewise, waste generation depends on the same factors, as well as others including: product line unit operations, skill of operators, and efficacy of process chemicals.

In the past, energy and waste issues were generally considered separately. However, the synergistic effect of reducing both energy use and waste production is being realized. The push towards "source reduction" over "end of pipe treatment" as a waste management practice is notable in this regard. For example, some process changes or material substitutions can simultaneously eliminate a waste stream and decrease energy use. In this way, improving one efficiency measure may favorably impact the second.

Before fully exploiting such benefits, manufacturers must understand the nuances of these two efficiency measures. Initial investigations must begin by characterizing energy use and waste generation in a well-defined datapool of manufacturers. Next, the relationships of certain facility parameters, such as manufacturing processes, should be investigated and the interaction of the energy consumption and waste generation characterized. Previous investigations have neglected both aspects.

Based on this background, this study aimed to begin filling the existing information void. Key parameters were identified which may influence the production efficiency measures of energy consumption and waste generation. The influence of these parameters on production efficiency was investigated. Finally, the relationship between the two efficiency measures was studied. It is hoped that the results of this analysis will guide future research to assist manufacturers in optimizing their overall production efficiency, and consequently in maintaining a high level of global competitiveness.

2. BACKGROUND

Introduction

Limited data exist for studying how manufacturing facility characteristics relate to industrial energy consumption and waste generation. Federal reporting requirements for toxic chemical usage, hazardous waste management, and energy consumption have resulted in most of the available information. Some states also have reporting requirements addressing both hazardous waste management and disposal. The reported information for both the Federal and State requirements are assimilated by the respective agency and made available for public review. Private parties also use specialized surveys to collect relevant information for studies, but generally do not release raw data for other investigations.

Mandated reporting by the government serves several purposes. First, with respect to hazardous waste, reporting waste practices and releases informs communities about the hazardous chemicals used in their environment and provides incentives for plants to adopt pollution prevention techniques. Secondly, because both energy use and waste generation affect production efficiency, the data are used to monitor the efficiency of U.S. industry and guide Federal programs leading to improving it. Lastly, the data is used by interested parties (including government, universities, and the private sector) to study trends and characteristics of energy consumption and waste generation.

A literature search revealed that only a limited number of studies have been conducted with the available waste databases, but considerably more investigations exist using energy consumption data. Most reports have been published by the overseeing agency of the Federal government and have limitations. For example, reports issued by Federal agencies frequently require up to two years to compile, analyze, and produce before public release. This problem makes developing current time-relevant conclusions difficult. Also, the data address entire segments of the manufacturing arena (for

example, the energy requirement for SIC 34, Fabricated Metal Products) in the United States. Thus, in general one has difficulty drawing inferences about smaller, more specialized, datasets such as Tennessee manufacturers in SIC 34.

Overview of Federal Industrial Energy and Waste Reporting Requirements, Databases, and Voluntary Programs

Industrial Energy Consumption

In the last twenty years, the Federal government has increased its interest in the characteristics and patterns of industrial energy consumption to conserve natural resources, protect national security concerns, and assure environmental quality. Prior to the energy crisis of the 1970's, the United States was relatively unconcerned about the availability or cost of energy for industrial use. However, when the oil embargo of 1973-74 quadrupled oil prices, the U.S. felt the venerability of being dependent on an energy source controlled by other countries, and national security issues were raised [1]. The externality cost of environmental degradation associated with energy production also concerns the Federal government [2]. Increasing residential and industrial demands for energy, particularly electricity has the potential to significantly deplete natural resources and degrade environmental quality. After considering the cost of environmental damage, it is estimated that the price of supplying electricity with coal and nuclear energy has increased 40% since 1970 [3].

As a result of this increasing interest, in 1978, the DOE began the Energy Information Administration (EIA) to collect, analyze, and disseminate information on industrial energy use [4]. The agency uses the Manufacturing Energy Consumption Survey (MECS) to collect energy consumption information on a triennial basis from a sample of active manufacturers in all SIC categories. The MECS is the only available comprehensive source of industrial energy consumption data on a national level. It focuses on consumption rates for different energy types (including coal and electricity) and the energy use for certain process equipment (for example, electric motors and boilers). From data collected with the survey, the EIA uses

statistical methods to draw inferences about energy consumption patterns for the entire manufacturing sector and individual SIC categories. The results are published in a report and made available for public review.

Industrial Hazardous Waste

The Federal government became interested in the types and quantities of hazardous waste being generated after two man-made environmental disasters, the Kepone Disaster in Hopewell, Virginia (1973) and Love Canal in Niagara Falls, New York (1976) [5]. These events spurred the enactment of environmental statutes focusing on the management of hazardous waste and the cleanup of current spills and formerly utilized disposal sites. The two most pertinent laws promulgated are:

- Resource Conservation and Recovery Act of 1976 (RCRA) - Provides a "cradle-to-grave" management concept for hazardous waste.
- Comprehensive Environmental Response, Compensation and Liability Act of 1980 (CERCLA) - Gives EPA the means to manage environmental damage from spills and at abandoned sites (also known as "Superfund").

The RCRA deals with managing hazardous waste. In the U.S., over 500,000 companies, which generate over 172 million metric tons of hazardous waste annually, must comply with RCRA rules [6]. Associated with statutory compliance, companies must report the quantities and management techniques (including disposal) for their hazardous waste on a biennial basis. However, most states oversee the enforcement of RCRA and require facilities to submit the same, or more in-depth, information annually. Although data submitted by individual facilities are available for public study, states generally do not assimilate it into a report format for public distribution.

Between these two statutes, the amendments to CERCLA, the Superfund Amendments and Reauthorization Act of 1986 (SARA), has the most extensive annual reporting requirements for companies using toxic chemicals. Specifically SARA Title III, the Emergency Planning and Community Right-to-Know Act (EPCRA), requires the development of a publicly accessible national

database termed the Toxic Release Inventory (TRI). Information from U.S. manufacturers on the release and transfer (disposal) of toxic chemicals from an EPA-developed list are included in the TRI [7]. This data is collected by the annual reporting of companies meeting certain threshold levels of toxic chemical usage. The first reporting year was 1987, and now a large volume of data exists which may be used to track how efficiently manufacturers utilize toxic chemicals.

Voluntary Programs

With respect to waste, EPA sponsors several voluntary programs. These non-regulatory programs are designed to encourage participating facilities to voluntarily take action to reduce pollution. Table 2-1 identifies five of the most popular current programs.

Each program is successful if measured by company participation. The 33/50 and Green Lights programs have well over 1,100 [7] and 1,350 participants [10], respectively. Also, since it was first initiated in 1991, the $NICE^3$ program has awarded 16 grants to interested state and industry partnerships [11], and the WasteWi$e program, established in 1994, has already attracted more than 320 companies [13]. The success of these programs may be attributed to manufacturers trying to avoid environmental regulation and lowering energy use. Regardless of the participants motivation, the Federal government is achieving results in its goal of increasing the nation's productivity while reducing energy use and pollution.

Previous Studies on Industrial Energy Consumption and Waste Generation

Industrial Energy Consumption

Unlike waste, industrial energy consumption has been fairly well studied. Most published reports, which were prepared by government agencies or public policy institutes, have focused on energy consumption trends (increases or decreases over time) or a specific fuel type used. The studies were usually complied with data obtained from the MECS. However, like

Table 2-1. EPA Sponsored Voluntary Programs and Objectives

Program	Year Established	Objective
33/50	1991	to reduce the use of 17 toxic chemical 33% by 1992, and 50% by 1995 [8]
Energy Star	1991	to promote the use of energy saving equipment (for example computers) to reduce pollution associated with electricity generation [9]
Green Lights	1991	to increase lighting efficiency to lower energy consumption, thus reducing air pollution associated with electricity generation [10]
National Industrial Competitiveness through Energy, Environment, and Economics ($NICE^3$)	1991	a DOE and EPA administered grant program to promote improvement in industrial competitiveness through the use of energy saving technologies and associated pollution prevention [11]
WasteWi$e	1994	to reduce solid waste through pollution prevention and recycling [12]

waste studies, most research neglected the potential links between industrial energy use and facility characteristics.

Using data from the MECS, it is possible to characterize energy consumption patterns for particular SICs or the entire manufacturing sector. For example, in 1988 the MECS was submitted to approximately 12,000 manufacturers. From this datapool, it was determined that U.S. manufacturers used about 20.5 quadrillion (10^{15}) British thermal units (BTU) of energy. This total may be broken down into specific categories and compared with usage in previous years. For example, the total purchased fuels and electricity was 9.7 quadrillion BTU in 1985 and 11.1 quadrillion BTU in 1988, an increase of 14% over the three year period [4]. Also, the most common energy form used was natural gas which accounted for nearly 30% (6 quadrillion BTU) of the fuel mix. Results from the 1991 MECS were not available for analysis at the time of this writing so use of the data source was limited to 1988 and prior years. Although the MECS provides useful data for drawing conclusions about energy use patterns on a national level, it lacks any state or plant level detail. Another drawback about using MECS data is that raw data cannot be obtained for analysis.

Because manufacturers, and hence the economy, depend heavily on energy availability and use, much research has been done on improving industrial energy efficiency. Such research is promoted by DOE and other agencies, as well as demanded by high energy intensity industrial sectors, to offset rising energy costs in-order to maintain a competitive position in the marketplace. Due to this research, energy use in manufacturing is fairly well documented. For example, it has been determined that electricity represents about one-third of the total energy use in manufacturing. Of that total, 70% is dedicated to electro-mechanical use [14].

To lower this usage, manufacturers are employing energy efficient processes, motors, and automation (robotics) identified by research findings. Facility lighting is another area in which manufacturers are utilizing efficient technologies. The EPA's Green Lights program has reported that over 220 billion KWH (750 trillion BTU) have been saved from industry switching to energy efficient lighting since 1991 [15].

Other studies involving energy consumption have been published. For example, work has been done to establish self assessment tools for energy

management and conservation [16]. This research resulted in the development of a formula to predict energy consumption using certain facility characteristics for a datapool of eleven printing companies. Other models have been developed to justify capital expenditures of energy saving equipment [17]. Studies also have examined how life styles (for example, level of income) affect national energy consumption rates [18].

Industrial Hazardous Waste

Historically, pollution studies, such as remedial cleanup technologies and air pollution effects, have focused on the fate and transport of chemicals in the environment (i.e. soil, water, air). Although these are important research areas to assure environmental quality, investigation of industrial waste generation characteristics is also needed to determine the set of production parameters which most significantly influence waste generation.

An extensive literature search revealed no prior in-depth work characterizing industrial waste generation. Limited data that do exist are, in most cases, contained in government reports, or policy journals that summarize Federal waste databases (including the TRI).

Available reports do characterize, on a broad scale, the waste types and quantities generated by U.S. manufacturers. For example, pertinent information concerning national pollution data and trends are provided by the 1991 TRI database [7]. Table 2-2 summarizes the data submitted by 23,719 waste generating facilities in 1991.

Although the chemical quantities reported in Table 2-2 appear relatively large, they were actually lower the those reported in 1990 since releases and transfers decreased by 9% and 19%, respectively. Furthermore since 1988, the EPA baseline year, releases have dropped 31% and transfers 34% [7]. This data is also useful in measuring the impact of Federal volunteer programs like EPA's 33/50 program. The 17 priority chemicals targeted under the program to be reduced 33% by the year 1992, have already been reduced 100 million pounds over that goal [19].

Few investigations target reasons for hazardous waste production. In a particular exception, it was noted that hazardous waste generation rates were influenced by production rates for a small number of manufacturers [20].

Table 2-2. TRI Releases and Transfers for 1991

Category	Type of Release or Transfer	Total (million lbs/yr)
1991 Releases[1]	Total	3,385
	Air releases	2,010
	Underground injection	710
	Land releases	421
	Water releases	244
1991 Transfers[2]	Total	3,865
	Recycling	2,354
	Treatment/disposal/other	661
	Energy recovery	438
	Publicly Owned Treatment Works	412

[1] a "release" is an on-site release of a toxic chemical including emissions to air, discharges to water, and disposal onto land and into underground injection wells [2]

[2] a "transfer" is the removal of a toxic chemical to an off-site facility for either recycling, energy recovery, treatment, or disposal [2]

Overall, data is lacking on the characteristics of industrial waste generation because waste producing manufacturers are not required to submit such information. To better understand the characteristics, data should be collected on facility parameters (including manufacturing floorspace, process unit operations, and energy consumption), as well as the quantity and type of waste generated. However, the federally available databases do not provide such detailed information needed for in-depth characterization.

Industrial Energy Consumption and Waste Generation

As mentioned above, a literature search revealed no significant studies shedding light on the relationship between industrial energy consumption and waste generation on a facility level. However, there is an interest in the relationship on a broader, global level. This evident as a plethora of investigations exist on the impact of energy production and industrial growth on air quality [21, 22, 23, 24]. Additional studies explore the energy and waste consequences of producing certain products [25]. Also, government programs such as Green Lights and Energy Star focus on reducing pollution by lowering electricity usage in certain classes of equipment [17].

Most studies attempting to link energy to waste are fueled by recent concerns about ozone destruction and global warming. This area has been widely studied because 60% of the greenhouse gases are produced from energy production and conversion [21]. This percentage is attributed to the common use of fossil fuels to generate electrical power in the U.S. For example, coal is used to produce over 55% of the electricity in the United States [23]. Of the greenhouse gases, 50% is attributed to carbon dioxide, a by-product from coal burning [22]. Power generation also accounts for the major fractions of sulfur oxides (80%), particulates (33%), and nitrogen oxides (44%) released to air [24]. To mitigate the releases of these air pollutants, electric utilities have spent over three billion dollars on pollution abatement and control equipment [26].

The air pollution studies have paved the way to quantifying energy and environmental consequences for producing certain product lines. For example, one study estimated that to produce a 1000 cc car engine requires 80,000 MJ of energy and generates 7,000 kg of carbon dioxide during the manufacturing process [25]. However, available have studies neglected to

identify and quantify the specific nature of the hazardous waste generated in the manufacture of each product.

Realizing the intuitive linkage between energy consumption and waste production, the EPA developed the voluntary Green Lights program to reduce both. As mentioned, the over 1,350 voluntary participants have reduced their consumption of electricity 220 billion KWH since the program began. This quantity translates into an estimated reduction of carbon dioxide, sulfur dioxide, and nitrogen oxides by 202, 1.3, and 0.6 million tons, respectively [17]. Although these studies provide needed information on the impact of manufacturing on the environment, research is lacking that can help determine what facility parameters predict hazardous waste generation rates.

Analysis Rationale

As is evident, few studies focus on the facility characteristics that influence energy use and waste generation. Such studies are needed to help manufacturers recognize and improve problem areas so they can effectively enhance production efficiency. Thus, the long-term objective of this thesis work was to lay a foundation for future studies to improve manufacturing efficiency.

In order to reach this end, the specific goal of this work was to investigate key parameters of active manufactures that may affect manufacturing efficiency as measured by energy use and waste generation rates. Regarding energy use, electricity and natural gas were chosen because they are by far the most commonly used energy forms in industry [4]. With respect to waste, it is preferable to study all types of waste releases (land, air, and water). Owing to the lack of plant specific data on air and water releases, and the heavily regulated area of hazardous waste, only land releases of hazardous waste were considered in this initial investigative effort.

To successfully complete this study, a several-pronged attack was designed. The initial step was to identify a small set of parameters thought likely to influence the energy use and hazardous waste generation rates for manufacturing facilities. Table 2-3 presents the list of the specific parameters chosen and the reason for their inclusion. In general, these parameters were selected because they are relatively easily obtainable and appear to be relevant. Next, data on plant-specific characteristics, energy use, and waste

Table 2-3. Parameters Selected for Use in Study

Parameters	Justification
Energy Consumption Rates (electricity and natural gas (BTU/yr)	Key dependent variable reflecting Process efficiency
Amount of Hazardous Waste Generated (tons/yr)	Key dependent variable reflecting manufacturing efficiency
SIC Code	Identifies a class of manufacturing unit operations associated with a specific product class
Number of Employees	Often related product SIC, production rates, and facility size
Manufacturing Floorspace (ft^2)	A direct measure of facility size which may be related to product SIC and production rates
Sales ($/yr)	A factor reflecting product SIC and production rates
Waste Disposal Codes	Provides information on the nature of primary wastes and insight into the manufacturing processes used
Number of Waste Streams	Used to determine the number of different processes utilized and may influence the quantity of waste generated

generation had to be collected. Once the data was obtained, simple statistical methods were used to describe the characteristics of energy consumption and industrial hazardous waste generation and to draw inferences about their interrelationships. Although not a definitive study, this work does provide a meaningful starting point for future investigations of this important relationship.

3. RESEARCH METHODOLOGY

Introduction

For a wide variety of reasons, obtaining timely and accurate data for studying the characteristics of industrial energy consumption and waste generation is not straightforward. Owing to the general unavailability of needed information for this study, several steps were taken to obtain the best possible dataset. The first step was to narrow the field by targeting specific industry groups among all manufacturers for study. Next, sources of waste production information and facility characteristics had to be identified and collected for each manufacturer. Finally, annual energy consumption data for each facility had to be obtained.

Data collection was the most difficult aspect of this study. Due to potential liability considerations, most companies hesitate to share current waste production information and do little systematic organization of historical energy consumption information. As a result, this work focused on using publicly available databases to obtain waste data, and surveying active manufacturers to gather facility characteristics and access to energy use data from utility suppliers.

Identification of Target Group and Data Sources

Due to the large number of active manufacturers available for study nationally (about 350,000), and for convenience in conducting a direct mail survey, the investigation was simplified by targeting Tennessee industries in Standard Industrial Classification (SIC) 34 (Fabricated metal products), SIC 36 (Electronics & Other Electric Equipment), and SIC 37 (Transportation Equipment). These SIC categories were selected from the pool of all Tennessee manufacturers for the following reasons:

- a relatively large number of companies in these categories are regionally located for convenience in direct communications.

- the author was familiar with these manufacturing groups due to prior work with The University of Tennessee's Waste Minimization and Energy Analysis and Diagnostic Center Programs.
- substantial waste quantities are typically generated by manufacturers in these industrial categories.

To collect information on waste generation for this target group, two publicly available databases were available for use: the 1991 Toxic Release Inventory (TRI) database and the 1991 Tennessee Annual Hazardous Waste Report (THWR). A major disadvantage in using these waste databases is that they have a time lag of several years between data collection and public availability owing to the limited resources of the government agencies involved. Thus, for each data source, calendar year 1991 information was the most recently available and was chosen for study. Between these two sources, the 1991 TWHR was selected because it includes detailed data on hazardous waste generation while the TRI database was eliminated because it mostly contains information on toxic chemical usage.

Facility information for individual target group plants was needed to help characterize the manufacturing process for relating energy use and waste generation. This information was collected by designing a short survey and mailing it directly to selected manufacturers identified in the 1991 THWR. A detailed discussion of the direct-mail survey is presented below.

Finally, facility energy consumption data were collected directly from the supplier of each survey respondent. With the permission of a surveyed facility representative, the supplier was contacted by phone and asked to submit energy consumption information for the calendar year 1991.

Description of the 1991 THWR

The 1976 Resource Conservation and Recovery Act (RCRA) mandates the collection of data about waste production and disposal from hazardous waste generators as well as treatment, storage, and disposal facilities (TSDFs). Because the State of Tennessee chose to administer the RCRA program, generators of hazardous waste and TSDFs must submit annual reports about the generation rates, and management practices for hazardous waste to the State.

Information is collected from both large and small quantity (1,000 and 100 kilograms per month) generators.

Due to the large number of manufacturers (over 300) reporting in SICs 34, 36, and 37, only facilities generating greater than 1 ton/yr of hazardous waste annually were considered for analysis. This data pool represented approximately 75% of the reporting facilities for the three SIC categories selected.

It was judged that the THWR database provided the best possible waste generation information for the target group. Although, over forty parameters (for example, address, telephone number, and EPA generator ID) were associated with each company in the database, only a select few were relevant to this study. Table 3-1 outlines the parameters chosen and their specific relevance to this investigation.

A computer file of the 1991 THWR database was obtained from The University of Tennessee's Energy, Environment and Resources Center. The data was in a standard comma-delineated format which was ported into Microsoft Excel and JMP 3.02 statistical software (see Chapter 4, Data Analysis Methodology) for manipulation and analysis.

However, important data were lacking on facility characteristics such as specific production processes, production rates, manufacturing floorspace, and energy consumption rates. Since this data was not contained in any available database, this information was collected from selected manufacturers using a mail-out survey.

Direct-Mail Industrial Survey

The most timely and direct method for obtaining the detailed facility characteristics needed for this study was by directly soliciting the companies in the target group. Because telephone conversations were deemed to be a costly and inefficient manner of data collection, a direct-mail survey was designed. The survey questions pertained to general facility characteristics, the energy forms used and consumption rates for the 1991 calendar year.

The survey (see Appendix A, Figures A1 to A2) was designed to collect a large amount of detailed information on the characteristics of each facility. More data was collected than needed to assist future studies on this subject. Table 3-2 identifies the survey data used and its value to this study.

Table 3-1. Parameters Selected for Study From the 1991 THWR

Field	Content
SIC code	4-digit code reflecting each company's industrial classification
Number of permanent employees	Total number of employees working at the reporting facility
Number of waste streams	A count of the reported hazardous waste streams per EPA generator identification code (calculated by author)
Waste disposal codes	Code based on RCRA reporting requirements assigned to each waste stream (see Appendix A)
Amount generated	Total quantity (tons) of waste generated/yr by facility
Average amount generated/waste stream	The average of amount of waste generated per reportable waste stream for each reporting facility (calculated by author)

Because a significant amount of data was sought, to maximize the response rate the survey was designed to be one page in length and require about 10 minutes to complete by a knowledgeable plant employee. The questions were designed to be either fill-in-the-blank for numerical data, or check boxes for categorical information. Furthermore, the survey was copied onto blue paper so it would stand-out on the recipients desk.

The survey, along with a personalized cover letter (see Appendix A, Figure A-3) to the environmental manager explaining the purpose of the study and requesting participation, was mailed to the selected companies (253 plants) in the 1991 THWR pool. Approximately one month later, follow-up postcards (see Appendix A, Figure A-4) were mailed to facilities not yet responding (210 plants) as a reminder. About one month after the postcards were mailed, a final letter (see Appendix A, Figure A-5) was mailed to the non-responding surveyed companies (181 plants) requesting their participation. After about four months from the initial mailing, completed surveys were no longer received and the survey portion of data collection (79 total responses) was deemed complete.

Energy consumption information for each survey participant was collected directly from their supplier (identified on the returned questionnaire) by telephone solicitation. After the initial contact with the supplier, the survey section authorizing energy data release by a company official was faxed to the supplier. In addition, a brief note on the fax cover sheet (see Appendix A, Figure A-6) explained the survey and the specific data needed.

Once all the data was collected, it was prepared for entry into a database format for analysis. Numerical data from the survey, such as manufacturing floorspace, was entered directly into a Microsoft Excel spreadsheet. Categorical data, for example, those questions answered by checked boxes, were coded and entered into the spreadsheet. Next, statistical methods were used to analyze the data with respect to the objectives of this thesis.

Table 3-2. Utilized Information From Direct-Mail Survey

Characteristic	Definition
SIC code	4-digit code representing the company's industrial classification used to verify the code supplied by company on their respective 1991 THWR
Manufacturing floorspace (ft^2)	Used as a primary measure of facility size
Manufacturing employees	Total number of employees directly associated with manufacturing and used as a secondary indicator of the size of production operations
Sales ($/yr)	Annual sales used as a production measure and to assess the ability of companies to finance pollution control equipment
Primary waste generating process	Production process generating the largest quantity of hazardous waste; provides information on the type of processes the facility uses
Electricity (BTU/yr)	Annual quantity of electricity consumed by facility and a primary dependent variable
Natural Gas (BTU/yr)	Annual quantity of natural gas consumed by facility and a primary dependent variable

4. DATA ANALYSIS METHODOLOGY

Introduction

Standard statistical methods were used to characterize and relate information in the 1991 THWR and the results from the industrial survey. Both databases contain categorical and numerical data, which because of their differences require different analysis methods. Categorical data, which are descriptive or representative characters (e.g. A, xy, 1), can only be counted and the frequency responses examined. On the other hand, regression analysis and analysis of variance (ANOVA) investigations may be used on paired numerical datasets (x_i, y_i). The details of the analysis available for each data type follow below.

To speed up the analysis process, as well as to increase the accuracy of the statistical calculations, a standard software package was utilized. Of the numerous packages available (such as: Statgraph, SAS, and JMP), JMP 3.0.2 developed by the SAS Institute, Inc. (Cary, North Carolina) was employed in this study. This software was chosen because it is particularly easy to execute, obtainable to the author at a discounted price, and written for the Macintosh computer which was used to perform this study and prepare this document.

Analysis of Categorical Data

Histograms were used to describe the frequency distributions of categorical data. These are bar graphs in which the bars represent the different categories, and their heights are proportional to the frequency of occurrence. Histograms provide a clear visual representation of the relationships between data for discrete categories (e.g. waste disposal codes).

Analysis of Numerical Data

Sample Mean, Median, and Sample Standard Deviation

The sample mean, median, and sample standard deviation are the basic tools for characterizing a numerical dataset of size n from a population N. The following definitions and formulas describe how these values are calculated [27].

1. Sample mean ($\bar{x}$) - The average of a sample size n from a population pool N and used to estimate the population mean (μ). The value is calculated with Equation 1:

$$\bar{x} = \frac{\sum_{i=1}^{N} x_i}{n} \qquad \text{Equation 4-1}$$

2. Median- The data point where half the data is less than and half greater than, or equal to it. The median is loosely defined as the "middlemost" data point [28].

3. Sample standard deviation (s) - Measures the spread of a sample distribution around the sample mean ($\bar{x}$) and is the square root of the sample variance (s^2). This measure is also used to estimate the population sample standard deviation (σ). The sample standard deviation is calculated as:

$$s = \sqrt{\frac{\sum_{i=1}^{n} (x - \bar{x})^2}{n-1}} \qquad \text{Equation 4-2}$$

Normal Distributions

Totally random processes and experimental errors tend to yield the familiar "bell-shaped" normal distribution of variables. The normal

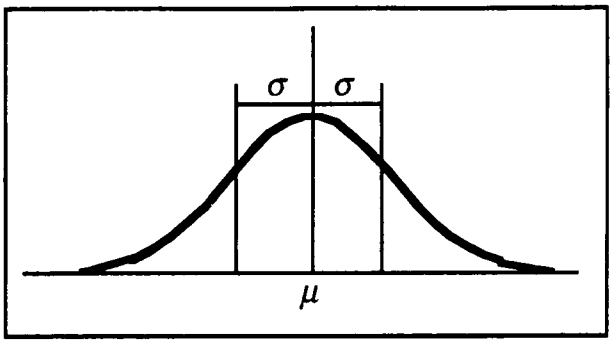

Figure 4-1. Example of a Normal Distribution.

distribution is a continuous probability density that may be attributed to the laws of chance [28]. Most statistical tests used to detect differences between sample means or sources of variation are based upon probability distributions functions (such as the "F" and "t") that rely on the normality assumption. An example of a "bell-shaped" normal distribution is shown in Figure 4-1.

Often the response variable (y) does not follow a normal distribution. In these cases, outside influences, which may or may not be controllable, are effecting the response. To counteract this problem, a mathematical formula (determined by trial and error) can be used to convert the dataset into a normal distribution. Any statistical tests must be performed with this converted dataset in order to draw valid inferences.

Standard methods for testing the significance of relationships are based on the normality assumption. Thus, before developing regression equations or performing ANOVA tests, the response variable (y) should be checked for normality. A normal quantile plot provides a visual means to determine if the parameter is normally distributed. The x-axis is the parameter value, and y-axis represents the expected normal score for each value on the ordinate. Equation 3 is the formula used to calculate the abscissa values.

$$y = \Phi^{-1}\left(\frac{r_i}{N+1}\right) \qquad \text{Equation 4-3}$$

where : Φ = the cumulative probability distribution for the normal distribution

r_i = the rank of the ith observation

N = the number of nonmissing observations

If the data plot in a straight line then they may be normally distributed [29]. If not, then the data should be examined for inconsistencies (such as outliers) or transformed into a dataset that is normally distributed. An example of a quantile plot is shown in Figure 5-6, page 36.

Besides the visual inspection of a normal plot as a test for normality, the data may be tested using the Shapiro-Wilk W Test. This statistic is based on the concept that if the data derive from a normal population there should be a high degree of correlation between where one expects observations to occur (i.e. within the "bell-shaped" curve) and their actual value [30]. Thus, a low Shapiro-Wilk correlation is taken as evidence against normality.

Relationships Between Numerical Parameters

Simple Regression

This study investigates, among other aspects, the relationships between n paired observations (x_i, y_i). The x variables (such as manufacturing floorspace) are selected as the independent variable and the y variables (for example, quantity of hazardous waste) is selected as the dependent variable. Studying the relationship is a two step process. First, a linear equation, known as the regression equation, is developed to estimate the independent variable for a given value of x between x_{min} and x_{max}. Next, the model is tested to determine the strength of the linear relationship using ANOVA techniques.

Simple regression models are commonly developed using standardized least-squares methods. This procedure focuses on developing a line that minimizes the difference (e_i) between the predicted value ($\hat{y}$) and the observed value (y_i) of the dependent variable for a given x_i [27]. The corrected sum-of-squares (SS) is used to determine these differences. The corrected SS for each variable (SS_{yy}, SS_{xx}) and their interaction (SS_{xy}) are given as:

$$SS_{yy} = \sum_{j=1}^{n} (y_j - \bar{y})^2 \qquad \text{Equation 4-4}$$

$$SS_{xx} = \sum_{j=1}^{n} (x_j - \bar{x})^2 \qquad \text{Equation 4-5}$$

$$SS_{xy} = \sum_{j=1}^{n} y_j (x_j - \bar{x}) \qquad \text{Equation 4-6}$$

Development of the simple regression model is based on the above equations. For a selected set of paired data, the best line fit is taken as [28]:

$$\hat{y} = \hat{\beta}_0 + \hat{\beta}_1 (x - \bar{x}) \qquad \text{Equation 4-7}$$

where: $\hat{y}$ = estimate of y

$\hat{\beta}_0 = \bar{y}$ = estimate of the y-intercept,

$\hat{\beta}_1 = \dfrac{SS_{xy}}{SS_{xx}}$ = estimate of the slope of the fitted line

Once the model is determined, it may be checked for significance of regression (i.e. strength of fit) This is done by testing whether the slope, $\hat{\beta}_1$, is zero using ANOVA. If the slope is found to equal zero, then the regression model would be considered invalid and no acceptable linear relationship exists between x and y. Thus, the best estimator of y_i for any x_i is the sample mean ($\bar{y}$).

Often paired datasets are not linearly related, in these cases curvilinear regression is applied. For cases where the exact relationship (e.g. exponential) between the paired data (x_i, y_i) is known, Equations 4 through 7 may be applied on the transformed data (x_i, log y_i) to determine the regression curve. For other situations where the exact functional relationship is not known polynomial regression may be used. This method develops an estimation formula of the following form

$$\beta_0 + \beta_1 x + \beta_2 x^2 + ... + \beta_p x^p \text{ [28]}$$

It should be noted that multiple regression techniques for relating multiple independent variables to a dependent variable were also available for

use. However, curvilinear and multiple regression methods were not explored in this preliminary study for the following reasons:

- simple regression analysis demonstrated substantial data scatter which limits the utility of more complex methods of analysis.

- the focus of this study was to investigate the relationships between an efficiency measure and a single facility parameter, not develop empirical equations to estimate the efficiency measures

Significance Testing and ANOVA Tables

Testing for model significance involves analyzing the variability contained in the SS_{yy} value. This value consists of two components that measure the variability in the y_j accounted for by the regression (model) line (Eq. 4), and the residual (error) variation left unexplained by the regression line [27]. Again, these values are calculated using sum-of-squares. The regression SS_R and error components SS_E are calculated with the following equations:

$$SS_R = \sum_{j=1}^{n} (\hat{y}_j - \bar{y})^2 \qquad \text{Equation 4-8}$$

$$SS_E = \sum_{j=1}^{n} (y_j - \hat{y}_j)^2 \qquad \text{Equation 4-9}$$

$$SS_{yy} = SS_R + SS_E \qquad \text{Equation 4-10}$$

The ANOVA table aids in testing the model's significance by providing a logical and simple method for partitioning the total variation SS_{yy} into its components, Model (SS_R) and Error (SS_E). Table 4-1 outlines the formulas and their positions in an ANOVA table. Once the variations (SS_R , SS_E) are calculated, the average or mean square is calculated. The mean squares estimate the sample variance (s^2) for the model and error. The ratio of the two variances (assuming the response variable is an independent normal variable) is described by a "F" probability distribution. Thus, the value of this

Table 4-1. Analysis of Variance for Regression Testing

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob>F
Model	1	SS_R	$MS_R = SS_R / 1$	$\frac{MS_R}{MS_E}$	Calculated by software package
Error	n - 2	SS_E	$MS_E = SS_E / n - 2$		
C Total	n - 1	SS_{yy}			

ratio is compared to appropriate "F" value ($F_{\alpha,1,n-2}$) from the distribution. The "F" value is determined from a statistical table indexed by the level of significance (the probability of incorrectly rejecting the models strength, usually taken as 0.05) and the degrees of freedom (an indexing term) for the numerator and denominator [27]. "F ratios" larger than the respective "F" value suggest that the regression model represents the majority of the variation and is significant [29]. To ease this decision making process, JMP calculates a probability (Prob>F) of obtaining a greater F value by chance alone if the specified model is insignificant. Prob>F's equal to, or less than the level of significance (0.05 for this study) are considered evidence of a regression effect [29].

Not normally included in an ANOVA table is the coefficient of determination, R^2. However, for this investigation it is included in the table to complete the information provided. The value R^2 represents the proportion of variability accounted for by the regression model and not unexplained error. Large R^2 values indicate that the model represents most of the variation which indicates that it is a good estimator of the response variable. The R^2 coefficient is calculated as [28]:

$$R^2 = \frac{SS_R}{SS_{yy}} \qquad \text{Equation 4-11}$$

Relationships Between Numerical and Categorical Parameters

When studying the relationship between a numerical variable "y" and discrete conditions of data "x" (categorical), the standard test is to determine if the group means are statistically different. Unlike a plot of two numerical parameters, graphs of these comparisons generated by JMP 3.02 use box plots to describe the relationships. Figure 4-2 highlights the features of the graphs used in this analysis and presented in Chapter 5 (Results and Discussion).

The means are compared using standard least-square and ANOVA techniques. For a description of an ANOVA table refer to Table 4-1, above. If the Prob>F suggests that a significant difference exist between the means, then the Tukey-Kramer Honest Significant Difference (HSD) test may be conducted to determine which category means differ. This method is a conservative test which will detect differences between means before similar comparative tests [27].

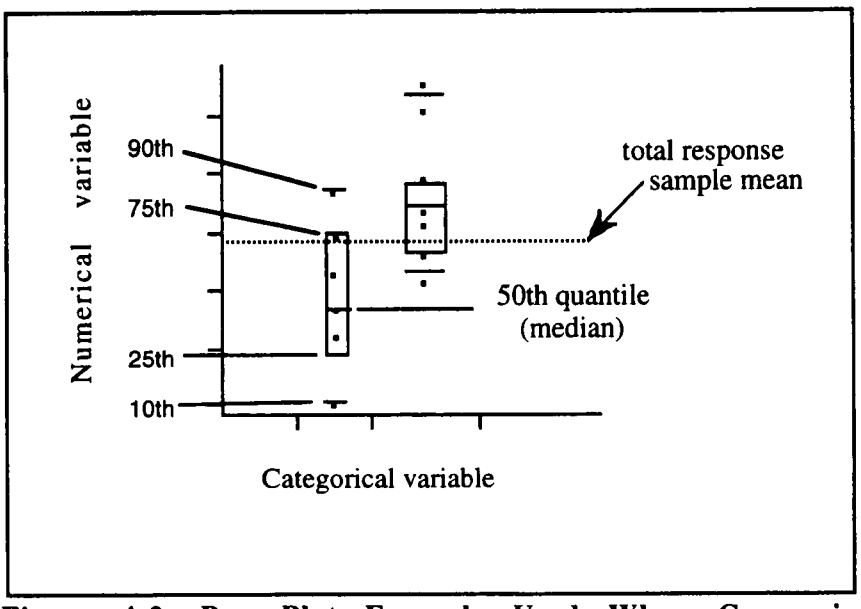

Figure 4-2. Box Plot Example Used When Comparing Categorical and Numerical Data

5. RESULTS AND DISCUSSION

Introduction

The client selection process described in Chapter 3 (Methodology) produced a fairly large datapool. However, the limited response rate to the industrial survey significantly reduced the usable dataset size. Table 5-1 lists the number of companies selected from the 1991 THWR database, completed industrial surveys, and the survey response rate for each of the three targeted SIC categories. The complete dataset is presented in Appendix A, Tables A-6 to A-8.

Obtaining completed surveys from active manufacturers was relatively difficult. Frequently encountered problems include:

- some plant contact personnel were hesitant to participate because they feared that the released information would be associated with their plant and accessible to environmental enforcement authorities
- contact personnel in some cases did not have sufficient time to properly collect plant data to complete the survey

Table 5-1. Datapool Size and Response Rates

SIC	Selected THWR companies mailed a questionnaire	Number of completed industrial surveys	Response rate (%)
34	138	39	21.0
36	54	17	31.4
37	61	23	37.7
Total dataset	253	79	31.2

Analysis of Data from the 1991 THWR

Characterization of Datapool

Field Definitions

In general, the information obtained from the 1991 THWR focused on characterizing waste generation (e.g. quantities and type) and facility parameters. Table 3-1 contains the fields and their definitions used in this analysis.

Reliability of Data

Data from Federal and State reporting programs have inherent reliability problems relating to inconsistencies and omissions. For example, the primary 1991 THWR limitations include [31]:

- lack of consistency in reported quantities of waste between generators and Treatment Storage and Disposal Facilities
- lack of consistency in estimating techniques for reportable quantities of hazardous waste from year to year
- some data requested were not reported
- omission of often significant air emissions and landfill waste data

Summary and Analysis of Statistics From 1991 THWR Numerical Data

Only parameters from targeted companies returning completed questionnaires were used. Because the THWR contains both numerical and categorical data, each data type must be analyzed differently as discussed in Chapter 4 (Data Analysis Methods). Table 5-2 summarizes the basic statistics for the numerical data.

Figures 5-1 to 5-4 present histograms illustrating the distribution among SIC 34, 36, and 37 participants of the mean for the numerical parameters listed in Table 5-2. The nature of the histograms suggest that the responding companies in SIC 34, 36, and 37 varied greatly in the number of total employees, amount of hazardous waste generated per facility, and amount generated/waste stream per facility.

Table 5-2. Statistics for the THWR Numerical Data

SIC Category	Statistic	Number of permanent employees	Hazardous waste amount generated (tons/yr)	Number of reported waste streams	Average amount generated/ waste stream (tons/yr)
34 (39 facilities)	total	7,238	47,353	87	12,617
	median	117	18	2	16
	mean	186	1,214	2.2	323.5
	std. dev.	236	3,869	1.6	887.3
	min. - max.	1* - 1,269	2 - 19,419	1 - 7	1- 4,855
36 (17 facilities)	total	7,456*	25,956	38	14,613
	median	409	12	2	2.7
	mean	466	1,527	2.2	860
	std. dev.	442	3,333	1.5	1,898
	min. - max.	60 - 1,800	1 - 9,990	1 - 5	1 - 6,028
37 (23 facilities)	total	14,216	54,459	46	7,028
	median	157	11	3.8	6
	mean	618	2,368	2	306
	std. dev.	1,191	6,870	4.2	887
	min. - max.	19 - 5,500	1 - 24,187	1 - 14	1 - 3,942
Total dataset (79 facilities)	total	28,910	127,768	213	34,257
	median	164	15	2	11
	mean	371	1,617	2.7	434
	std. dev.	713	4,810	2.7	1,181
	min. - max.	1 - 5,500	1 - 24,187	1 - 14	1 - 6,028

* one or more facilities actually reported that there was only one employee

** only 16 facilities reported

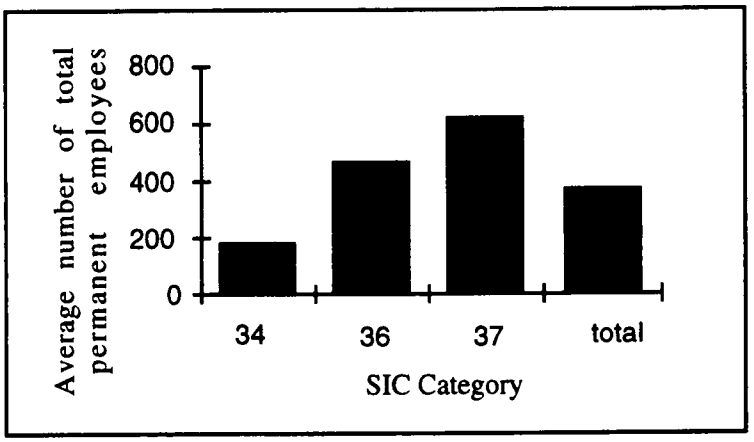

Figure 5-1. Average number of total permanent employees per reporting facility from the 1991 THWR.

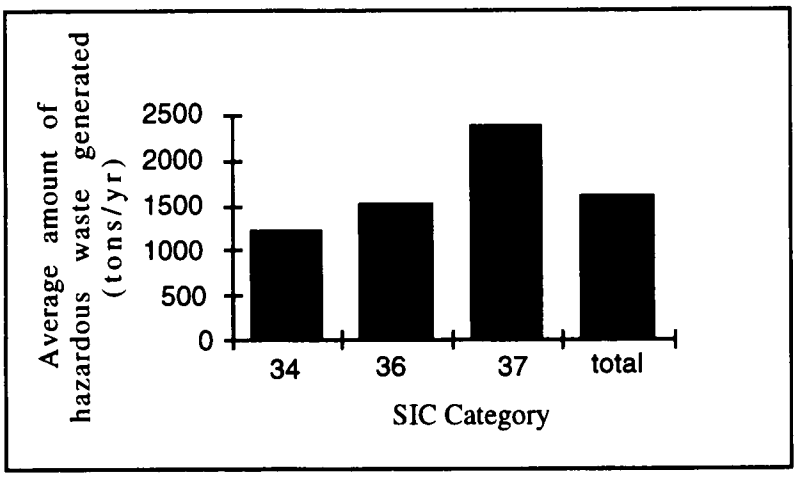

Figure 5-2. Average amount of hazardous waste generated per facility from the 1991 THWR.

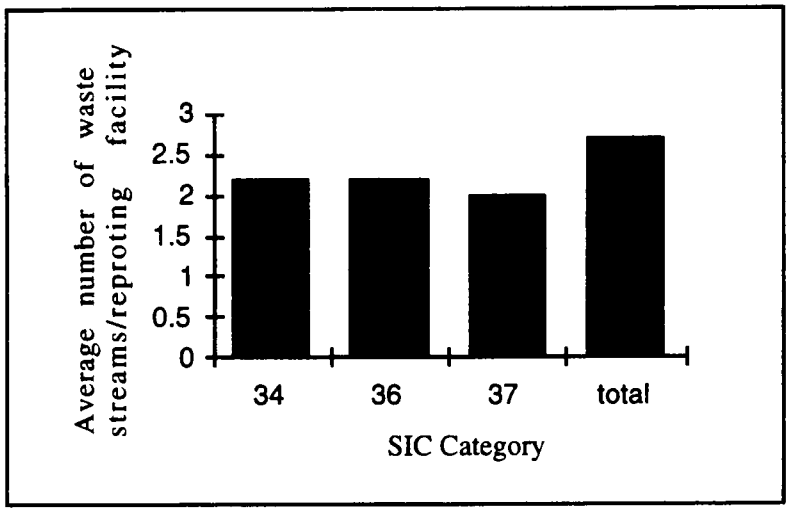

Figure 5-3. Average number of waste streams per reporting facility from the 1991 THWR.

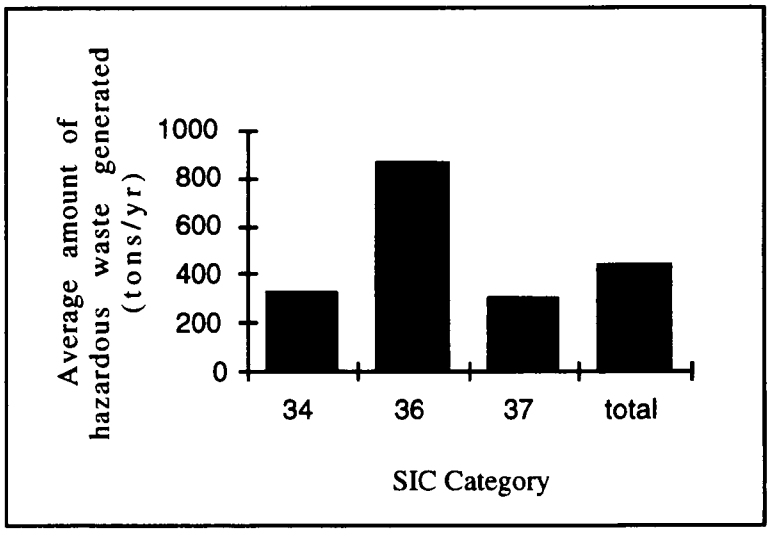

Figure 5-4. Average amount of hazardous waste generated/waste stream per reporting facility from the 1991 THWR.

It is noted that, SIC 37 dominates the other two chosen industrial categories with respect to the average total number of permanent employees and average amount of hazardous waste generated per facility. This may be expected because SIC 37 companies produce transportation equipment which, on average, requires large facilities and considerable manpower for materials handling. However, SIC 36 generated, on average for all respondents, the greatest quantity of hazardous waste per stream. Interestingly, all participating companies had a similar number of hazardous waste streams regardless of the other parameter values.

Discussion of Numerical Parameter Distributions

The histogram of each numerical parameter is useful in determining the distribution of that parameter. For example, considering the amount of hazardous waste generated quantities for SIC 34, the values had a range of 2 to 19,419 tons/yr, with a mean and median of 1,214 and 18 tons, respectively (from Table 5-2). Inspection of Figure 5-5, the normal quantile plot, shows that the data is heavily skewed to the left indicating that most companies, in this datapool, generate small amounts of waste with only a few generating large quantities. The dataset is not normally distributed and can not be used to perform valid statistical tests. Thus, a transformation function was needed to normalize the values.

The transformed function determined by trial and error to be suitable was the common log (of both variables) which produced a relatively straight line. Figure 5-6 shows the histogram and normal quantile plot of the transformed data for the parameter amount of waste generated. However, the Shapiro-Wilkes test for normality has a Prob<W = 0.0016 suggesting the distribution is not actually normal (which requires Prob<W => 0.05). Nonetheless, considering the limited reliability of the dataset, the transformed data used in subsequent analysis was assumed to be normal. The transformed data for the entire dataset is presented in Appendix B, Figure B-1. Also, the normal quantile plots of the transformed dataset for the numerical parameter, total number of permanent employees, for SIC 34 and the total dataset is presented in Figures B-2 and B-3. These two parameters were the only ones used in statistical tests, hence only their data was transformed. Numerical data from SIC 36 and 37 was not transformed due to the limited size of the dataset.

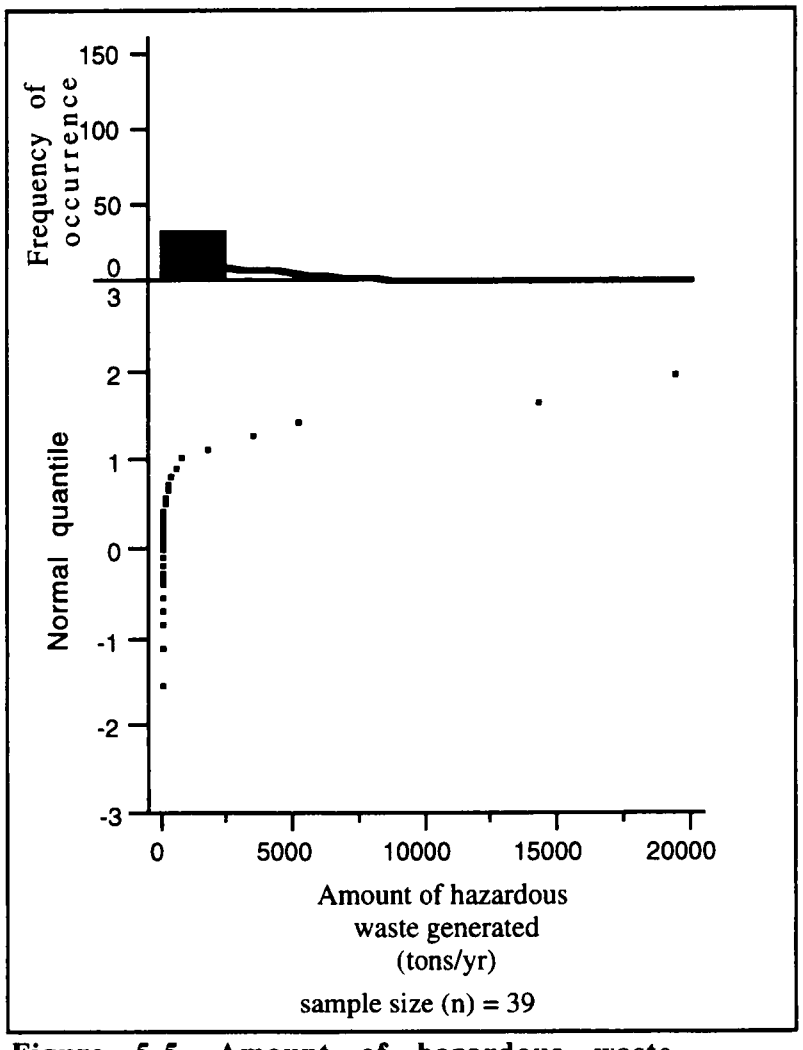

Figure 5-5. Amount of hazardous waste generated (tons/yr) for SIC 34 respondents.

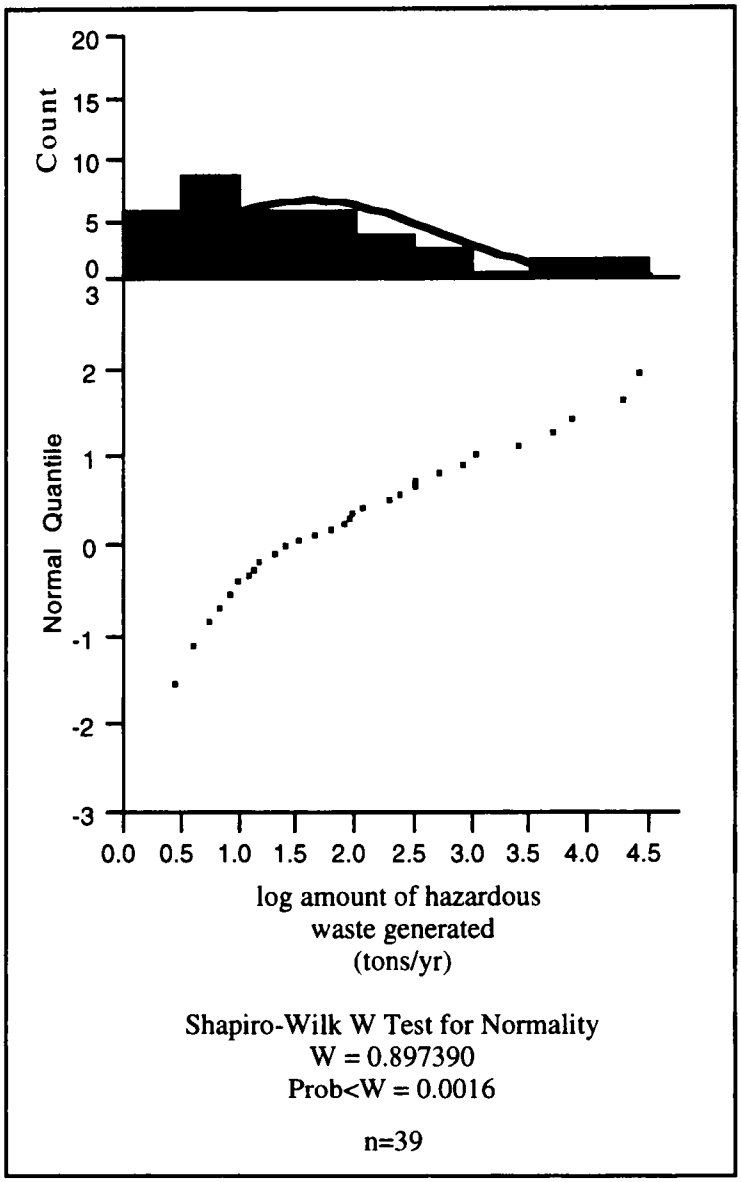

Figure 5-6. Log amount of hazardous waste generated (tons/yr) for SIC 34 respondents.

Analysis and Discussion of the 1991 THWR Categorical Data

Categorical data from the 1991 THWR includes: the number of reportable waste streams/facility, waste disposal codes, and waste generating plant SIC category. Figures 5-7 through 5-17 are histograms that characterize the categorical data parameters for SIC 34, 36, 37, and the total dataset.

The Figure 5-7 histogram shows that for the total dataset, waste disposal codes MOMX, DOMX, DOO1, and DOO2 are the most frequently encountered waste streams (see Appendix A, Tables A-1 through A-5, for a description of the waste disposal codes and SIC category titles). These codes describe why the waste stream is considered hazardous. The most frequently reported disposal codes for the entire dataset suggest that the majority of the waste generating processes in the surveyed plants use solvents or corrosive chemicals. Figure 5-8 reveals that the companies in this study reported most frequently a single waste stream. This trend prevails throughout SIC 34, 36, and 37 respondents separately (Figures 5-9, 5-12, and 5-15).

Considering SIC 34 data in detail, Figure 5-10, shows that MOMX, D002, DOMX, and D001 represent over 60% of the reported waste disposal codes. Again, this result suggests that in this datapool, most of the manufacturing processes used either solvents or corrosive chemicals. Inspection of Figure 5-11 reveals that SIC 3471, plating and polishing, was the most common of the included waste generating industry types. These operations tend to generate corrosive wastes which corresponds well with the fact that waste disposal code

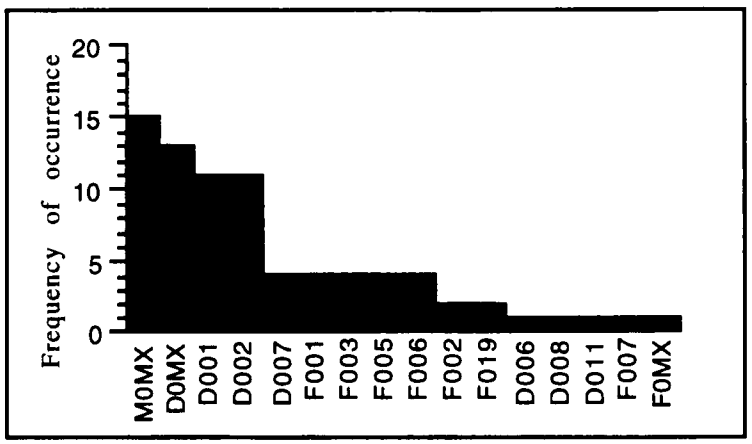

Figure 5-7. Waste disposal codes for the total dataset.

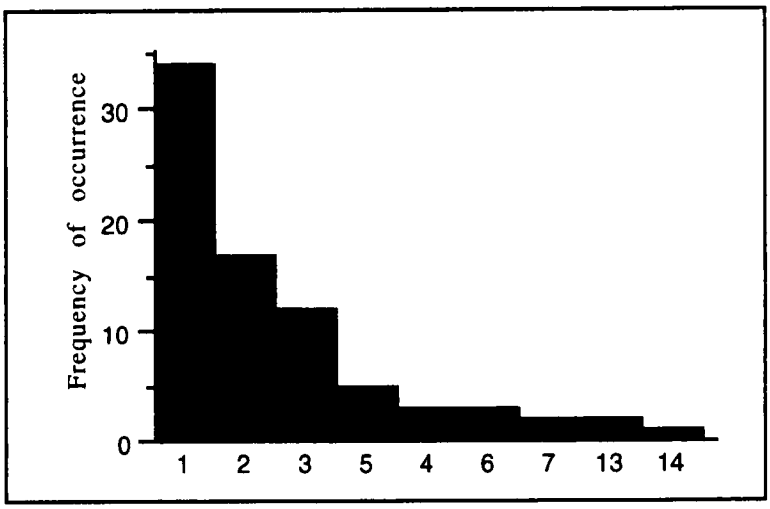

Figure 5-8. Waste stream count per facility for the total dataset.

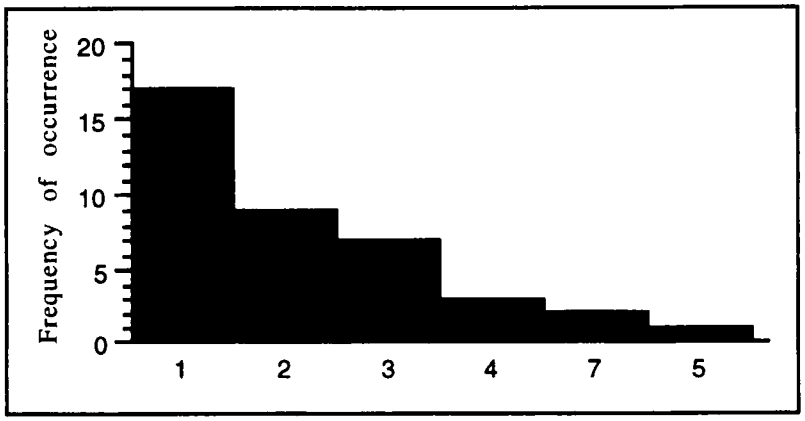

Figure 5-9. Waste stream count per facility for SIC 34 respondents.

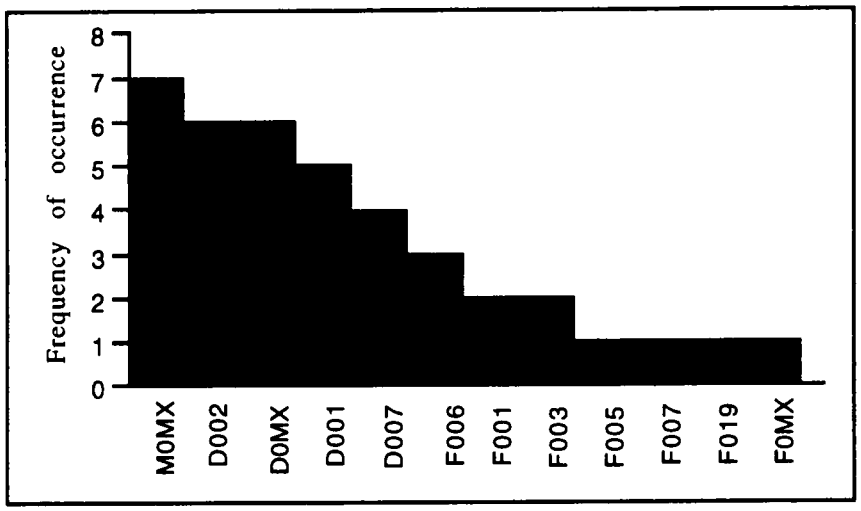

Figure 5-10. Waste disposal codes for SIC 34 respondents.

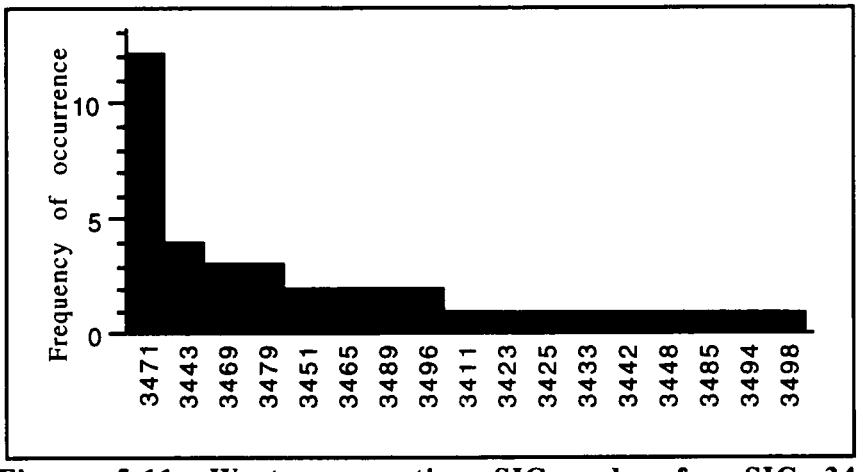

Figure 5-11. Waste generating SIC codes for SIC 34 respondents.

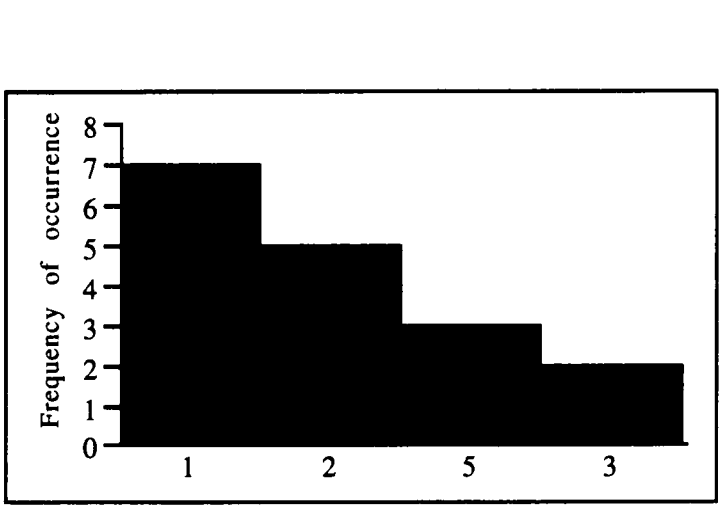

Figure 5-12. Waste stream count per facility for SIC 36 respondents.

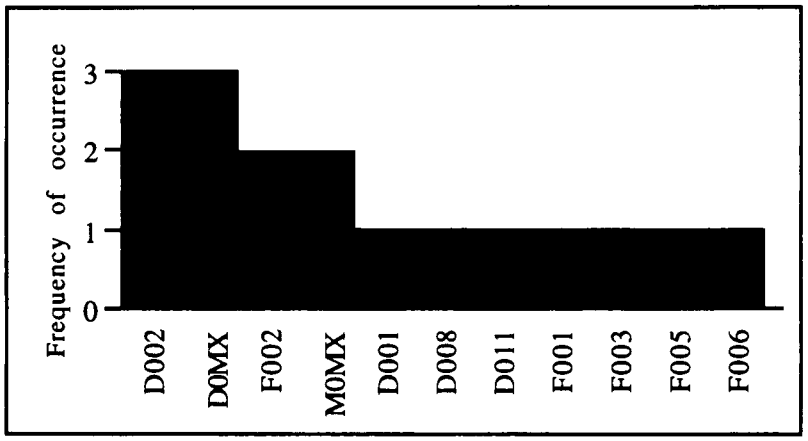

Figure 5-13. Waste disposal codes for SIC 36 respondents.

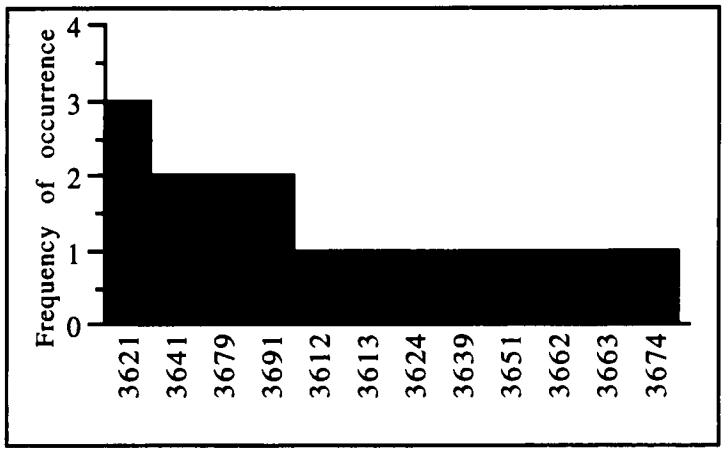

Figure 5-14. Waste generating SIC codes for SIC 36 respondents.

Figure 5-15. Waste stream count per facility for SIC 37 respondents.

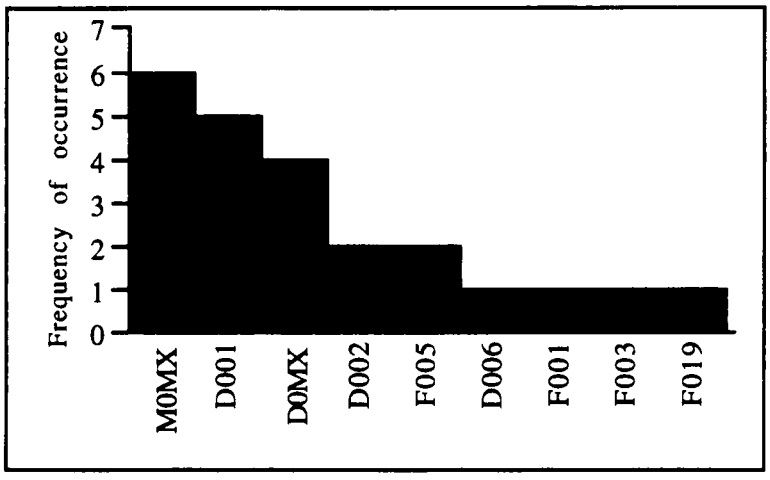

Figure 5-16. Waste disposal codes for SIC 37 respondents.

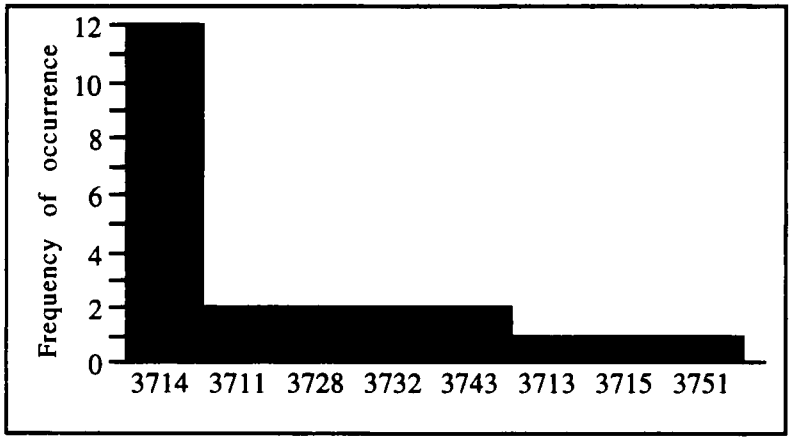

Figure 5-17. Waste generating SIC codes for SIC 37 respondents.

D002 (corrosive wastes) represented about 15% of the reported disposal codes for SIC 34 participants.

For SIC 36, Figures 5-13 and 5-14 reveal a similar pattern as seen for SIC 34 respondents. The most reported waste disposal codes are DOO2, DOMX, and F002, all of which are corrosive waste streams. Specifically, SIC's 3621, 3641, 3679, and 3691 correspond to manufacturing systems which use corrosive chemicals for functional metal-plating and/or etching of electronic components.

For SIC 37, Figures 5-16 and 5-17 show that DOO1, MOMX, and DOMX were the most often reported waste codes and SIC 3714 (motor vehicle parts and accessories) generated the largest number of waste streams. The most often reported waste code was D001, an ignitable characteristic hazardous waste, is commonly associated with parts cleaning. Manufacture of transportation equipment requires significant metalworking to produce component parts. Prior to assembly, the parts are usually cleaned with a hydrocarbon-derived solvent. Thus, waste streams of this type are expected to be commonly reported for SIC 37 plants.

Interrelationships Between Fields in the 1991 THWR

In this section, simple regression analysis is used to investigate possible relationships between selected parameters from the 1991 THWR. The two relationships investigated are:

1. Amount of hazardous waste generated versus Total number of permanent employees
2. Amount of hazardous waste generated versus Number of waste streams per facility

Because the datapool for SIC 36 and 37 is of limited size, data for these industrial categories are not used in this section. For a discussion of simple regression analysis and ANOVA tables, refer to Chapter 4 (Data Analysis Methodology).

Amount of Hazardous Waste Generated versus Total Number of Permanent employees

It is of interest to determine if the quantity of hazardous waste generated has a demonstrateable relationship to facility size and production rates as represented by the total number of permanent employees. It is assumed that, on average, larger facilities employ more workers to meet production requirements; and higher production rates may relate to higher generation rates of hazardous waste. Unfortunately, production rate data do not exist in the 1991 THWR database to test this relationship.

Plotting the log of each parameter (e.g. Figure 5-18) accomplishes simple scale compression, and is needed to meet normality requirements for making valid statistical decisions. The log of all numerical parameters are used throughout this analysis.

As can be seen from Figure 5-18 and Table 5-3, the relationship between the two parameters is weak. The R^2 value is approximately zero and the Prob>F = 0.71 is much greater than the 0.05 significance level at which the model was tested. Also, the statistical tests are supported by the scatter plot produced by the two parameters which indicates no firm relationship. The entire dataset exhibits a similar relationship (see Appendix B, Figure B-4 and Table B-1).

Amount of Hazardous Waste Generated versus Number of Waste Streams per Facility

This relationship was examined to determine if the total quantity of hazardous waste produced correlates with the number of waste streams a facility generates. Inspection of Figure 5-19 and Tables 5-4 and 5-5 reveal that regardless of the number of waste streams produced, the average quantity of hazardous waste generated per stream does not vary significantly. This is supported by the result that the Prob>F = 0.865 is much greater than the 0.05 level of significance. Thus, one can conclude that for the selected SIC 34 companies reporting in the 1991 THWR, the total quantity of reportable hazardous waste generated is not related to the number of waste streams. The total dataset exhibits that same relationship for these parameters (see Appendix B, Figure B-5 and Tables B-2 and B-3).

Several possibilities may explain this result. First, companies may combine waste streams to facilitate disposal. For example, all corrosive wastes,

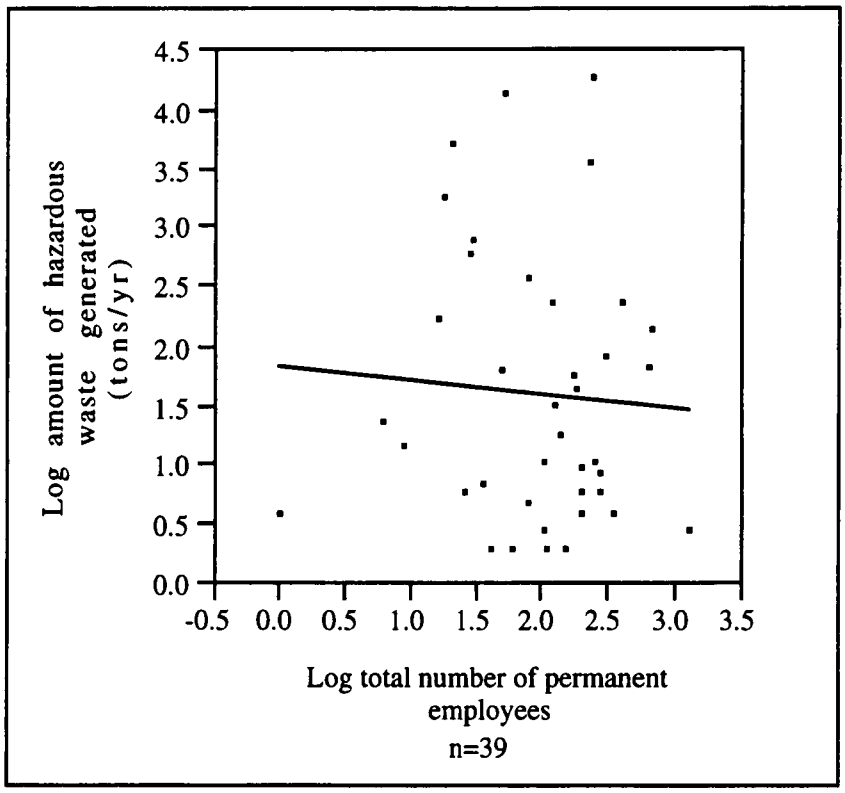

Figure 5-18. Log amount of hazardous waste generated versus log total number of permanent employees for SIC 34 respondents.

Table 5-3. ANOVA Table for Log Amount of Hazardous Waste Generated versus Log Total Number of Permanent Employees for SIC 34 Respondents

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob>F	R^2
Model	1	0.185	0.185	0.142	0.708	0.004
Error	37	48.207	1.302			
C Total	38	48.392				

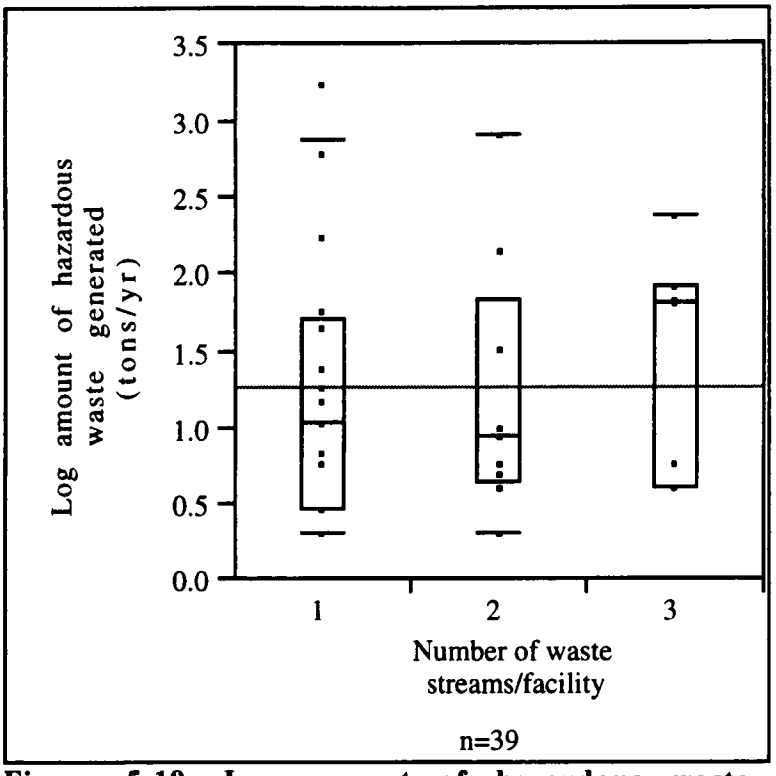

Figure 5-19. Log amount of hazardous waste generated versus number waste streams per facility for SIC 34 respondents.

Table 5-4. ANOVA Table for Log Amount of Hazardous Waste Generated versus Number Waste Streams per Facility for SIC 34 Respondents

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob>F	R^2
Model	2	0.202	0.101	0.145	0.865	0.009
Error	30	20.957	0.698			
C Total	32	21.160				

Table 5-5. Average Amount of Hazardous Waste Generated/Waste Stream per Facility for SIC 34 Respondents

Number of waste streams	Number Reported	log Amount of hazardous waste generated (tons/yr)	Amount of hazardous waste generated (tons/yr)
1	17	1.238	162.880
2	9	1.209	111.780
3	7	1.417	67.290

assuming they are compatible, may be barreled and disposed together. Also, a waste stream, by definition, is the quantity of waste leaving the plant envelope for disposal or treatment. Thus, the quantity for each waste stream consists of all component point sources. For example, a facility with three metal plating lines may produce a large quantity of hazardous waste from the numerous tanks (i.e. point sources). This quantity may be reported as a single waste stream. However, the point source releases that comprise that waste stream are large in number. Because point source data are unavailable, this relationship could not be investigated.

Analysis of Data from the Industrial Survey

Characterization of Datapool

Field Definitions

The direct-mail survey was used to collect information about the facility characteristics thought to influence energy use and hazardous waste generation rates. Table 3-2 lists the information sought from the questions included on the direct-mail survey sent to the 253 selected facilities from SIC 34, 36 and 37.

Reliability of Data

Collecting data using a direct-mail survey questionnaire may lead to errors and inconsistencies. Examples of these problems include:

- unknowledgeable personnel responding to survey with inaccurate information
- misunderstanding of questions poised to plant personnel
- data reported for wrong calendar year (not 1991)
- unanswered questions led to limited sample sizes for certain parameters

Summary and Analysis from the Industrial Survey Numerical Data

Table 5-6 summarizes the descriptive statistics for numerical data obtained from the mailed survey. Figures 5-20 to 5-22 are histograms showing

Table 5-6. Statistics for the Industrial Survey Numerical Data

SIC Category	Statistic	Manufacturing floorspace (ft^2)	Electricity consumption (million BTU/yr)	Natural gas consumption (million BTU/yr)
34	total	4,386,163	659,097	379,310
	median	70,000	10,760	5,657
	mean	112,466	24,410	15,805
	std. dev.	189,801	35,824	29,020
	min. - max.	2,000 - 1,088,875	850 - 145,733	194 - 140000
	# of responses	39	27	24
36	total	2,575,516	258,754	116,119
	median	100,510	25,144	4,725
	mean	151,501	28,751	14,515
	std. dev.	218,457	32,454	18,479
	min. - max.	10,000 - 760,000	2,249 - 107,083	77 - 48,700
	# of responses	17	9	8
37	total	5,840,600	259,284	159,024
	median	70,000	11,988	10,329
	mean	278,214	25,928	17,669
	std. dev.	532,618	29,442	20,297
	min. - max.	0 - 2,120,000	322 - 80,992	129 - 59,013
	# of responses	21	10	9
Total dataset	total	12,802,279	1,177,135	654,453
	median	70,000	11,250	7,048
	mean	166,263	25,590	15,962
	std. dev.	328,182	33,241	25,049
	min. - max.	0 - 2,120,000	322 - 145,733	77 - 140,000
	# of responses	77	46	41

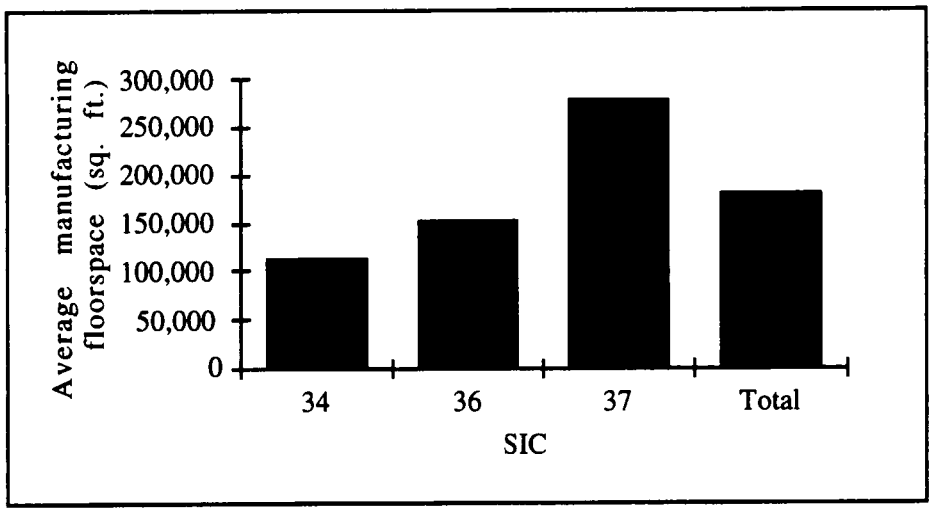

Figure 5-20. Histogram of average manufacturing area (ft^2) per reporting facility from industrial survey.

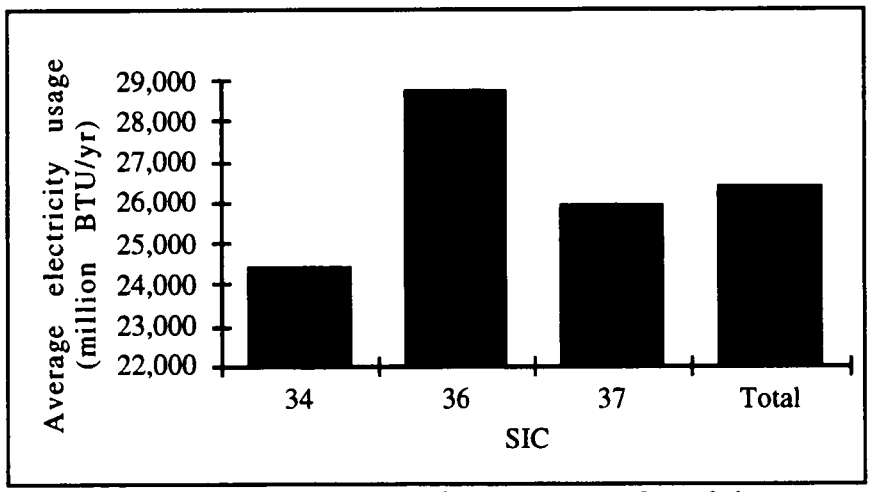

Figure 5-21. Histogram of average electricity usage (million BTU/yr) per reporting facility from industrial survey.

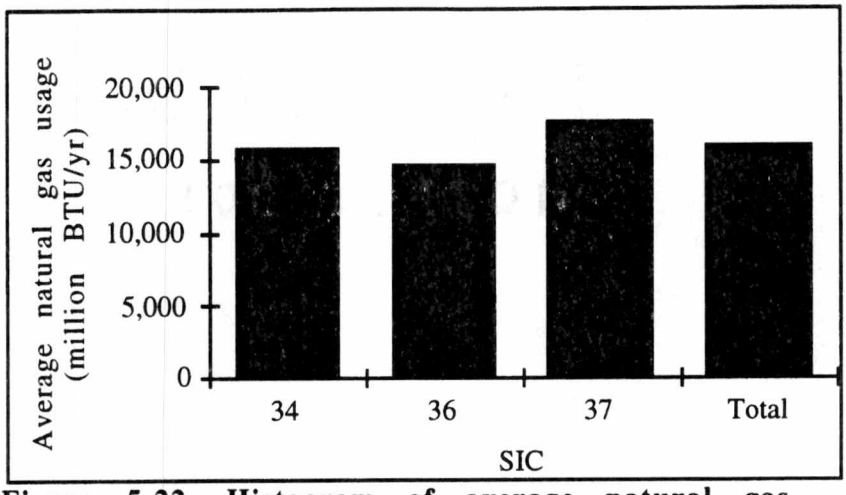

Figure 5-22. Histogram of average natural gas usage (million BTU/yr) per reporting facility from industrial survey.

the distributions of the averages for manufacturing area, electricity usage per year, and the annual natural gas consumption for SIC 34, 36, 37 participants and for the total dataset.

As can be seen from Figure 5-20, SIC 37 companies had the largest average plant floorspace area dedicated to manufacturing. This result is expected because as mentioned above, the manufacture of transportation equipment, such as cars, trucks, and boats, requires relatively large staging areas. Inspection of the electricity consumption histogram, Figure 5-21, shows that SIC 36 used the largest average quantity on a plant basis. Figure 5-22 indicates that all SIC facilities in the datapool have approximately the same average natural gas usage regardless of the substantial variation in manufacturing floorspace. It is worth noting that care should be taken when drawing conclusions about the energy consumption data because the datapool was relatively small with respect to responding companies from SIC 36 and 37 (see Table 5-1).

Discussion of Numerical Parameter Distributions

Again the numerical parameters were wide ranging (See Table 5-6). Thus, it was convenient to transform the data using the common log to compress the scale and provide an approximate normal distribution to perform valid statistical tests. Only data from SIC 34 and the total dataset was used because of the limited datapool size for SIC 36 and 37.

The transformed data for the manufacturing floorspace parameter is shown in Figure 5-23. It is noted that the log function provides a straight line in the normal quantile plot and a near perfect bell shape in the frequency distribution graph. Also, the Shapiro-Wilk tests suggests that the transformed data is normally distributed with a Prob<W of 0.4790. Transforming the data of this parameter for entire dataset also produces a similar result (Figure B-6). Furthermore, the quantile plots of the numerical parameters electricity and natural gas usage, indicate they are not normally distributed. Thus, these data were transformed to approximate achieve an approximate normal distribution (Figures B-7 to B-10). The transformed data for these three parameters are used in analysis discussed below.

Analysis and Discussion of the Industrial Survey Categorical Data

Figures 5-24 to 5-35 are histograms characterizing the responses to the categorical data requested in the industrial survey for SIC 34, 36, 37 respondents. Because the number of responses are different for each parameter within a SIC category, no useful comparisons can be made for processes between the SIC groups. However, inspection of each histogram yields information about the type of facilities willing to participate in the survey. Most of the respondents fell into the following categories:

- employed fewer than 200 employees
- generated less than $50 million/yr in sales
- produced most of their hazardous waste using parts cleaning, solvent-based painting, or metal plating

These results indicate that most facilities participating in the survey can be appropriately classified as medium-sized manufacturers.

Interrelationships Between Fields in the Industrial Survey

Parameters Influencing Energy Consumption

In this analysis, the relationship between the quantity of energy consumed and facility size, and the reported primary waste generating processes were investigated separately. These two parameters were considered to have the most potential influence in determining net energy consumption.

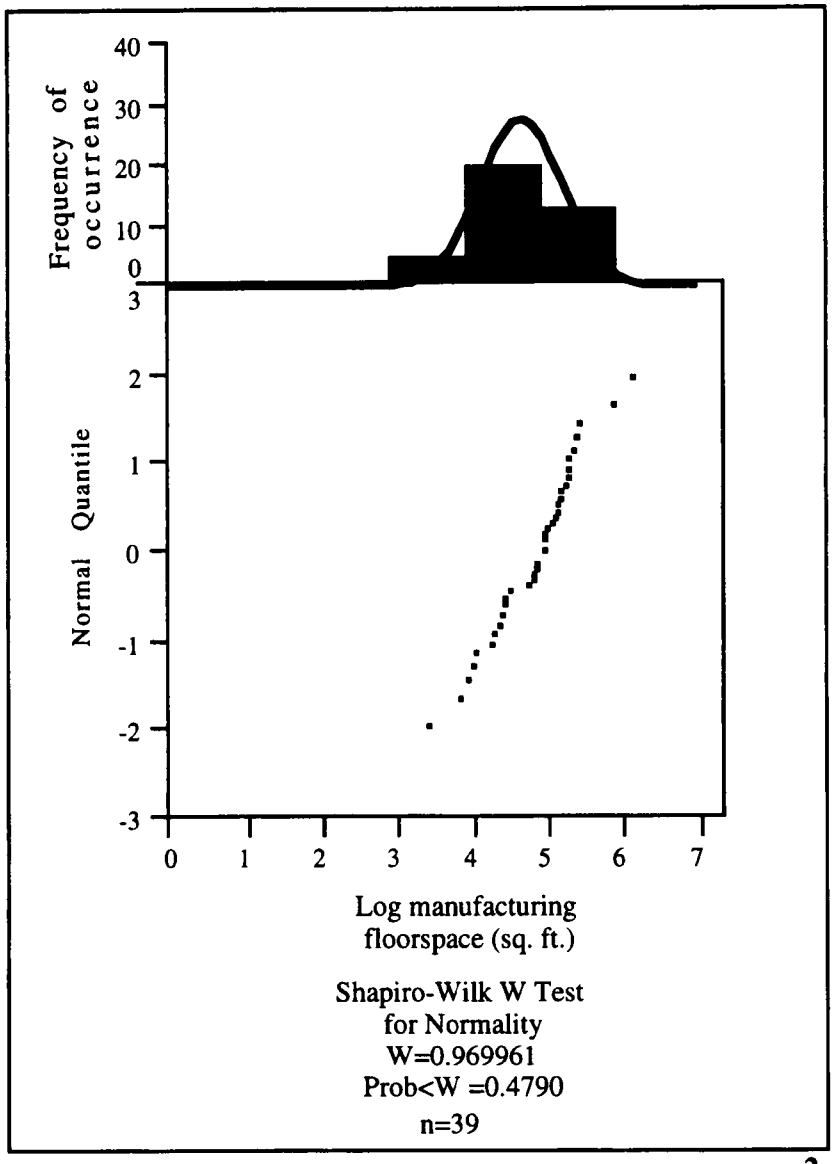

Figure 5-23. Log manufacturing floorspace (ft^2) for SIC 34 respondents.

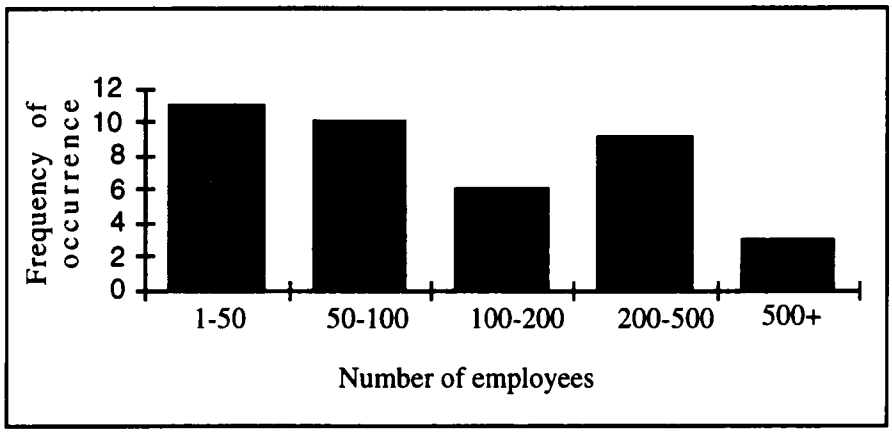

Figure 5-24. Histogram of reported ranges of manufacturing employees for SIC 34 respondents.

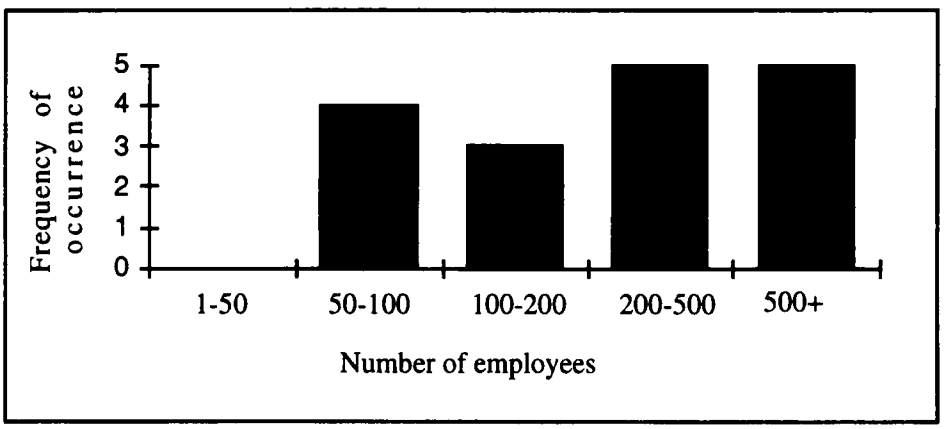

Figure 5-25. Histogram of reported ranges of manufacturing employees for SIC 36 respondents.

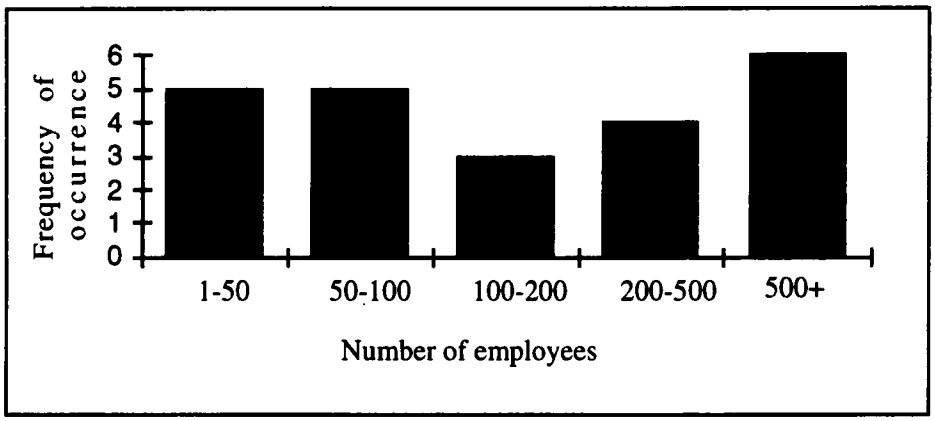

Figure 5-26. Histogram of reported ranges of manufacturing employees for SIC 37 respondents.

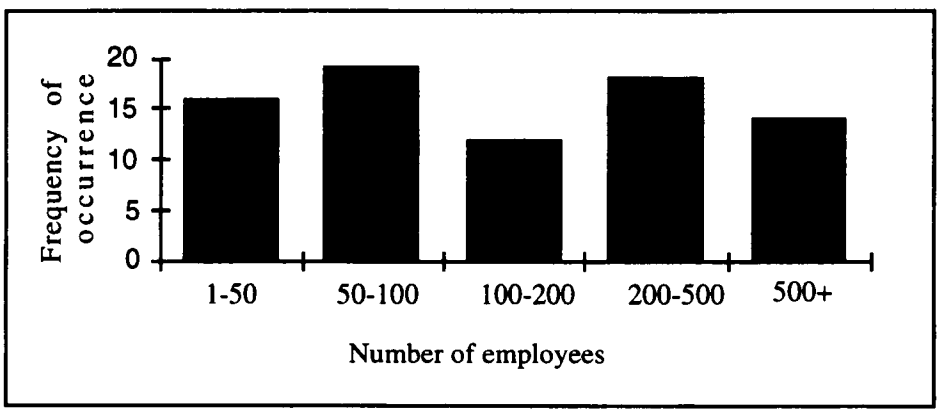

Figure 5-27. Histogram of reported ranges of manufacturing employees for total dataset.

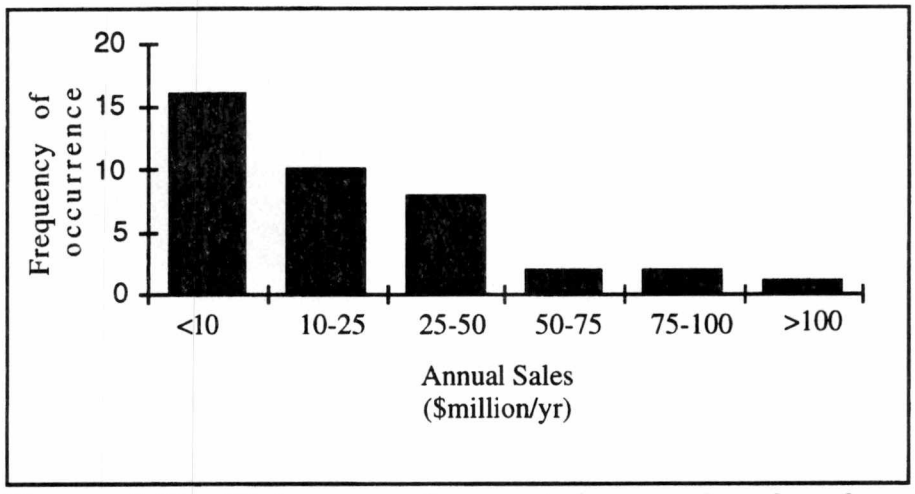

Figure 5-28. Histogram of reported annual sales for SIC 34 respondents.

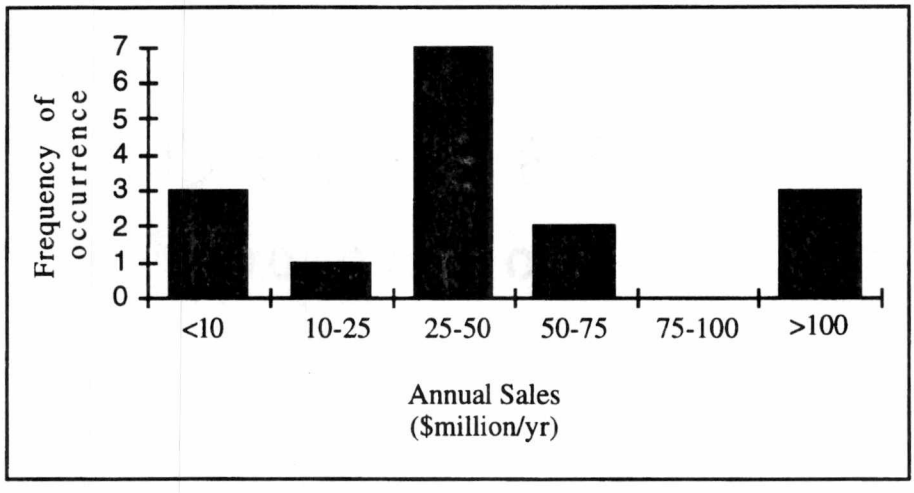

Figure 5-29. Histogram of reported annual sales for SIC 36 respondents.

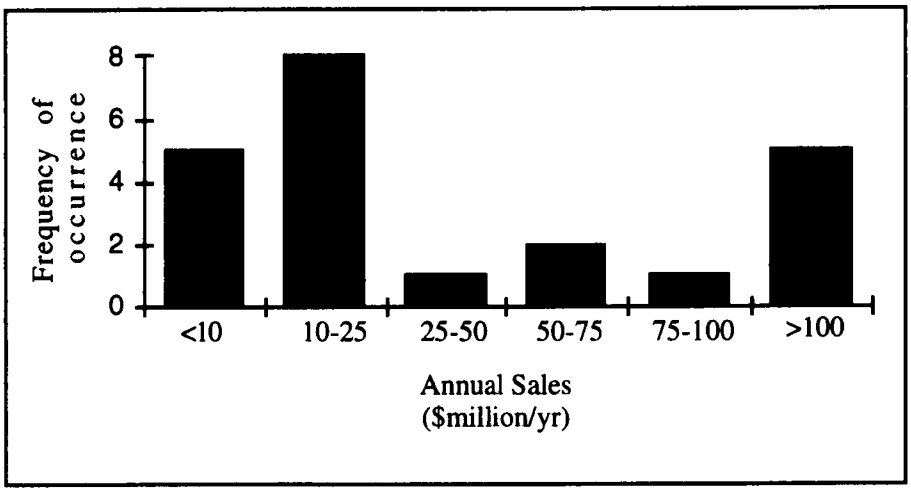

Figure 5-30. Histogram of reported annual sales for SIC 37 respondents.

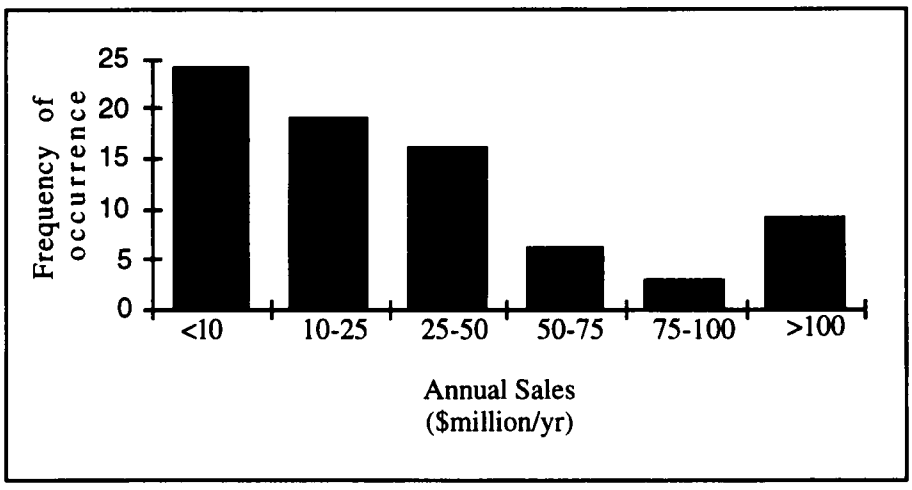

Figure 5-31. Histogram of reported annual sales for the total dataset.

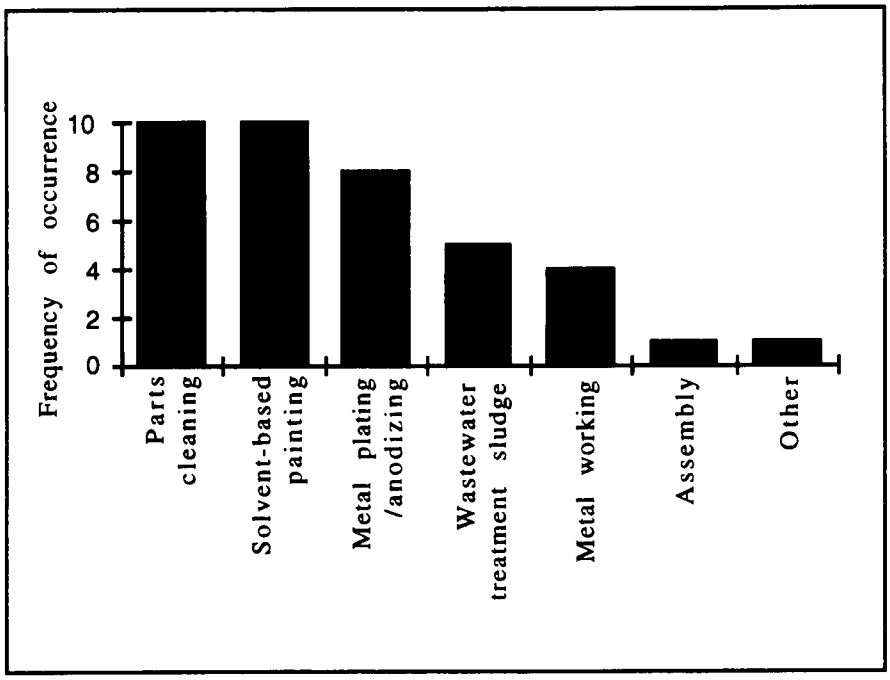

Figure 5-32. Histogram of reported largest waste generating processes for SIC 34 respondents.

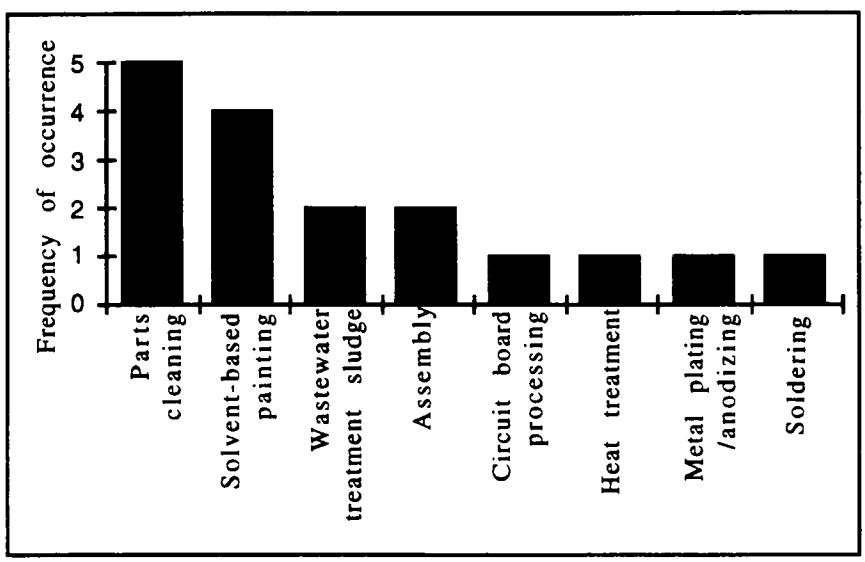

Figure 5-33. Histogram of reported largest waste generating processes for SIC 36 respondents.

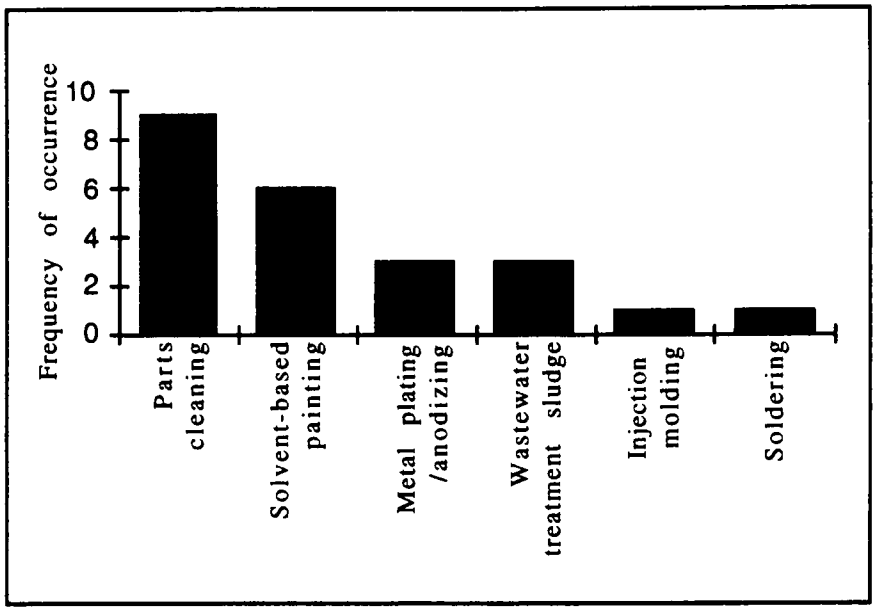

Figure 5-34. Histogram of reported largest waste generating processes for SIC 37 respondents.

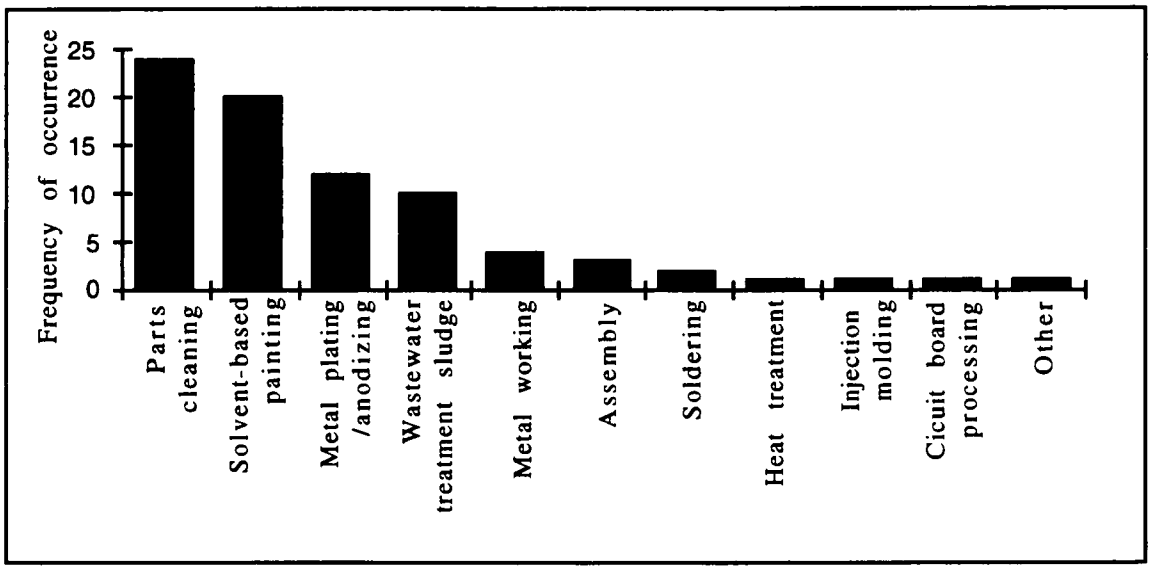

Figure 5-35. Histogram of reported largest waste generating processes for the total dataset.

Manufacturing floorspace is a measure of a facility's size and may indirectly reflect production rates in many cases. The influence of the primary waste generating process on energy use was selected due to the results from Figure 5-19 which suggested that the number of waste streams at a facility appears unrelated to the total quantity of hazardous waste generated. Thus, it is of interest to determine if the same relationship holds for energy usage. Investigation of these relationships focused on participants in SIC 34 respondents and the total dataset due to the limited response rate from companies in SIC 36 and 37.

Annual Electricity Usage versus Manufacturing Floorspace

As can be seen from Figure 5-36, the plot shows a strong positive relationship between electricity use and manufacturing floorspace for companies in SIC 34. The R^2 value of 0.56 also suggests the model is a fairly strong predictor of electricity consumption (BTU/yr) based on a facility's manufacturing floorspace. Also the ANOVA table (Table 5-7) reveals a Prob>F = 0.000 is less than the level of significance, alpha = 0.05, suggesting that the regressor is related to the electricity consumption for the responding facilities. The graph for the entire dataset (Figure B-11 and Table B-4) shows a similar relationship.

Although not the focus of this study, an example of how a workable regression equation may be developed using this data is presented. It should be noted that the equation is only valid when the statistical tests suggests a model is significant, and between the maximum and minimum values of x. Table 5-8 presents the parameter estimates (produced with JMP 3.02) for the y-intercept and slope which can be calculated with the methods presented in Chapter 4 (Equations 4 to 7) The resulting empirical equation is:

$$a = 0.819b + 6.099 \qquad \text{Equation 5-1}$$

where: $a = \log y$

$b = \log x$

y = electricity consumption (million BTU/yr)

x = log manufacturing floorspace (ft^2)

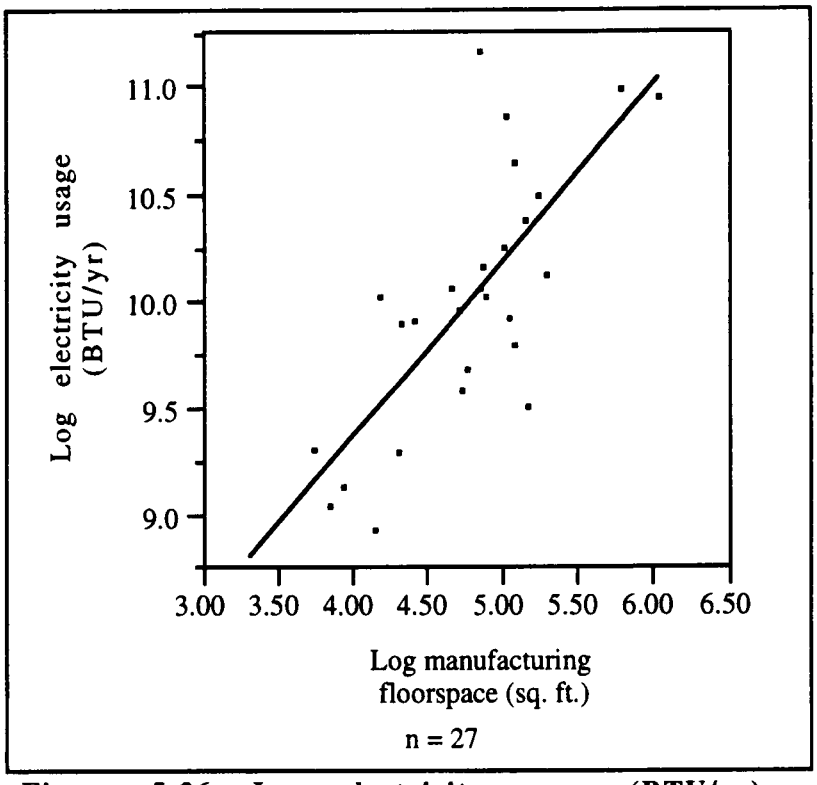

Figure 5-36. Log electricity usage (BTU/yr) versus manufacturing floorspace (ft^2) for SIC 34 respondents.

Table 5-7. ANOVA Table for Log Electricity Usage (BTU/yr) versus Log Manufacturing Floorspace (ft^2) for SIC 34 Respondents

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob>F	R^2
Model	1	5.204	5.204	32.027	0.000	0.561
Error	25	4.062	0.162			
C Total	26	9.266				

Table 5-8. Parameter Estimates for Log Electricity Usage (BTU/yr) versus Log Manufacturing Floorspace (ft^2) for SIC 34 Respondents

Term	Estimate
Intercept	6.099
Log manufacturing floorspace (ft^2)	0.819

This equation implies that:

$$\log y = 0.819 \log x + 6.099 \qquad \text{Equation 5-2}$$

$$y = 10^{0.819 \log x + 6.099} \qquad \text{Equation 5-3}$$

$$y = (10^{\log x})^{0.819} (10^{6.099}) \qquad \text{Equation 5-4}$$

$$y = (x)^{0.819} (10^{6.099}) \qquad \text{Equation 5-5}$$

Thus, it can be seen that using a dataset transformed with the common logarithmic function yields a power function as the regression equation. This model can be tested by applying it to the entire dataset. For example, a facility with 100,000 ft^2 of manufacturing floorspace, from the model, is estimated to use approximately 15,600 million BTU/yr. of electricity. The total dataset graph (Figure B-11) shows that for a facility of this size, the estimated BTU/yr electricity is about 13,300 million BTU/yr. However, these two estimates are only within 15%, which provides evidence that the model is not valid for estimating values of the dependent variable outside this dataset.

Annual Natural Gas Usage versus Manufacturing Floorspace

Figure 5-37 reveals a weak relationship between natural gas usage and manufacturing floorspace. From Table 5-9, the low R^2 value of 0.11 combined with a Prob>F = 0.11, which is greater than alpha = 0.05, suggest that the effect of this regressor is insignificant on the natural gas consumption (BTU/yr) for SIC 34 participants. The same result was obtained for the entire dataset (Figure B-12 and Table B-5). This finding is expected because natural gas associated with, other than for space heating, more specialized applications (e.g. industrial boilers, and drying ovens) not used by most plants.

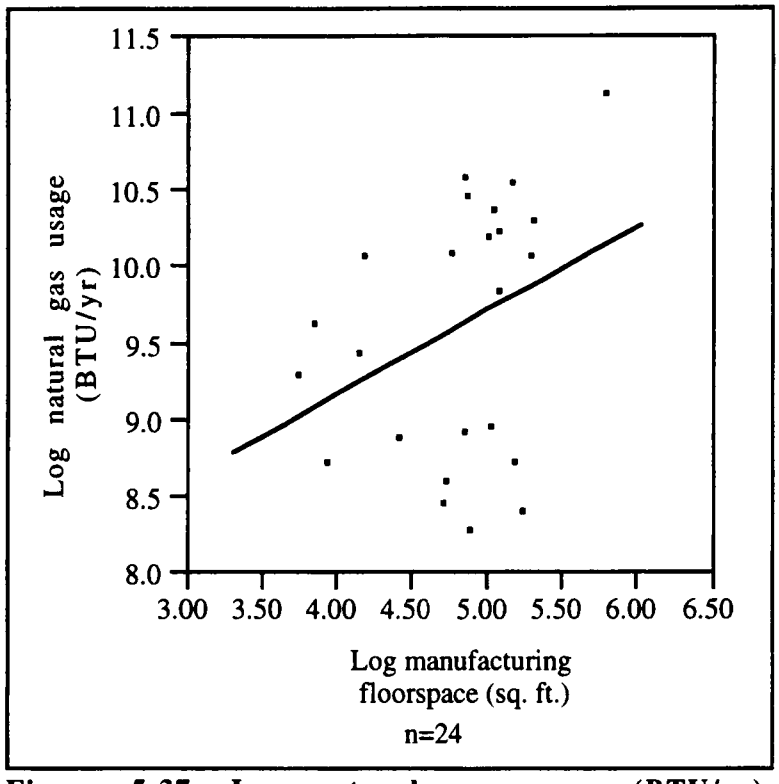

Figure 5-37. Log natural gas usage (BTU/yr) versus log manufacturing floorspace (ft^2) for SIC 34 respondents.

Table 5-9. ANOVA Table for Log Natural Gas Usage (BTU/yr) versus Log Manufacturing Floorspace (ft^2) for SIC 34 Respondents

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob>F	R^2
Model	1	1.797	1.797	2.771	0.110	0.112
Error	22	14.266	0.648			
C Total	23	16.063				

Annual Electricity Consumption versus Primary Waste Generating Process

The next analysis examined whether the quantity of energy consumed is related to the primary waste generating process. Figure 5-38 is a quantile box plot comparing the mean quantity of electricity consumed for the top three waste generating processes for companies reporting in the SIC 34 group. Inspection of the plot and its respective ANOVA (Table 5-10) shows that the average electricity consumed per year for plants reporting a principal waste producing process is not significantly different among the selected SIC categories. The Prob>F = 0.536, which is greater than the 0.05 significance level, confirms this result. Inspecting Table 5-11 data, which contain the means for each process, shows that the values are in relative statistical agreement. Use of the entire database (Figure B-13, Tables B-6 and B-7) demonstrates similar results.

Annual Natural Gas Usage versus Primary Waste Generating Process

Figure 5-39 presents a quantile box plot showing the relationship between the average natural gas consumed for the top three reported waste generating processes. The respective ANOVA, Table 5-12, reveals that with a Prob>F = 0.003 less than the 0.05 level of significance, one process may consume, on average, more natural gas than the other two processes. It is seen from Table 5-13 that solvent-based painting uses considerable more natural gas than the other processes. This is validated by inspecting the Tukey-Kramer test results (Table 5-14) for mean differences which indicates that solvent-based painting requires more natural gas than both metal plating/anodizing and parts cleaning for companies in the analyzed datapool. This may be expected because painting operations typically use drying ovens fueled by natural gas. Examining the entire database (Figure B-14, Tables B-8 to B-10) demonstrates similar results.

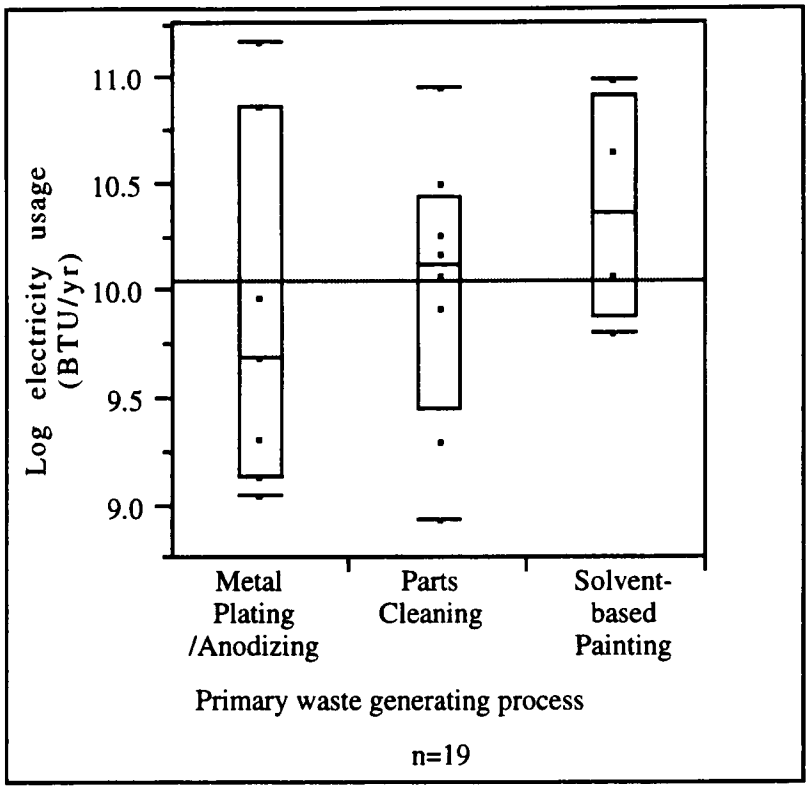

Figure 5-38. Log electricity usage (BTU/yr) versus primary waste generating processes for SIC 34 respondents.

Table 5-10. ANOVA Table for Log Electricity Usage (BTU/yr) versus Primary Waste Generating Processes for SIC 34 Respondents

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob>F	R^2
Model	2	0.652	0.326	0.652	0.535	0.075
Error	16	8.002	0.500			
C Total	18	8.654				

Table 5-11. Average Electricity Usage (million BTU/yr) for the Primary Waste Generating Processes for SIC 34 Respondents

Process	Number	log average quantity of electricity used	Quantity of electricity used
Metal Plating/Anodizing	7	9.883	33,900
Parts Cleaning	8	10.010	21,980
Solvent-based Painting	4	10.383	40,580

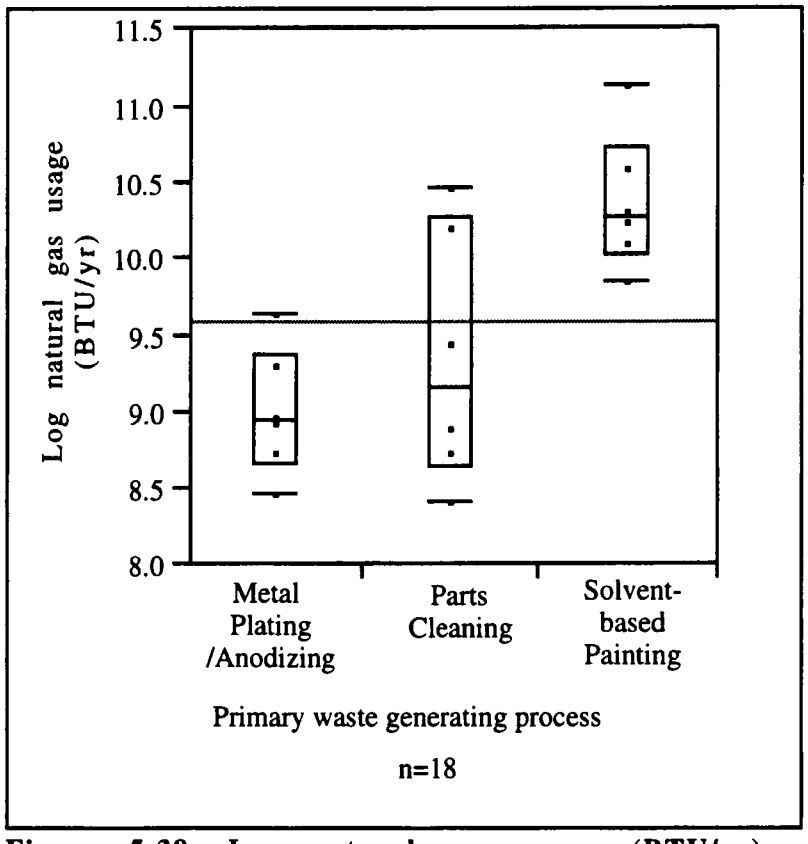

Figure 5-39. Log natural gas usage (BTU/yr) versus primary waste generating processes SIC 34 respondents.

Table 5-12. ANOVA Table for Log Natural Gas Usage (BTU/yr) versus Primary Waste Generating Processes for SIC 34 Respondents

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob>F	R^2
Model	2	6.045	3.022	8.518	0.003	0.532
Error	15	5.322	0.355			
C Total	17	11.368				

Table 5-13. Average Natural Gas Usage (million BTU/yr) for the Primary Waste Generating Processes for SIC 34 Respondents

Primary waste generating process	Number	Log average quantity of natural gas used	Average quantity of natural gas used
Metal Plating/Anodizing	6	9.00	1,470
Parts Cleaning	6	9.360	832
Solvent-based Painting	6	10.371	39,360

Table 5-14. Tukey-Kramer HSD Test for Log Natural Gas Usage (BTU/yr) for the Primary Waste Generating Processes for SIC 34 Respondents

	Solvent-based painting	Parts-cleaning	Metal-plating /Anodizing
Solvent-based painting	-0.893	0.117	0.475
Parts cleaning	0.117	-0.893	-0.535
Metal Plating/Anodizing	0.475	-0.535	-0.893

Note: Positive values demonstrates pairs of means that are significantly different.

Relationships Between 1991 THWR and Industrial Survey Data

Overview of Analysis

Combining the information from both the 1991 THWR and industrial survey provides a means to further characterize industrial energy use and hazardous waste generation. Again, this analysis was limited to respondents in SIC 34 and the total dataset due to the low survey response rates from SIC 36 and 37. Thus, using the available data, the following questions were investigated for respondents:

1. Is the manufacturing floorspace related to the reported level of annual sales?
2. Is the quantity of hazardous waste generated related to reported level of annual sales?
3. Does the quantity of hazardous waste generated relate to the plant manufacturing floorspace?
4. Does the primary waste generating process significantly affect the quantity of hazardous waste generated?

Details of Results

Manufacturing Floorspace versus Annual Sales

As mentioned earlier, manufacturing floorspace and annual sales may directly reflect production levels. Thus, it is desirable to determine if facilities with large areas dedicated to manufacturing are associated with a high level of sales.

Figure 5-40 displays the relationship between the level of annual sales and the manufacturing floorspace. As is apparent from the graph and Table 5-15, the Prob>F = 0.000 and R^2 = 0.478 suggest the mean is significantly different between the sales levels. Inspection of Table 5-16 reveals that companies with sales less than $10 million/yr has considerably less area dedicated to manufacturing floorspace. Specifically, Table 5-17 data shows the two largest sales levels are not significantly different, but they are different from the lowest sales level. These results suggest that, in general, larger facilities have greater annual sales. This is expected because in most cases high sales reflects

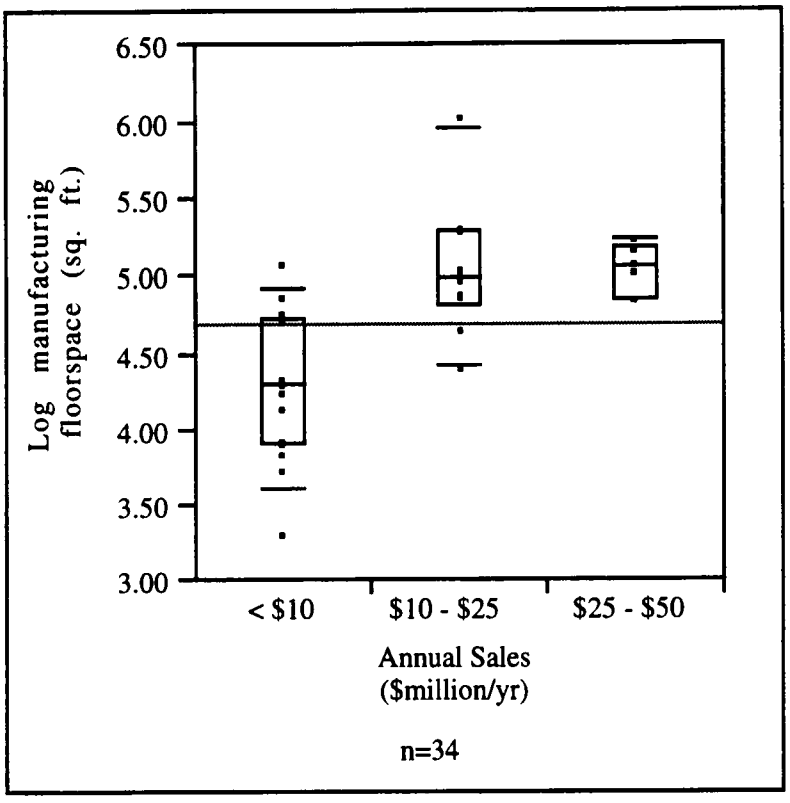

Figure 5-40. Log manufacturing floorspace (ft^2) versus annual sales ($ million/yr) for SIC 34 respondents.

Table 5-15. ANOVA Table for Log Manufacturing Floorspace (ft^2) versus Annual Sales ($ million/yr) for SIC 34 Respondents

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob>F	R^2
Model	2	4.825	2.413	14.196	0.000	0.478
Error	31	5.269	0.170			
C Total	33	10.094				

Table 5-16. Mean of Log Manufacturing Floorspace (ft^2) for the Three Largest Levels of Annual Sales for SIC 34 Respondents

Sales level ($ million/yr)	Number of responses	Log manufacturing floorspace (ft^2)	Manufacturing floorspace (ft^2)
< 10	16	4.282	31,338
10 - 25	10	5.043	200,630
25 - 50	8	5.029	113,565

Table 5-17. Tukey-Kramer HSD Test for Average Log Manufacturing Area (ft^2) for the three Largest Levels of Annual Sales ($ million/yr) for SIC 34 Respondents

	$10 - $25	$25 - $50	< $10
$10 - $25	-0.453	-0.466	0.352
$25 - $50	-0.466	-0.507	0.307
< $10	0.352	0.307	-0.358

Note: Positive values demonstrates pairs of means that are significantly different.

high production rates, which in many instances, require large manufacturing areas. The same result was found when considering the entire dataset (Figure B-15 and Tables B-11 to B-13).

Quantity of Hazardous Waste versus Annual Sales

Owing to the previous result, it was desirable to determine if the annual quantity of hazardous waste generated is related to a facility's size and production volumes, as reflected in annual sales (i.e. large production rates).

As Figure 5-41 and data in Tables 5-18 and 5-19 reveal, there is little difference between the average quantity of reportable hazardous waste among the companies in the top three sales levels. This conclusion is supported by the low R^2 = 0.02, and the large Prob>F ratio of 0.687. The same trend holds for the entire dataset, (see Appendix B, Figure B-16 and Table B-14 to B-15). This result suggests that waste generation is independent of production rates and facility size, as reflected by annual sales. Thus, other factors, such as specific manufacturing processes and operating methods, likely have a larger influence on generated amounts of hazardous waste.

Quantity of Hazardous Waste versus Manufacturing Floorspace

To verify that the quantity of hazardous waste generated is unrelated to facility size, the relationship was tested with the reported floorspace as the independent variable. Unlike annual sales, this regressor represents the total area dedicated to manufacturing and may be a more appropriate indicator of facility size.

Inspection of Figure 5-42 reveals a scatter plot that suggests no relationship between hazardous waste generation and manufacturing floorspace. Also, from Table 5-20, the Prob>F = 0.2336 is greater than the level of significance which supports the lack of a relationship. The value of R^2 = 0.04 also adds to this inference. It is worth noting that annual sales and manufacturing floorspace are measures of a facilities "size of operation", and the quantity of hazardous waste generated does not significantly relate either parameter. Thus, it may be concluded, for this dataset, that a facility's manufacturing floorspace has little demonstrateable relationship to the quantity of hazardous waste generated. This result was also found for the total dataset (Figure 17 and Tables B-16).

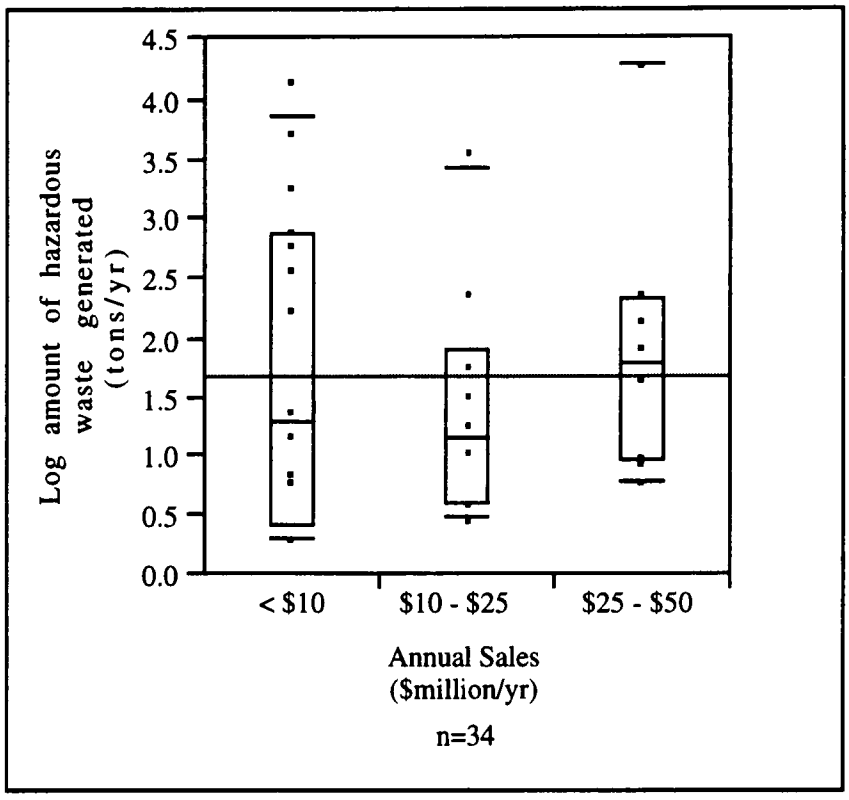

Figure 5-41. Log amount of hazardous waste generated (tons/yr) versus annual sales ($ million/yr) for SIC 34 respondents.

Table 5-18. ANOVA Table for Log Amount of Hazardous Waste Generated (tons/yr) versus Annual Sales ($ million/yr) for SIC 34 Respondents

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob>F	R^2
Model	2	1.082	0.541	0.381	0.685	0.024
Error	31	43.928	1.417			
C Total	33	45.010				

Table 5-19. Mean of Log Amount of Hazardous Waste Generated (tons/yr) for the Three Largest Levels of Annual Sales for SIC 34 Respondents

Sales level ($ million/yr)	Number	log average amount of hazardous waste generated (tons/yr)	Amount of hazardous waste generated (tons/yr)
< 10	16	1.737	1,460
10 - 25	10	1.4196	390
25 - 50	8	1.889	2,495

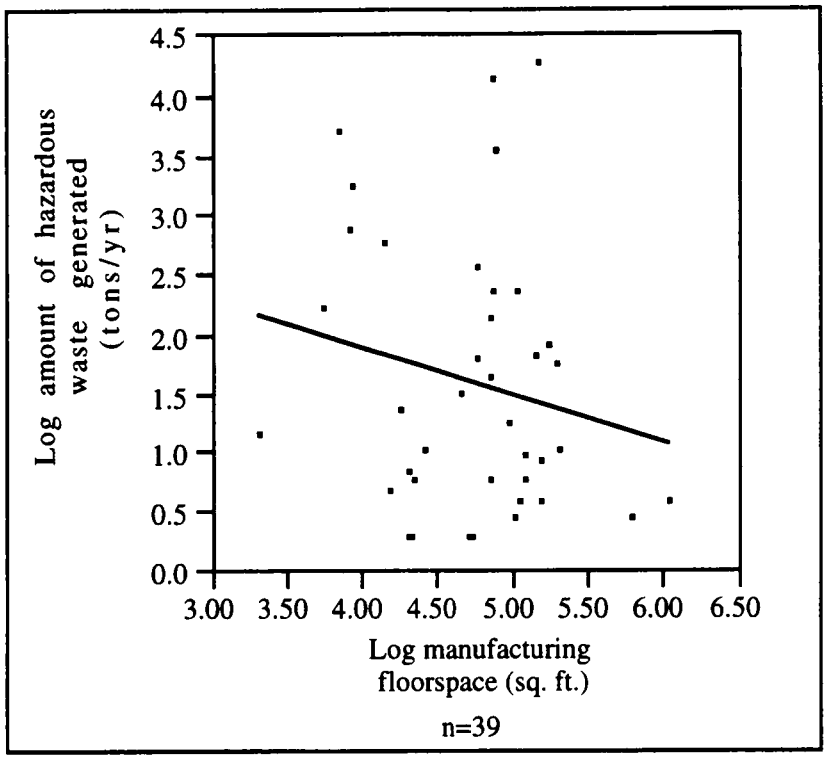

Figure 5-42. Log total amount of hazardous waste generated (tons/yr) versus log manufacturing floorspace (ft^2) for SIC 34 respondents.

Table 5-20. ANOVA Table for Log Total Amount of Hazardous Waste Generated (tons/yr) versus Log Manufacturing Floorspace (ft^2) for SIC 34 Respondents

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob>F	R^2
Model	1	1.845	1.845	1.466	0.233	0.038
Error	37	46.547	1.258			
C Total	38	48.392				

Quantity of Hazardous Waste versus Primary Waste Generating Processes

The primary waste generating process was selected as a parameter to investigate the extent to which hazardous waste generation rates may be process-related.

Figure 5-43 is a plot comparing the average quantity of hazardous waste for the top three waste generating processes reported by survey participants. The Prob>F = 0.002 from Table 5-21 suggests that at least one process generates, on average, more hazardous waste than the other processes. Inspecting Table 5-22 shows that average quantity of hazardous waste produced for metal plating is larger than for parts cleaning and solvent-based painting. The Tukey-Kramer test results (Table 5-23) show that metal plating/anodizing generates significantly more waste than parts cleaning and solvent-based painting operations. Considering the quantity of wastewater generated during most electro-plating operations, this result was anticipated.

Analysis of the total dataset showed similar results for the largest waste producing process (Figure B-18 and Tables B-17 through B-19). However, in addition to metal plating, wastewater treatment sludge was also found to be significantly different in terms of hazardous waste generation amounts than for parts cleaning and solvent-based painting. High water usage is generally associated with the most waste producing processes, which when converted to wastewater would contribute to the larger reported amounts.

Linkages Between Industrial Energy Consumption and Hazardous Waste Generation

Overview of Analysis

In this section, data from several different databases was combined to study the relationship between industrial hazardous waste generation and energy usage. First globalized data from two national databases (1988 MECS and TRI) were used to study the linkage. Next, data from the 1991 TWHR and direct-mail industrial survey were combined to determine the relationship using plant specific information.

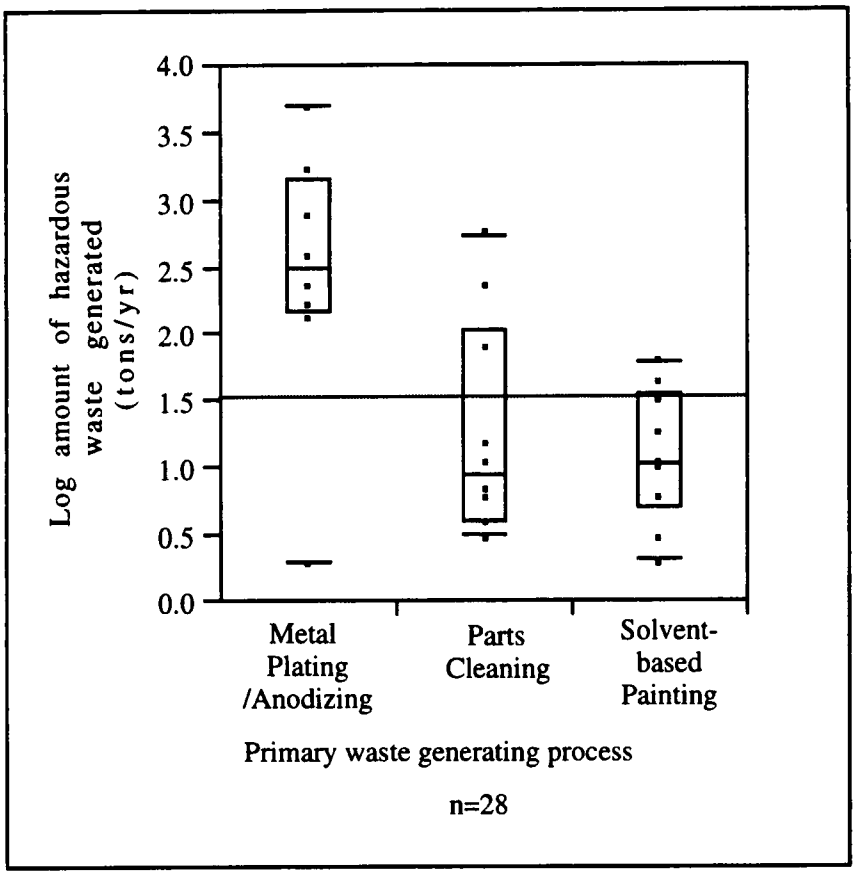

Figure 5-43. Log total amount of hazardous waste generated (tons/yr) versus primary waste generating processes for SIC 34 respondents.

Table 5-21. ANOVA Table for Log Total Amount of Hazardous Waste Generated (tons/yr) versus Primary Waste Generating Processes for SIC 34 Respondents

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob>F	R^2
Model	2	9.581	4.790	7.784	0.002	0.383
Error	25	15.384	0.615			
C Total	27	24.965				

Table 5-22. Mean of Log Amount of Hazardous Waste Generated (tons/yr) for the Primary Waste Generating Processes for SIC 34 Respondents

Primary waste generating process	Number reported	Log average amount of hazardous waste generated (tons/yr)	Average amount of hazardous waste generated
Metal Plating/Anodizing	8	2.441	1,090
Parts cleaning	10	1.259	97
Solvent-based painting	10	1.060	198

Table 5-23. Tukey-Kramer HSD Test for Log Amount of Hazardous Waste Generated (tons/yr) for the Primary Waste Generating Processes for SIC 34 Respondents

	Metal Plating/Anodizing	Parts cleaning	Solvent-based painting
Metal Plating/Anodizing	-0.976	0.255	0.454
Parts cleaning	0.255	-0.873	-0.675
Solvent-based painting	0.454	-0.675	-0.873

Note: Positive values show pairs of means that are significantly different.

Relationships Between the 1988 MECS and the 1988 TRI

As mentioned in the Chapter 4 (Data Analysis Methodology), a cursory investigation was performed on the relationship between industrial energy usage and waste generation using global data from the 1988 MECS and the 1988 TRI.

Figure 5-44 reveals a positive relationship between total waste generation and energy usage. The R^2 value of 0.49 and Prob>F = 0.000 from Table 5-24 supports the relationship shown in the graph. This result is important as it suggests a quantitative link between the two primary dependent variables which were the focus of this study. However, the appearance of a quantitative relationship is subject to limitations. For instance, the data from these two sources have different uses. The MECS data estimates energy consumption for the entire manufacturing population (variable number of plants in each SIC category). On the other hand, the TRI data only represents specifically reported information for a different set of plants. Because of these differences, care must be used when ascribing particular significance to the results obtained.

Considering at the results in detail, and considering the intuitive outcome one expects, the relationship is valid. For example, SIC 33 (Primary metal industries), 28 (Chemicals and allied products), and 29 (Petroleum refining and related industries) require, by the nature of their processes, large quantities of energy. Also, the by-products generated in these industries are some of the most heavily regulated waste streams by EPA. Considering these facts and inspecting Figure 5-44, it is apparent that SICs 28, 29, and 33 companies consume and generate large quantities of energy and waste, respectively. Inspecting the other end of the scale reveals a similar result. Both SIC 21 (Tobacco products) and 23 (Apparel and other fabric products) use low energy consuming and waste generating processes. When considering the preliminary nature of this investigation, and the limited data available, the outcome is relatively significant and motivates further study. However, the result provides no information on the relationships between energy use and waste generation on a facility level which is addressed next.

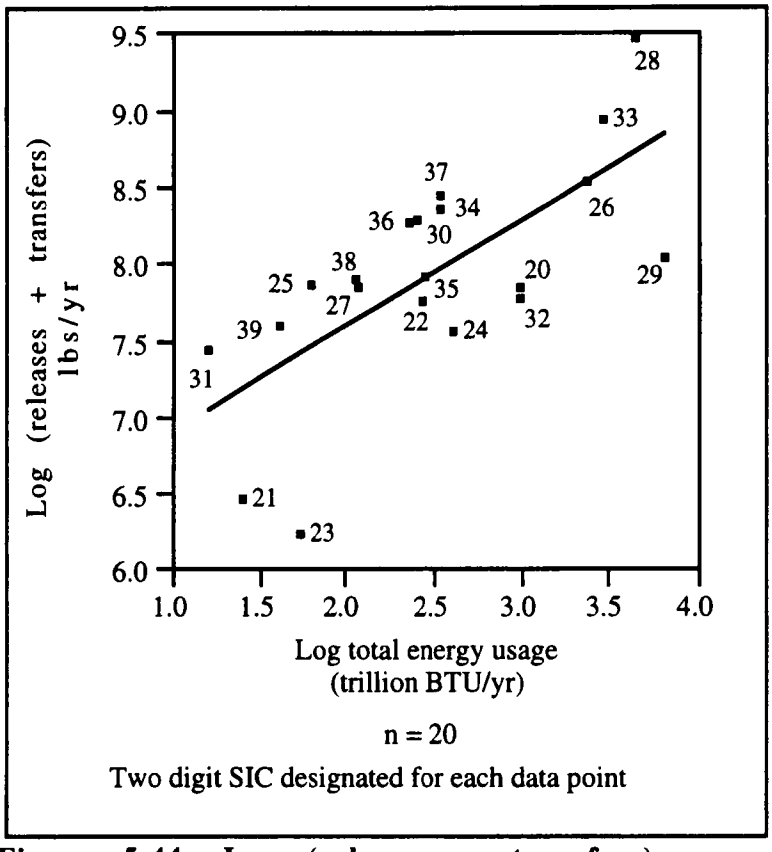

Figure 5-44. Log (releases + transfers) (lbs/yr) from the 1988 TRI versus log total energy usage (trillion BTU/yr) from the 1988 MECS.

Table 5-24. Log (Releases + Transfers) (lbs/yr) from the 1988 TRI versus Log Total Energy Usage (trillion BTU/yr) from the 1988 MECS

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob>F	R^2
Model	1	4.916	4.916	17.234	0.000	0.489
Error	18	5.134	0.285			
C Total	19	10.050				

Relationships Between the 1991 THWR and Industrial Survey

Quantity of Hazardous Waste versus Electricity Consumption

Based on the author's industrial experience, electricity consumption is expected to reflect, in part, facility size, as well as production efficiency. Figure 5-36 and Table 5-7 validate electricity's relationship to manufacturing floorspace, a direct measure of facility size. Regarding process efficiency, electricity is used to power most industrial equipment and should reflect the efficacy of the manufacturing processes used in a given plant.

The relationship between the quantity of electricity consumed (BTU/yr) and the amount of hazardous waste generated is shown in Figure 5-45. As can be seen, the plot is generally scattered suggesting a somewhat weak relationship between the two parameters. Data in the ANOVA Table 5-25 with a Prob>F = 0.064, which is larger than the level of significance of 0.05, and a low R^2 = 0.13 supports this result. Again, a similar result was found for the entire database (Figure B-19 and Table B-20).

Because the database contained such a large range of reported generation amounts, it was of interest to determine if an underlying relationship could be determined by eliminating the extreme values. Investigation into the range of values for total amount of hazardous waste generated revealed that over 50% of the reported values fell between the 25th and 75th quartiles (5 tons <= annual amount generated <= 234 tons). Thus, the values in this range were chosen for detailed analysis.

As can be seen from Figure 5-46 and Table 5-26, the reduced dataset shows no relationship between the quantity of hazardous waste generated and electricity usage. In fact, the relationship is less significant than utilizing the entire SIC 34 dataset. Thus, one can infer that other factors must influence hazardous waste generation.

Considering electricity consumption as a measure of a facility's "size of operation", this result agrees with the previous finding that hazardous waste generation rates do not relate to facility size (i.e. manufacturing floorspace and annual sales).

When assuming electricity consumption measures production efficiency, this result is difficult to interpret considering the limited dataset and the relative closeness of the Prob>F to the level of significance (0.06 to 0.05). It was previously shown that manufacturing area is related to energy

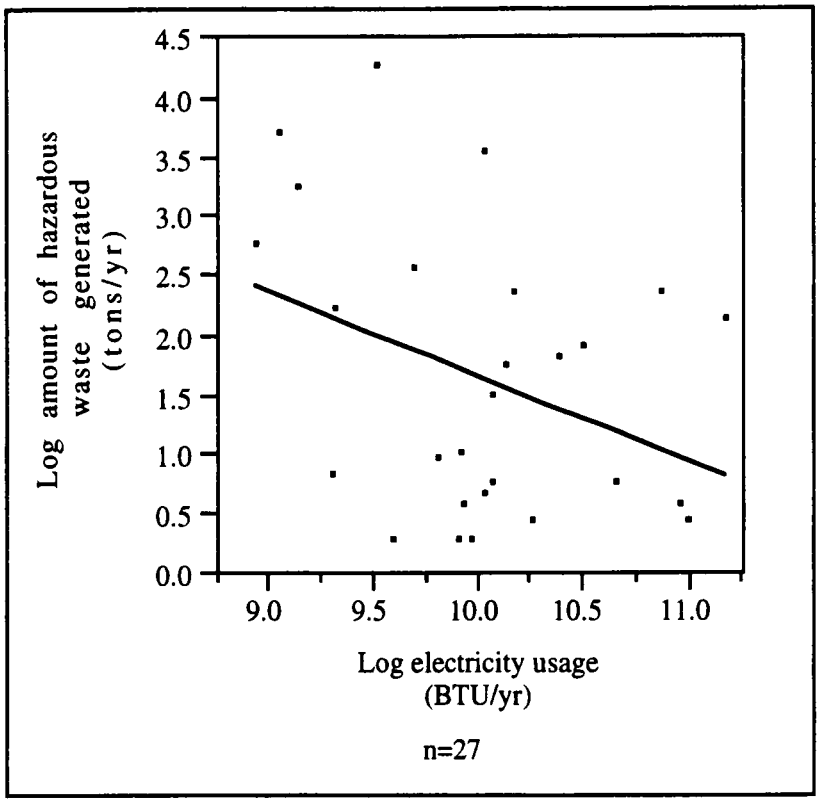

Figure 5-45. Log amount of hazardous waste generated (tons/yr) versus log electricity consumption (BTU/yr) for SIC 34 respondents.

Table 5-25. ANOVA Table for Amount of Hazardous Waste Generated (tons/yr) versus Electricity Consumption (BTU/yr) for SIC 34 Respondents

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob>F	R^2
Model	1	4.632	4.632	3.737	0.064	0.130
Error	25	30.982	1.239			
C Total	26	35.614				

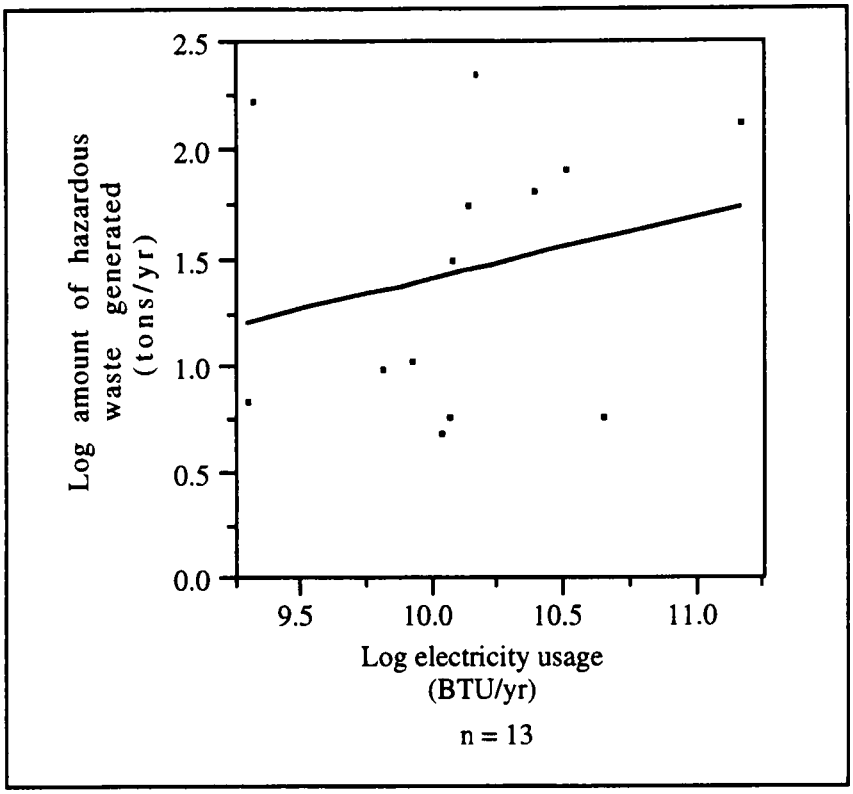

Figure 5-46. Log amount of hazardous waste generated (tons/yr) versus log electricity consumption (BTU/yr) for a reduced dataset of SIC 34 respondents.

Table 5-26. ANOVA Table for Amount of Hazardous Waste Generated (tons/yr) versus Electricity Consumption (BTU/yr) for a Reduced Dataset of SIC 34 Respondents

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob>F	R^2
Model	1	0.247	0.247	0.622	0.446	0.054
Error	11	4.359	0.396			
C Total	12	4.606				

consumption (see Figure 5-36). This result was assumed to be attributable to large numbers of production equipment (e.g. pumps, fans, conveyors, and electric heaters). It follows that more equipment may be associated with higher throughput which could contribute to large waste quantities. Thus, questions arise about the use of electricity throughout the facility. Factors effecting electricity use include:

- types of equipment utilized
- the number and age of specific-pieces of production equipment
- operating hours for each class of equipment

Considering all the factors influencing energy consumption, as well as the limitations of the datapool, it is difficult to draw a firm conclusion about the relationship between waste generation and energy consumption.

Quantity of Hazardous Waste versus Natural Gas Consumption

Natural gas consumption was identified as a primary dependent variable because like electricity consumption, it is a primary production resource. However, it is a limited measure because it is typically used in processes which require heating. As shown in Figure 5-39 and Table 5-12 through 5-14, its use is associated with solvent-based painting operations and is probably used to fuel drying ovens commonly used in these operations.

Figure 5-47 represents the relationship between the amount of hazardous waste generated and natural gas consumption. Again, as is the case with electricity consumption, it appears that the relationship is not significant. From Table 5-27, the R^2 = 0.014 and a Prob>F = 0.58 supports this conclusion. Analyzing this relationship for the total database yields a similar result (Figure B-20 and Table B-21).

A weak relationship between natural gas consumption and hazardous waste generation is expected because as mentioned, natural gas is typically used in heating applications (with occasional use for heat-driven cooling equipment). Furthermore, it was found to be most frequently related to solvent-based painting processes which was found not to have a statistically significant relationship to waste produced in a facility.

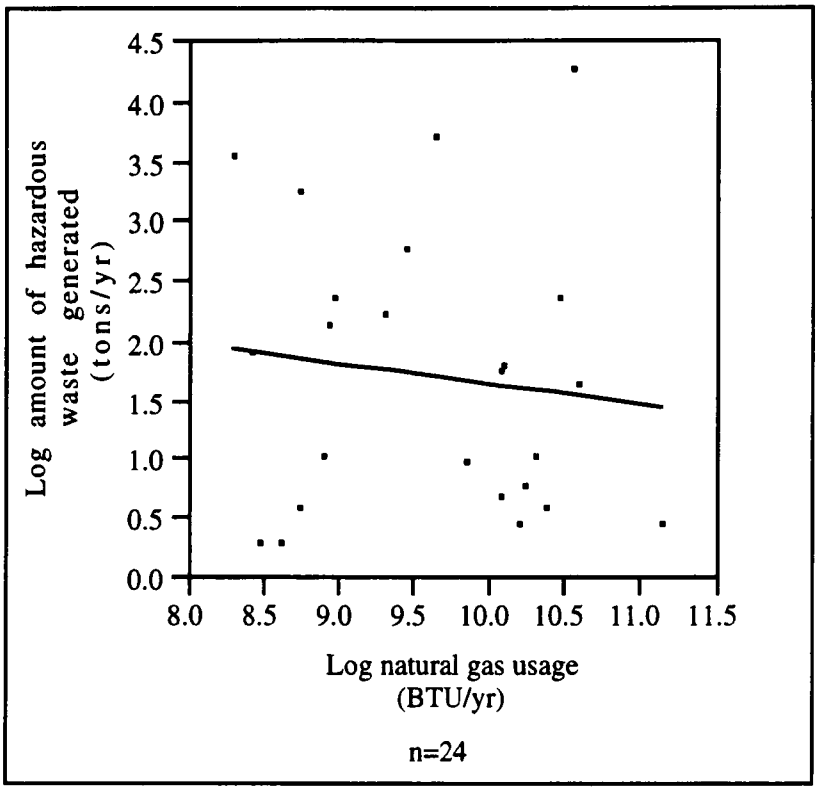

Figure 5-47. Log amount of hazardous waste generated (tons/yr) versus natural gas usage (BTU/yr) for SIC 34 respondents.

Table 5-27. ANOVA Table for Log Amount of Hazardous Waste Generated (tons/yr) versus Natural Gas Usage (BTU/yr) for SIC 34 Respondents

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob>F	R^2
Model	1	0.459	0.459	0.323	0.575	0.014
Error	22	31.282	1.421			
C Total	23	31.742				

Quantity of Hazardous Waste/Manufacturing Floorspace versus Electricity Usage

In a further analysis, the relationship of hazardous waste generation rates normalized to floorspace and electricity consumption was studied. This normalization factor was chosen because of its reliability and demonstrated independence from the amount of hazardous waste generated.

Interestingly, Figure 5-48 reveals a fairly strong relationship between the normalized waste generation rate and the quantity of electrical energy consumed. This argument is supported by the ANOVA data, Table 5-28, which shows a Prob>F=0.001. This value is much less than the 0.05 level of significance implying that the regressor does have a notable effect. Also, considering the overall dataset reliability, the model has a relatively large R^2 value of 0.344.

This result clarifies the uncertain relationship between the quantity of hazardous waste generated and electricity usage, and affirms the basic hypothesis of this work, namely, that waste generation can be related to energy consumption in manufacturing facilities. The result is also supported with the plot of globalized data from the 1988 MECS and TRI (Figure 5-40), presented earlier, which revealed a positive relationship between waste generation and energy consumption.

However, the findings for the total dataset do not follow the results found for SIC 34 (Figures B-21 and Table 22). This is likely due to the influence of the limited and incomplete data from SIC 36 and 37 respondents. It should be noted that these categories did not have sufficient numbers of data points to draw conclusions about their datasets.

Quantity of Hazardous Waste/Manufacturing Area versus Natural Gas Consumption

To conclude the investigation of energy usage and hazardous waste generation rates relationships, the link between the normalized waste generation rate and natural gas usage was investigated.

A weak relationship of the normalized waste generation amounts and the quantity of natural gas consumed is shown in Figure 5-49. The ANOVA data, Table 5-29, show a high Prob>F = 0.3079 and a large low R^2 of 0.0472 which supports the scatter plot. This result is further validated by the result of the

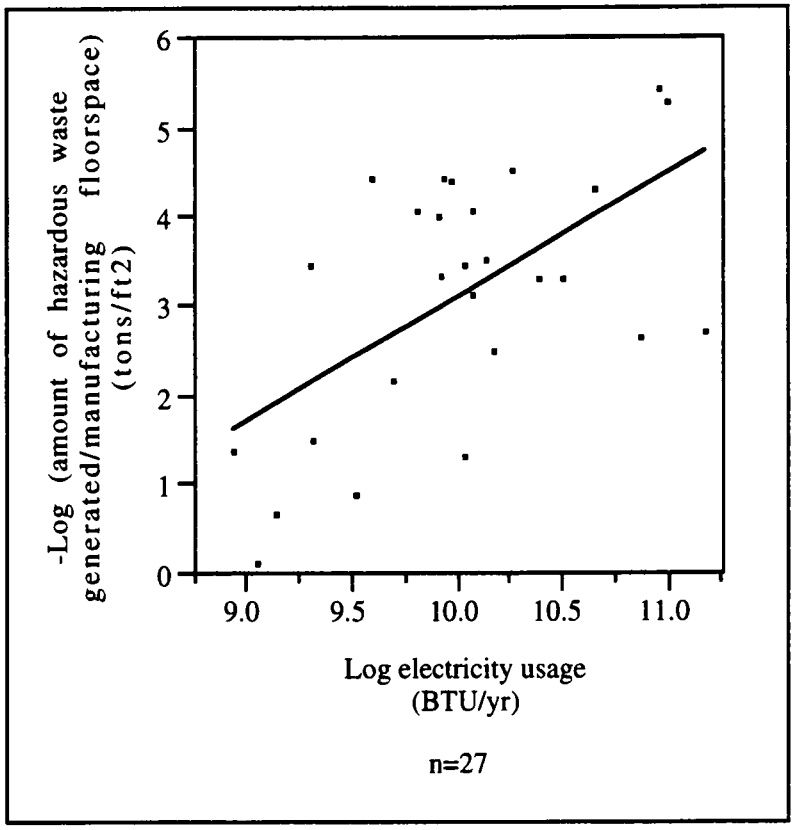

Figure 5-48. -Log (amount of hazardous waste generated/manufacturing floorspace) (tons/ft^2) versus log electricity usage (BTU/yr) for SIC 34 respondents.

Table 5-28. ANOVA Table for -Log (Amount of Hazardous Waste Generated/Manufacturing Floorspace) (tons/ft^2) versus Log Electricity Usage (BTU/yr) for SIC 34 Respondents

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob>F	R^2
Model	1	17.978	17.978	13.103	0.001	0.344
Error	25	34.300	1.372			
C Total	26	52.278				

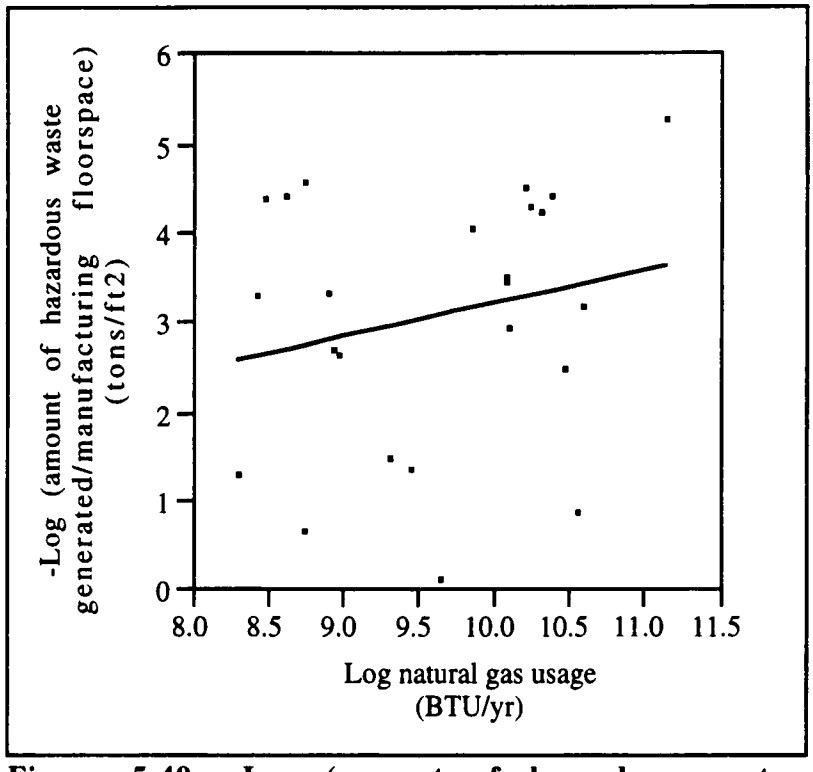

Figure 5-49. -Log (amount of hazardous waste generated/manufacturing floorspace) (tons/ft^2) versus log natural gas usage (BTU/yr) for SIC 34 respondents.

Table 5-29. ANOVA Table for -Log (Amount of Hazardous Waste Generated/Manufacturing Floorspace) (tons/ft^2) versus Log Natural Gas Usage (BTU/yr) for SIC 34 Respondents

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob>F	R^2
Model	1	2.247	2.247	1.089	0.307	0.047
Error	22	45.369	2.062			
C Total	23	47.616				

quantity of hazardous waste versus natural gas consumed test (Figure 5-47). In addition, the same overall result was obtained for the entire dataset (Figure B-22 and Table B-23).

6. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The objective of this study was to investigate the relationships between the generation of hazardous waste and selected facility characteristics for Tennessee manufacturers in SIC 34, 36, 37, and the aggregate group. In particular, the study focused on the characteristics: manufacturing floorspace, production processes yielding waste, and energy consumption rates. To this end, data from the 1991 THWR and a mailed industrial survey were used to provide most of the information needed to draw inferences about these relationships. Data from the 1988 MECS and TRI was also used for a cursory investigation of the relationship between industrial waste generation and energy use. In both cases, once data were collected simple descriptive statistics, histograms, and single variable regression were used to explore data trends and linkages.

A wide variety of companies participated in this study. Mostly, they were medium-sized companies which generated only one reportable hazardous waste stream. In general, the wastes were either corrosive or ignitable and produced from solvent-based painting, parts cleaning, and metal-plating operations.

Analysis of the globalized data in the 1988 MECS and TRI revealed an apparent link between energy use and waste production. This result should be accepted with caution because of the limitations of each database. However, the result does suggest a need to further investigate the factors influencing these two efficiency measures.

Due to limited survey responses for facilities in SIC 36 and 37, only detailed investigation of the characteristics and interrelationships for companies in SIC 34 and all SIC groups combined were conducted. Based on the data assembled, it was found that the reported quantity of hazardous waste generated was primarily related to specific manufacturing processes. Waste generation rates were found to be independent of both facility size and energy consumption rates. However, when the quantity of hazardous waste generated was normalized to facility size, it was discovered that the normalized waste

quantity increases as the quantity of energy consumed became larger. Specific results of the investigation are listed below.

Characterizations and Interrelationships from the 1991 THWR

The following results were determined from investigating the selected fields from the 1991 THWR:

- SIC 37 respondents had the largest reported number of permanent employees and amount of hazardous waste generated per reporting facility. SIC 36 companies had the greatest quantity of hazardous waste per stream.
- Forty-three percent of all facilities in the datapool reported only one hazardous waste stream.
- Disposal codes MOMX, DOMX, DOO1, and DOO2 were reported most frequently suggesting that the majority of surveyed plants use ignitable solvents or corrosive materials.
- The quantity of hazardous waste generated showed no apparent relationship to the number of permanent employees.
- The amount of hazardous waste generated and reported per year was found to be unrelated to the number of waste streams per facility for SIC 34, 36, 37 respondents and the total dataset.

Characterizations and Interrelationships from the Industrial Survey

The following list summarizes the results derived from the set of returned industrial surveys:

- SIC 37 companies had the largest average floorspace dedicated to manufacturing.
- SIC 36 facilities used the most electricity per plant. However, on a per plant basis, the average natural gas consumption was approximately equal among all three surveyed SIC groups.
- The quantity of electricity consumed per year was found to be related to manufacturing floorspace area for SIC 34

participants and the total dataset, but was unrelated to natural gas consumption.

- For SIC 34 and the total dataset, the manufacturing processes reported did not significantly relate to the annual average quantity of electricity consumed, while solvent-based painting was associated with higher than average natural gas usage.

Relationships between the 1991 THWR and the Industrial Survey

This section focused on the relationships between selected facility parameters and hazardous waste generation. As mentioned, the returned surveys were minimal for SIC 36 and 37 companies so this analysis concentrated on SIC 34 plants and the entire database.

- Plants with large manufacturing floorspace areas were associated with higher levels of annual sales.
- The level of annual sales had no apparent relationship to the average quantity of hazardous waste generated.
- The quantity of hazardous waste generated was not significantly related to the manufacturing floorspace.
- Plants with metal-plating operations produced more hazardous waste on an annual basis per facility than those with parts cleaning and solvent-based painting.

Linkages Between Industrial Energy Consumption and Hazardous Waste Generation

Relationships Between the 1988 MECS and the 1988 TRI

This section focused on using global data available from Federal databases to draw a inference about energy use and waste production. The result showed that the two variables were loosely related. Large energy consuming industries such as SIC 33 (Primary metal industries) and 28 (Chemical and allied products) were found to generate relatively large quantities of hazardous waste. The same relationship holds for industrial groups using less energy. Although this outcome is interesting, it is not definitive because the data from each report is disjointed and intended for

different uses. The result does support the argument for further study of the linkages between industrial energy use and waste generation.

Relationships Between the 1991 THWR and Industrial Survey

This analysis used data from both the 1991 THWR and direct-mail survey to investigate the relationship between the two manufacturing efficiency measures, energy consumption and hazardous waste generation.

- The annual generation amounts of hazardous waste were not related to the quantity of either electricity or natural gas energy consumed per year.
- The data for annual electricity consumption for SIC 34 was found to be related to the normalized variable, amount of hazardous waste per manufacturing floorspace. However, there was no relationship found between these two parameters for the total dataset. No significant linkages were revealed when relating the normalized variable to the quantity of natural gas consumed per year.

Recommendations

It should be noted that in view of the lack of prior published work in the area of this thesis, this study was designed to be an initial attempt to understand the linkages between hazardous waste generation and energy consumption on a facility level. Several methods were identified during the study which would improve the understanding of the relationship between the two efficiency measures in future studies. Specifically, it would be prudent to collect more data on process-related parameters, increase the datapool size, and improve data integrity, and utilize more advanced statistical analysis techniques.

Because the manufacturing process was determined to have the greatest apparent influence on waste generation, future studies should focus on a set of key process parameters. Detailed data in this area would better describe facility characteristics which may help identify previously overlooked relationships. Parameters for which data should be collected include:

- details about facility operating and work shift schedules
- specific production information including: process steps (unit operation), production rates, dollar value of products, physical characteristics of product, and number of product lines
- information on equipment used in plant such as: specific number, age, and type of equipment
- details on each reported waste stream including: identification and generation rates for each point source in each plant surveyed
- data on significant ancillary operations in plant (e.g. cafeterias)
- details on production lines which produce waste (e.g. number of machines or lines, operating hours, production capacity)
- information on pollution prevention activities and historical reductions for each surveyed facility

Better and more conclusive inferences may also be drawn with a larger datapool. Although the overall response rate for this study was approximately 31%, which is considered acceptable, the author feels that more companies could be encouraged to participate in future efforts. The following suggestions may help increase industry participation:

- redesign questionnaire to reduce the time requirement to complete survey
- obtain sponsorship from national or regional trade organizations (e.g. Printers Association) to gain the facility management's trust and cooperation
- work with local utilities to identify "forward looking companies" that would likely be willing to participate
- include a $1 bill in the initial mailing as a "token of appreciation" for participation

Better quality data would lead to an improved understanding of waste and energy linkages. Specifically, two methods may improve the dataset. The

first is to conduct personal interviews with each facility's environmental manager to collect the detailed process data. Such interviews would allow first-hand inspection of the facility, thus giving the researcher a better understanding of the significance of the data collected.

Secondly, energy and waste data should be obtained from the same time period. One of the major obstacles in this study was obtaining energy and waste data from the same time period. To alleviate this data collection problem in future studies, a pool of companies should be identified and energy information collected regularly over time. In this manner, when waste data becomes available, the two sets of information can be grouped for a specific set of plants from the same time period. This method would provide the most matched and reliable information about energy usage and waste generation rates for each facility.

Finally, more advanced statistical analysis, such as multiple and curvilinear regression, should be used to determine the relationships between parameters. Using these methods may reveal that the efficiency measures are related to more than one dependent variable (e.g. manufacturing area and number of employees). The methods may also reveal that the relationships are not linear, but are best described by a polynomial function. Regardless of the relationships, the advanced methods will better describe the dataset.

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APPENDIXES

APPENDIX A

APPENDIX A

University of Tennessee
Energy, Environment and Resources Center
Industrial Energy/Waste Survey

Company name: _____ Date: _____

I. ENERGY INFORMATION

Please check the energy forms used by your facility in its manufacturing processes. Also please identify the utility company's name for each energy form used.

	Utility Company
❑ Electricity:	_____
❑ Natural Gas:	_____
❑ Other (fuel oil, coal, etc.):	_____

If you prefer that we contact your energy suppliers directly to request energy consumption data, please give your approval by providing your facility name and signature below:

I give the University of Tennessee's Energy, Environment, and Resources Center permission to collect _____'s 1991 energy consumption data.

Signature _____ Date: _____

II. FACILITY CHARACTERISTICS

A. In 1991 what was the approximate under-roof floor space (ft^2) in the following areas?

Total sq. ft _____	Manufacturing _____	R & D _____
Offices _____	Warehouse/Storage _____	Other _____

B. Approximately how many people did your facility employ in 1991, including temporary and part-time workers if applicable?

Manufacturing Permanent:	❑1-50	❑50-100	❑100-200	❑200-500	❑ >500
Temporary:	❑1-50	❑50-100	❑100-200	❑200-500	❑ >500
Part-time:	❑1-50	❑50-100	❑100-200	❑200-500	❑ >500
Administrative:	❑1-50	❑50-100	❑100-200	❑200-500	❑ >500

C. Please list your major product(s) and their SIC (Standard Industrial Classification) code.

Products Manufactured	SIC Category
_____	_____
_____	_____
_____	_____

Figure A-1. Front page of the industrial survey mailed to selected manufacturers.

D. What were your 1991 production manufacturing rates? (please provide best estimate(s) if records are unavailable)

a) Individual parts or components (e.g. bolts) shipped _____ /year.

b) Assemblies (e.g. televisions) shipped _____ /year.

c) Reconditioned/repaired components or assemblies shipped (if any) _____ /year.

E. Please check the approximate annual sales at your facility for 1991.

❑ less than $10 million ❑ $10 - 25 million ❑ $25 - 50 million

❑ $50 - 75 million ❑ $75 - 100 million ❑ greater than $100 million

III. MANUFACTURING PROCESSES AND WASTE GENERATION

A. Please rank, based on its relative significance, each of the following processes that generated hazardous waste during 1991. (please fill in each blank)
(1 = heavy , 2 = moderate, 3 = light, 4 = negligible, 5 = Not applicable)

___ metal plating/anodizing ____ metal working (i.e. drilling & lathing) ___ etching

___ wastewater treatment sludge ____ injection molding ___ heat treatment

___ water-based painting ____ solvent-based painting ___ welding

___ glass melting ____ photographic imaging ___ soldering

___ parts cleaning ____ circuit board processing ___ assembly

B. Please estimate the amount of non-hazardous solid waste your facility generated in 1991.
(use historical data if available)

❑ less than 5 tons (< 10,000 lbs) ❑ 5 - 50 tons (10,000 -100,000 lbs) ❑ 50 - 100 tons (100,000 - 200,000 lbs)

❑ 100 - 500 tons (200,000 - 1,000,000 lbs) ❑ 500 - 1,000 tons (1,000,000 - 2,000,000 lbs) ❑ greater than 1,000 tons (> 2,000,000 lbs)

C. If your facility produced a non-hazardous wastewater treatment sludge in 1991, please answer the following questions:

i) Is the annual quantity disposed included in the answer above (question III-B)? ❑ YES ❑ NO

ii) If yes, what percent of your solid waste does it occupy? _____ %

iii) If no, please estimate the quantity you generated. _____ lbs

This completes the questionnaire. Thank you very much for your help. If you would like a copy of the final report, when available, please check this box. ❑

Please fax or use the self-addressed stamped envelope to return the completed questionnaire to:

Todd Thomas, Graduate Student
University of Tennessee
Energy, Environment and Resource Center
327 South Stadium Hall
Knoxville, TN 37996-0710
Ph. (615) 974-4719 / Fax (615) 974-1838

Figure A-2. Back page of the industrial survey mailed to selected manufacturers.

Date

Name
Address
City, State, Zip

Salutation:

I am a graduate student at The University of Tennessee (Engineering Science and Mechanics Department). I am also a member of a research team at the Energy, Environment and Resources Center studying the relationship between industrial energy use and waste generation. I will use some of the data from this research project for my master's thesis where I am examining the correlation between an individual plant's manufacturing energy use and its hazardous and solid wastes generation.

Our research project targets active Tennessee manufacturers in Standard Industrial Classifications (SIC) 34, 36, and 37. Because your facility's SIC code is one of these, I am writing to request your help in our project. You may be assured complete confidentiality of your answers to our survey questions. Your responses will not be linked to your facility; rather the data will be grouped for statistical analysis.

For the study, we need three types of data from you for calendar year 1991. Completing the enclosed one-page survey will help in collecting these essential data. The first data we need to gather is your plant's annual energy consumption. To obtain the energy information, please ask your energy supplies to mail or fax to me your 1991 (January 1 to December 31) energy usage and costs (fax 615-974-1838). Your suppliers will provide this no-cost service at your request. If it is more convenient, we can collect the energy information directly from the supplier. Simply indicate your permission for the supplier to release these data under question No. I on the survey form.

Second, we would like data on your facility's characteristics. This information includes total square footage, number of employees (permanent and temporary), production rates, and approximate annual sales. The third type of information we seek concerns your manufacturing processes and waste generation. We have provided space for you to rank your manufacturing processes based on the quantity of hazardous waste they generate.

We will collect your 1991 hazardous waste generation information from the Tennessee annual report data for hazardous waste generation. However, we would like an estimate of the amount of solid (non-hazardous) waste your plant generated in 1991.

Thank you very much for your assistance and if you want a copy of the final report, you can request it on the second page of the questionnaire. I would be happy to answer any questions you might have. Please feel free to contact me at (615)974-4719. My fax number is (615)974-1838.

Todd Thomas
Graduate Research Assistant

Enclosures

Figure A-3. Initial cover letter sent to selected manufacturers requesting participation.

Dear Sir/Madam, PLEASE REPLY

Three weeks ago I sent you a short survey on industrial energy use and waste generation. If you have not had the opportunity to fill out the survey, I would appreciate your completing it at your earliest convenience. The survey is short and should require only 10 minutes of your time. Because the survey has been sent to a small, but representative sample of Tennessee manufactures, your response is extremely important.

You can return the survey with the SASE provided or fax it to me at (615) 974-1838.

If you misplaced the survey, you may obtain another by calling

(615) 974-4719

Remember, if you want a copy of the finished report please indicate on the back of the survey.

Todd Thomas

Figure A-4. Follow-up reminder postcard sent to selected facilities.

Date

Name
Address
City, State, Zip

Salutation:

A few weeks ago I wrote to you about a project that I am working on for my Master's thesis. The enclosed questionnaire is vital to my research on industrial energy use and waste generation. I know you are very busy, but if you or someone in your office could take a few minutes to complete this short survey, I would be most grateful. By participating you will receive a copy of the final report so you may compare your company's efficiency with the pooled statistics of Tennessee manufactures in your Standard Industrial Classification (SIC). Of course, all information will remain confidential and statistical analysis will only be performed on pooled data.

Because some time has passed since the first request, let me give you a brief overview of the study. I am examining, for Tennessee manufacturers in SIC 34, 36, 37, the relationship between the quantity of energy consumed and waste generated. Understanding this important relationship may help your company, and all Tennessee companies, increase production efficiency. Also, I am interested in the above relationship combined with other plant characteristics such as: number of employees, annual sales, production processes, etc. Studying these characteristics may provide companies with a way to estimate, using plant characteristics, a baseline value for energy consumption and waste generation.

For the study, three types of data from the 1991 calendar year are essential. First, I need data on your plant characteristics. Completing the enclosed survey will provide this information. Secondly, I need your 1991 energy consumption data. If historical records are unavailable, I can obtain this information from your energy suppliers, just indicate your approval under question No. 1 on the survey. Lastly, I need quantities for your waste generation. I will collect hazardous waste data from the 1991 Tennessee hazardous waste annual report. However, if possible, please estimate a quantity for your non-hazardous solid waste on the survey.

I want to thank you in advance for your help and consideration with this project. If you have any questions or need to contact me for any reason, call (615) 974-4719, or FAX (615) 974-1838. Also, please mail the completed survey by April 20, 1994, so I may get the results to you by mid-summer.

Sincerely,

Todd Thomas, Research Assistant
Department of Engineering Science and Mechanics

Figure A-5. Final cover letter sent to selected manufacturers requesting participation.

FAX

FROM:
Todd Thomas
University of Tennessee
Energy, Environment and Resources Center
327 South Stadium Hall
Knoxville, TN 37996-0710
Phone: (615) 974-4719
FAX: (615) 974-1838

To:

Organization:

FAX :

Voice:

Number of pages (including cover):

Date:

As you know from our phone conversation, our center is conducting an industrial study to determine the correlation between an individual plant's energy consumption and its waste output. One or several of your clients wishes to participate in our survey and has approved the release of their 1991 calendar year (Jan. 1- Dec. 31) energy consumption data.

Thus, we need the following information from your utility company:

Electricity usage: ❑ Natural Gas usage: ❑ Both electricity and natural gas usage: ❑

I have attached a copy of their release as well as the names and addresses.

Note: We are not interested in billing charges only consumption information. Therefore, please don't feel obligated to provide billing information unless it is difficult to separate the two values. Also, please include units with any consumption information you provide.

Thank you for your effort.

Figure A-6. Example of the fax cover letter sent to energy suppliers.

Table A-1. Brief Descriptions of the Waste Disposal Codes Reported by Participating Facilities[1]

Waste Disposal Code	Description
D001	exhibits the characteristic of ingnitability
D002	exhibits the characteristic of corrosivity
D006	exhibits the characteristic of toxicity
D007	exhibits the characteristic of toxicity
D008	exhibits the characteristic of toxicity
D011	exhibits the characteristic of toxicity
D0MX[2]	mixed characteristic waste
F001	spent halogenated solvents used in degreasing
F002	spent halogenated solvents
F003	spent non-halogenated solvents
F005	spent non-halogenated solvents
F006	wastewater treatment sludges from electroplating operations
F007	spent cyanide plating solutions from electroplating operations
F019	wastewater treatment sludges from the chemical conversion coating of aluminum
F0MX[2]	mixed listed wastes
M0MX[2]	mixed characteristic and listed wastes

[1] see 40 CFR Part 261 for further information

[2] unique disposal code associated with THWR and not contained in 40 CFR, Part 261

Table A-2. Descriptions of the Major Groups from the 1987 Standard Industrial Classifications

SIC major group	Description
20	Food and kindred products
21	Tobacco products
22	Textile mill products
23	Apparel and other finished products made form fabrics and similar materials
24	Limber and wood products, except furniture
25	Furniture and fixtures
26	Paper and allied products
27	Printing, publishing, and allied industries
28	Chemicals and allied products
29	Petroleum refining and related industries
30	Rubber and miscellaneous plastics products
31	Leather and leather products
32	Stone, clay, glass, and concrete products
33	Primary metal industries
34	Fabricated metal products, except machinery and transportation equipment
35	Industrial and commercial machinery and computer equipment
36	Electronic and other electrical equipment and components, except computer equipment
37	Transportation equipment
38	Measuring, analyzing, and controlling instruments; photographic, medical and optical goods; watches and clocks
39	Miscellaneous manufacturing industries

Table A-3. Short Titles for Participating Facilities in SIC 34

SIC category	Major Products
3411	Metal cans
3423	Hand and edge tools
3425	Saw blades and handsaws
3433	Heating equipment, except electric
3442	Metal doors, sash, and trim
3443	Fabricated plate work (boiler shops)
3448	Prefabricated metal buildings
3451	Screw machine products
3465	Automotive stampings
3469	Metal stampings
3471	Plating and polishing
3479	Metal coating and allied services
3485[1]	N/A
3489	Ordnance and accessories
3494	Valves and pipe fittings
3496	Misc. fabricated wire products
3498	Fabricated pipe and fittings

[1] no title listed; probably a reporting error

Table A-4. Short Titles for Participating Facilities in SIC 36

SIC category	Major Products
3612	Transformers, except electronic
3613	Switchgear and switchboard apparatus
3621	Motors and generators
3624	Carbon and graphite products
3639	Household appliances
3641	Electric lamps
3651	Household audio and video equipment
3662[1]	N/A
3663	Radio & TV communications equipment
3674	Semiconductors and related devices
3679	Electronic components
3691	Storage batteries

[1] no title listed; probably a reporting error

Table A-5. Short Titles for Participating Facilities in SIC 37

SIC category	Major Products
3711	Motor vehicles and car bodies
3713	Truck an bus bodies
3714	Motor vehicle parts and accessories
3715	Truck trailers
3728	Aircraft parts and equipment
3732	Boat building and repairing
3743	Railroad equipment
3751	Motorcycles, bicycles, and parts

Table A-6. Facility Characteristics from the Direct-Mail Industrial Survey

Response #	SIC	Total Sq. Ft	Mfg. Sq. Ft.	log Mfg. Sq. Ft.	R&D Sq. Ft.	Office Sq. Ft.	Storage Sq. Ft.	Other Sq. Ft.	Mfg Emp	Temp Emp	PT Emp	Admin Emp	Sales
1	34	155000	95000	4.978	0	6000	54000	0	C	X	X	A	B
2	34	1543875	1088875	6.037	5000	150000	300000	0	E	A	A	D	B
3	34	32500	25000	4.398	0	2500	5000	0	B	A	X	A	B
4	34	200000	108000	5.033	9600	9600	69600	0	C	A	X	A	B
5	34	280000	142790	5.155	0	16984	120226	0	E	B	X	C	D
6	34	56000	54000	4.732	0	1800	0	200	B	A	A	A	A
7	34	16000	14000	4.146	0	1500	0	500	A	A	X	A	A
8	34	257471	192611	5.285	0	50000	14860	0	C	A	X	A	B
9	34	164510	148310	5.171	0	24200	0	0	C	X	X	A	C
10	34	60000	45000	4.653	0	5000	10000	0	B	X	X	A	B
11	34	67220	57940	4.763	0	2000	12180	0	B	A	A	A	E
12	34	175000	155000	5.190	0	20000	10000	0	D	A	X	B	C
13	34	60000	51000	4.708	0	6000	3000	0	B	X	X	A	A
14	34	91000	74860	4.874	0	6420	9720	0	D	A	A	A	B
15	34	24200	20000	4.301	0	3000	1200	0	A	X	X	A	A
16	34	60000	58000	4.763	0	2000	0	0	B	X	X	A	A
17	34	158000	100000	5.000	0	8000	50000	0	B	A	X	A	B
18	34	74000	72000	4.857	0	2000	0	0	B	X	X	A	A
19	34	288175	154200	5.188	2600	6375	12500	0	D	A	X	A	E
20	34	160000	70000	4.845	5000	15000	70000	0	D	A	A	B	C
21	34	35000	20000	4.301	0	5000	10000	0	A	A	A	A	A
22	34	256762	168970	5.228	560	12577	65058	9597	D	A	X	A	C
23	34	70000	15000	4.176	0	5000	50000	0	B	X	X	A	D
24	34	128000	120000	5.079	0	8000	0	0	C	A	X	A	C
25	34	750000	600000	5.778	0	60000	0	0	E	X	X	E	F
26	34	14000	8000	3.903	0	1100	4000	900	A	X	X	A	A
27	34	20000	8600	3.934	0	1400	10000	0	A	X	X	A	A
28	34	18000	17500	4.243	0	500	0	0	A	X	X	A	A
29	34	95138	73955	4.869	0	6183	15000	0	B	X	X	A	B

Table A-6. (continued)

Response #	SIC	Total Sq. Ft	Mfg. Sq. Ft.	log Mfg. Sq. Ft.	R&D Sq. Ft.	Office Sq. Ft.	Storage Sq. Ft.	Other Sq. Ft.	Mfg Emp	Temp Emp	PT Emp	Admin Emp	Sales
30	34	39000	22000	4.342	0	1000	16000	0	A	X	A	A	A
31	34	10000	5500	3.740	0	1500	3000	0	A	A	A	A	A
32	34	10800	2000	3.301	600	1200	7000	0	A	X	X	A	A
33	34	155000	70000	4.845	0	10000	75000	0	C	X	X	A	C
34	34	41900	20900	4.320	0	6400	5000	9600	A	X	X	A	A
35	34	140000	70000	4.845	960	10000	8000	40000	D	A	A	B	C
36	34	131000	121000	5.083	0	10000	0	0	D	X	X	B	A
37	34	214000	203000	5.307	0	11000	0	0	D	B	X	B	B
38	34	137685	106240	5.026	6400	4968	4724	15353	D	A	A	B	C
39	34	20410	6912	3.840	0	1000	12068	430	A	X	X	A	A
40	36	227400	130000	5.114	0	17400	56000	24000	C	A	X	A	C
41	36	56000	48000	4.681	0	3000	4000	1000	B	A	A	A	A
42	36	151000	103000	5.013	15000	30000	3000	0	C	A	A	B	
43	36	11400	10000	4.000	0	1400	0	0	B	X	X	A	A
44	36	185360	128036	5.107	0	29260	28064	0	E	A	X	B	C
45	36	135000	60000	4.778	0	5000	70000	0	C	X	X	A	D
46	36	54000	42000	4.623	0	6000	0	6000	B	X	X	A	B
47	36	200000	137500	5.138	0	2500	60000	0	D	A	X	A	C
48	36	243962	100510	5.002	10440	13760	109401	9851	D	A	X	A	D
49	36	275000	125000	5.097	0	75000	50000	0	E	X	X	B	F
50	36	92073	64271	4.808	315	7857	820	18810	D	A	X	A	C
51	36	150000	46523	4.668	0	3040	87469	12968	D	A	X	A	C
52	36	1200000	680000	5.833	60000	60000	400000	0	E	X	D	B	F
53	36	1600000	760000	5.881	60000	80000	700000	0	E	A	A	D	F
54	36	167642	102100	5.009	17548	14346	0	33648	D	X	X	A	C
55	36	33780	19676	4.294	816	6826	5000	1462	B	A	X	A	A

Table A-6. (continued)

Response #	SIC	Total Sq. Ft	Mfg. Sq. Ft.	log Mfg. Sq. Ft.	R&D Sq. Ft.	Office Sq. Ft.	Storage Sq. Ft.	Other Sq. Ft.	Mfg Emp	Temp Emp	PT Emp	Admin Emp	Sales
56	36	130000	18900	4.276	0	9900	101200	0	E	X	X	B	C
57	37	90000	65000	4.813	0	25000	0	0	B	X	X	A	B
58	37	490000	•	•	•	•	•	•	D	A	X	D	B
59	37	500000	420000	5.623	20000	28000	50000	0	E	A	A	C	F
60	37	108000	97200	4.988	1200	3600	6000	0	D	X	X	A	B
61	37	220000	125000	5.097	2000	20000	70000	3000	E	A	X	C	F
62	37	44000	36000	4.556	0	8000	0	0	A	X	X	A	A
63	37	61000	40000	4.602	0	2000	5000	14000	B	X	X	A	A
64	37	178000	171500	5.234	0	6500	0	0	D	X	X	A	B
65	37	500000	•	•	•	•	•	•	E	A	X	A	
66	37	72469	40000	4.602	0	2000	30469	0	B	A	X	A	B
67	37	300000	275000	5.439	0	10000	15000	0	C	A	A	A	D
68	37	87600	46000	4.663	0	1600	40000	0	A	X	X	A	A
69	37	615000	265000	5.423	5000	25000	320000	0	E	C	A	B	F
70	37	35200	22400	4.350	0	7200	0	5600	A	X	X	A	A
71	37	8000	0	•	0	3000	0	5000	A	X	X	A	A
72	37	3500000	2120000	6.326	100000	280000	1000000	0	E	B	X	E	F
73	37	35000	24500	4.389	0	3000	7500	0	B	A	X	A	B
74	37	99500	60000	4.778	0	500	25000	10000	C	X	X	A	C
75	37	95000	66000	4.820	0	4000	25000	0	B	A	A	A	B
76	37	140000	100000	5.000	10000	10000	20000	0	C	A	A	A	E
77	37	2115000	1522000	6.182	18000	178000	266000	131000	E	E	E	E	F
78	37	430000	275000	5.439	2500	40000	100000	12500	D	A	X	B	D
79	37	110000	70000	4.845	10000	10000	20000	0	A	A	X	A	B

Table A-7. Process and Energy Consumption Data for Respondents from the Direct-Mail Industrial Survey

Response #	SIC	Proc. 1	Proc. 2	Proc. 3	Solid Waste	N.G. (10^6 Btu)	log N.G. Btu	Elec. (10^6 Btu)	log Elec. Btu	Gas Yr	Sludge Amount	Sludge	Elec Yr	ton/ft2	log ton/ft2
1	34	H	E	F	C	•	•	•	•		X	X		0.00018947	3.722
2	34	E	H	C	C	•	•	88643.76	10.948	1/92-4/94	X	X	91	0.00000367	5.435
3	34	E	F	X	B	779.4	8.892	8317.091	9.920	91	X	N	91	0.00044	3.357
4	34	B	A	F	B	24000	10.380	8598.240	9.934	91	X	X	91	0.00003704	4.431
5	34	B	H	E	F	•	•	24428.214	10.388		X	X	91	0.00046922	3.329
6	34	F	E	X	A	403.9	8.606	3911.516	9.592	91	X	X	91	0.00003704	4.431
7	34	E	X	X	B	2764.7	9.442	850.816	8.930	91	X	X	91	0.04307143	1.366
8	34	B	A	X	C	11973	10.078	13736.712	10.138	91	X	N	91	0.00029593	3.529
9	34	B	A	L	B	35870	10.555	3290.304	9.517	91	X	X	91	0.1309352	0.883
10	34	H	E	G	A	•	•	11847.828	10.074	2/93-12/93	X	X	91	0.00071111	3.148
11	34	H	E	X	A	12356.1	10.092	•	•	91	X	N	1/92-4/94	0.00112185	2.950
12	34	F	M	G	C	•	•	•	•		X	N	2/93-5/94	0.00005806	4.236
13	34	A	K	X	C	288.4	8.460	9399.207	9.973	91	75000	Y	91	0.00003922	4.407
14	34	P	L	X	B	194	8.288	10760.745	10.032	91	X	X	91	0.04706118	1.327
15	34	H	X	X	C	•	•	•	•		X	N	2/92-3-93	0.0001	4.000
16	34	A	B	X	B	•	•	4846.404	9.685	2/93-12/93	X	X	91	0.00672414	2.172
17	34	E	G	F	F	15932.4	10.202	17900.839	10.253	91	0	N	91	0.00003	4.523
18	34	F	M	O	C	•	•	•	•	8/91-4/91	X	X	8/91-4/91	0.19890278	0.701
19	34	E	O	A	E	533.3	8.727	•	•	91	X	X	3/93-5/94	0.00002594	4.586
20	34	E	B	F	B	•	•	11625.188	10.065		104500	Y	91	0.00008571	4.067
21	34	E	F	X	A	•	•	1964.629	9.293		X	N	91	0.00035	3.456
22	34	E	H	X	C	265.246	8.424	31876.869	10.503	91	75000	Y	91	0.00049121	3.309
23	34	O	H	E	D	11973	10.078	10875.750	10.036	91	X	N	91	0.00033333	3.477
24	34	H	X	X	D	7048	9.848	6450.420	9.810	91	X	N	91	0.00008333	4.079

Table A-7. (continued)

Response #	SIC	Proc. 1	Proc. 2	Proc. 3	Solid Waste	N.G. (10^6 Btu)	log N.G. Btu	Elec. (10^6 Btu)	log Elec. Btu	Gas Yr	Sludge Amount	Sludge	Elec Yr	ton/ft2	log ton/ft2
25	34	H	O	E	F	140000	11.146	98948.000	10.995	91	500000	Y	91	0.000005	5.301
26	34	A	E	X	B	•	•	•	•		X	N	2/92-4/94	0.1	1.000
27	34	A	B	X	A	544.2	8.736	1372.012	9.137	91	X	N	91	0.20767442	0.683
28	34	B	A	X	A	•	•	•	•		X	X	4/92-5/94	0.00137143	2.863
29	34	E	C	X	E	29647.7	10.472	14674.329	10.167	91	1125000	Y	91	0.00316409	2.500
30	34	H	B	X	B	•	•	•	•		4000	Y	5/93-4/94	0.00027273	3.564
31	34	A	X	X	B	1955.4	9.291	2058.118	9.313	91		N	91	0.03163636	1.500
32	34	E	H	C	B	•	•	•	•		X	N		0.0075	2.125
33	34	H	O	C	C	39209	10.593	•	•	91	X	X	2/92-5/94	0.00064286	3.192
34	34	F	L	X	A	•	•	8065.968	9.907	2/92-4/93	X	X	91	0.00009569	4.019
35	34	A	H	E	F	860.596	8.935	145733.344	11.164	91	1000000	Y	91	0.00197143	2.705
36	34	H	C	X	C	17152.2	10.234	45062.966	10.654	91	X	N	91	0.00004959	4.305
37	34	H	X	X	B	20381.2	10.309	•	•	91	X	X		0.00005419	4.266
38	34	A	H	X	F	912.081	8.960	72754.076	10.862	91	1000000	Y	91	0.00227786	2.642
39	34	A	B	X	A	4266	9.630	1103.304	9.043	91	X	X	91	0.75491898	0.122
40	36	H	O	X	E	5882	9.770	38808.770	10.589	91	X	X	91	0.00006154	4.211
41	36	A	X	X	B	3567	9.552	3262.759	9.514	91	X	N	91	0.00060417	3.219
42	36	E	0	F	C	34414	10.537	•	•	91	X	X		0.08832039	1.054
43	36	E	O	X	A	•	•	2248.644	9.352			N	91	0.0001	4.000
44	36	H	C	X	D	•	•	•	•	7/91-4/94	X	X	8/91-4/94	0.00003905	4.408
45	36	B	O	X	D	•	•	•	•		X	X		0.165	0.783
46	36	L	X	X	B	21674	10.336	27920.123	10.446	91	X	X	91	0.00011905	3.924
47	36	B	A	H	C	•	•	•	•		X	N	6/93-4/94	0.00184	2.735

Table A-7. (continued)

Response #	SIC	Proc. 1	Proc. 2	Proc. 3	Solid Waste	N.G. (10^6 Btu)	log N.G. Btu	Elec. (10^6 Btu)	log Elec. Btu	Gas Yr	Sludge Amount	Sludge	Elec Yr	ton/ft2	log ton/ft2
48	36	O	E	X	E	•	•	•	•		X	X		0.00178092	2.749
49	36	H	E	X	F	48700.4	10.688	•	•	91	X	X	2/93-5/94	0.000016	4.796
50	36	E	N	X	B	•	•	25143.710	10.400		0	N	91	0.00028006	3.553
51	36	E	N	X	B	•	•	17515.843	10.243		0	N	91	0.00002149	4.668
52	36	N	X	X	F	•	•	•	•		X	N	6/92-5/93	0.00060882	3.216
53	36	E	H	X	F	237.2	8.375	107083.368	11.030	91	1320000	Y	91	0.00793158	2.101
54	36	O	E	F	D	76.95	7.886	•	•	91	0	N	6/93-5/94	0.00011753	3.930
55	36	J	X	X	A	1567.6	9.195	2861.494	9.457	91	0	N	91	0.00010165	3.993
56	36	H	X	X	D	•	•	33910.162	10.530		0	N	91	0.00010582	3.975
57	37	E	H	O	D	•	•	•	•		X	N		0.00010769	3.968
58	37	A	L	H	D	34414	10.537	•	•	91	X	X	1/92-5/94	•	•
59	37	A	E	B	D	59013	10.771	80992.520	10.908	91	80000	Y	91	0.0575881	1.240
60	37	E	X	X	D	•	•	22093.382	10.344		X	X	91	0.00001029	4.988
61	37	G	F	E	B	2254.5	9.353	•	•	91	0	N	1/94-5/94	0.000024	4.620
62	37	E	O	X	A	•	•	•	•		X	X		0.00002778	4.556
63	37	H	E	X	B	•	•	•	•		X	X		0.000175	3.757
64	37	H	X	X	C	•	•	9679.161	9.986		0	N	91	0.00020408	3.690
65	37	B	E	H	E	128.903	8.110	68331.008	10.835	91	0	N	91	•	•
66	37	E	X	X	A	•	•	•	•		X	X	5/93-4/94	0.000075	4.125
67	37	E	X	X	C	11570	10.063	•	•	91	X	X		0.00008	4.097
68	37	E	X	X	B	•	•	322.434	8.508	2/93-12/93	X	X	91	0.00004348	4.362
69	37	H	M	X	F	•	•	•	•	3/93-5/94	2000	N	3/93-5/94	0.00000377	5.423
70	37	H	E	X	A	•	•	•	•		X	X		0.00026786	3.572

Table A-7. (continued)

Response #	SIC	Proc. 1	Proc. 2	Proc. 3	Solid Waste	N.G. (10^6 Btu)	log N.G. Btu	Elec. (10^6 Btu)	log Elec. Btu	Gas Yr	Sludge Amount	Sludge	Elec Yr	ton/ft2	log ton/ft2
71	37	E	X	X	A	•	•	•	•		X	N		•	•
72	37	H	E	X	F	•	•	•	•		200000	Y		0.00034387	3.464
73	37	A	X	X	F	7456.8	9.873	6376.744	9.805	91	1870000	N	91	0.00044898	3.348
74	37	N	B	A	C	10329.4	10.014	14297.644	10.155	91	90000	Y	91	0.39421667	0.404
75	37	E	O	X	D	•	•	•	•		X	X		0.00001515	4.820
76	37	E	X	X	C	129.5	8.112	7031.790	9.847	91	X	X	91	0.00035	3.456
77	37	B	K	F	F	•	•	988.115	8.995		X	X	91	0.00060053	3.221
78	37	H	O	E	E	33728	10.528	49171.973	10.692	91	0	N	91	0.00008	4.097
79	37	B	E	N	B	•	•	•	•	8/92-4/94	X	X	8/92-4/94	0.06597143	1.181

Table A-8. Data From Selected Companies in the 1991 THWR

Response #	SIC	AMTGEN	log AMTGEN	EMP	log EMP	Waste Streams	AG/WS	Log AG/WS	EPA Code	Waste SIC 1
1	34	18	1.255	140	2.146	1	18.000	1.255	M0MX	3448
2	34	4	0.602	350	2.544	2	2.000	0.301	D0MX	3443
3	34	11	1.041	103	2.013	1	11.000	1.041	D0MX	3451
4	34	4	0.602	200	2.301	3	1.333	0.125	F006	3496
5	34	67	1.826	630	2.799	3	22.333	1.349	F019	3479
6	34	2	0.301	150	2.176	1	2.000	0.301	F001	3451
7	34	603	2.780	28	1.447	1	603.000	2.780	D0MX	3479
8	34	57	1.756	174	2.241	1	57.000	1.756	F006	3471
9	34	19419	4.288	245	2.389	4	4854.750	3.686	D007	3496
10	34	32	1.505	127	2.104	2	16.000	1.204	F005	3465
11	34	65	1.813	50	1.699	3	21.667	1.336	F003	3465
12	34	9	0.954	277	2.442	2	4.500	0.653	D001	3494
13	34	2	0.301	110	2.041	2	1.000	0.000	D002	3471
14	34	3523	3.547	225	2.352	4	880.750	2.945	D0MX	3469
15	34	2	0.301	40	1.602	1	2.000	0.301	M0MX	3443
16	34	390	2.591	80	1.903	7	55.714	1.746	D002	3471
17	34	3	0.477	102	2.009	1	3.000	0.477	D001	3469
18	34	14321	4.156	52	1.716	7	2045.857	3.311	D007	3471
19	34	4	0.602	1	0.000	3	1.333	0.125	D0MX	3471
20	34	6	0.778	200	2.301	2	3.000	0.477	D001	3498
21	34	7	0.845	35	1.544	1	7.000	0.845	D001	3469
22	34	83	1.919	307	2.487	3	27.667	1.442	F001	3489
23	34	5	0.699	78	1.892	2	2.500	0.398	M0MX	3411
24	34	10	1.000	200	2.301	2	5.000	0.699	F003	3443
25	34	3	0.477	1269	3.103	1	3.000	0.477	M0MX	3433
26	34	800	2.903	30	1.477	2	400.000	2.602	F007	3471
27	34	1786	3.252	18	1.255	1	1786.000	3.252	D002	3471
28	34	24	1.380	6	0.778	1	24.000	1.380	M0MX	3471

Table A-8. (continued)

Response #	SIC	AMTGEN	log AMTGEN	EMP	log EMP	Waste Streams	AG/WS	Log AG/WS	EPA Code	Waste SIC 1
29	34	234	2.369	117	2.068	5	46.800	1.670	D002	3443
30	34	6	0.778	26	1.415	1	6.000	0.778	D007	3489
31	34	174	2.241	16	1.204	1	174.000	2.241	F006	3471
32	34	15	1.176	9	0.954	1	15.000	1.176	F0MX	3479
33	34	45	1.653	180	2.255	1	45.000	1.653	M0MX	3442
34	34	2	0.301	59	1.771	1	2.000	0.301	D002	3425
35	34	138	2.140	664	2.822	2	69.000	1.839	D002	3471
36	34	6	0.778	270	2.431	3	2.000	0.301	M0MX	3423
37	34	11	1.041	250	2.398	1	11.000	1.041	D001	3485
38	34	242	2.384	400	2.602	3	80.667	1.907	D0MX	3471
39	34	5218	3.718	20	1.301	4	1304.500	3.115	D007	3471
40	36	8	0.903	230	2.362	3	2.667	0.426	D011	3612
41	36	29	1.462	83	1.919	2	14.500	1.161	D0MX	3691
42	36	9097	3.959	287	2.458	3	3032.333	3.482	M0MX	3674
43	36	1	0.000	66	1.820	1	1.000	0.000	D002	3621
44	36	5	0.699	450	2.653	2	2.500	0.398	D001	3621
45	36	9900	3.996	200	2.301	2	4950.000	3.695	D0MX	3691
46	36	5	0.699	92	1.964	5	1.000	0.000	F002	3624
47	36	253	2.403	•	•	5	50.600	1.704	F006	3613
48	36	179	2.253	378	2.577	2	89.500	1.952	D008	3641
49	36	2	0.301	906	2.957	1	2.000	0.301	F005	3621
50	36	18	1.255	529	2.723	1	18.000	1.255	F001	3679
51	36	1	0.000	885	2.947	1	1.000	0.000	F003	3679
52	36	414	2.617	500	2.699	1	414.000	2.617	D002	3651
53	36	6028	3.780	1800	3.255	1	6028.000	3.780	D002	3639
54	36	12	1.079	440	2.643	5	2.400	0.380	M0MX	3663

Table A-8. (continued)

Response #	SIC	AMTGEN	log AMTGEN	EMP	log EMP	Waste Streams	AG/WS	Log AG/WS	EPA Code	Waste SIC 1
55	36	2	0.301	60	1.778	2	1.000	0.000	F002	3662
56	36	2	0.301	550	2.740	1	2.000	0.301	D0MX	3641
57	37	7	0.845	131	2.117	3	2.333	0.368	F001	3714
58	37	80	1.903	678	2.831	13	6.154	0.789	D0MX	3728
59	37	24187	4.384	793	2.899	14	1727.643	3.237	D002	3714
60	37	1	0.000	400	2.602	1	1.000	0.000	D001	3714
61	37	3	0.477	525	2.720	3	1.000	0.000	F005	3714
62	37	1	0.000	69	1.839	1	1.000	0.000	D006	3714
63	37	7	0.845	133	2.124	1	7.000	0.845	M0MX	3714
64	37	35	1.544	150	2.176	6	5.833	0.766	D001	3715
65	37	120	2.079	850	2.929	6	20.000	1.301	M0MX	3714
66	37	3	0.477	75	1.875	1	3.000	0.477	M0MX	3714
67	37	22	1.342	140	2.146	2	11.000	1.041	M0MX	3732
68	37	2	0.301	55	1.740	1	2.000	0.301	D001	3714
69	37	1	0.000	740	2.869	1	1.000	0.000	D001	3714
70	37	6	0.778	48	1.681	1	6.000	0.778	M0MX	3713
71	37	1	0.000	19	1.279	1	1.000	0.000	D0MX	3711
72	37	729	2.863	5500	3.740	3	243.000	2.386	M0MX	3711
73	37	11	1.041	170	2.230	2	5.500	0.740	D0MX	3743
74	37	23653	4.374	157	2.196	6	3942.167	3.596	D002	3714
75	37	1	0.000	183	2.262	1	1.000	0.000	F005	3714
76	37	35	1.544	120	2.079	1	35.000	1.544	F003	3732
77	37	914	2.961	2500	3.398	13	70.308	1.847	F019	3728
78	37	22	1.342	700	2.845	2	11.000	1.041	D001	3751
79	37	4618	3.664	80	1.903	5	923.600	2.965	D0MX	3743

APPENDIX B

APPENDIX B

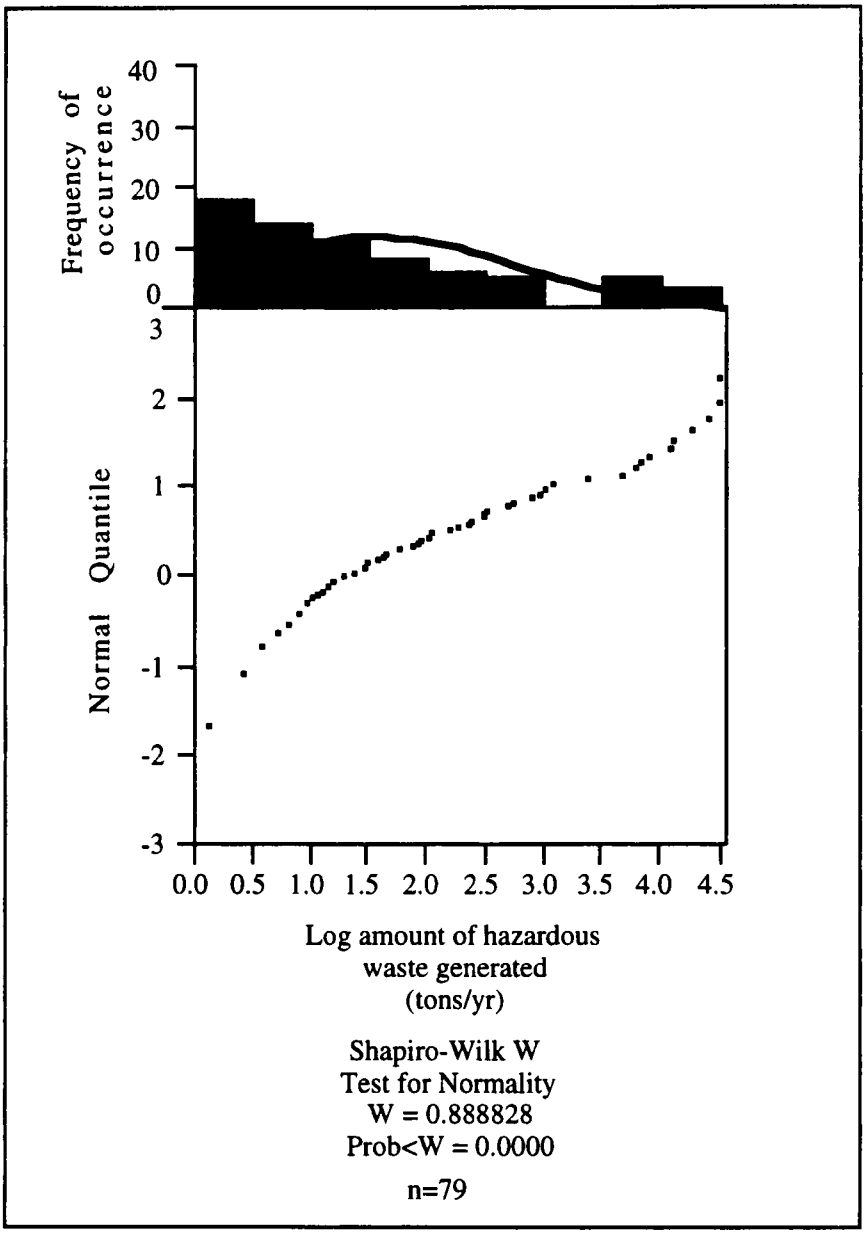

Figure B-1. Log amount of hazardous waste generated (tons/yr) for the total dataset.

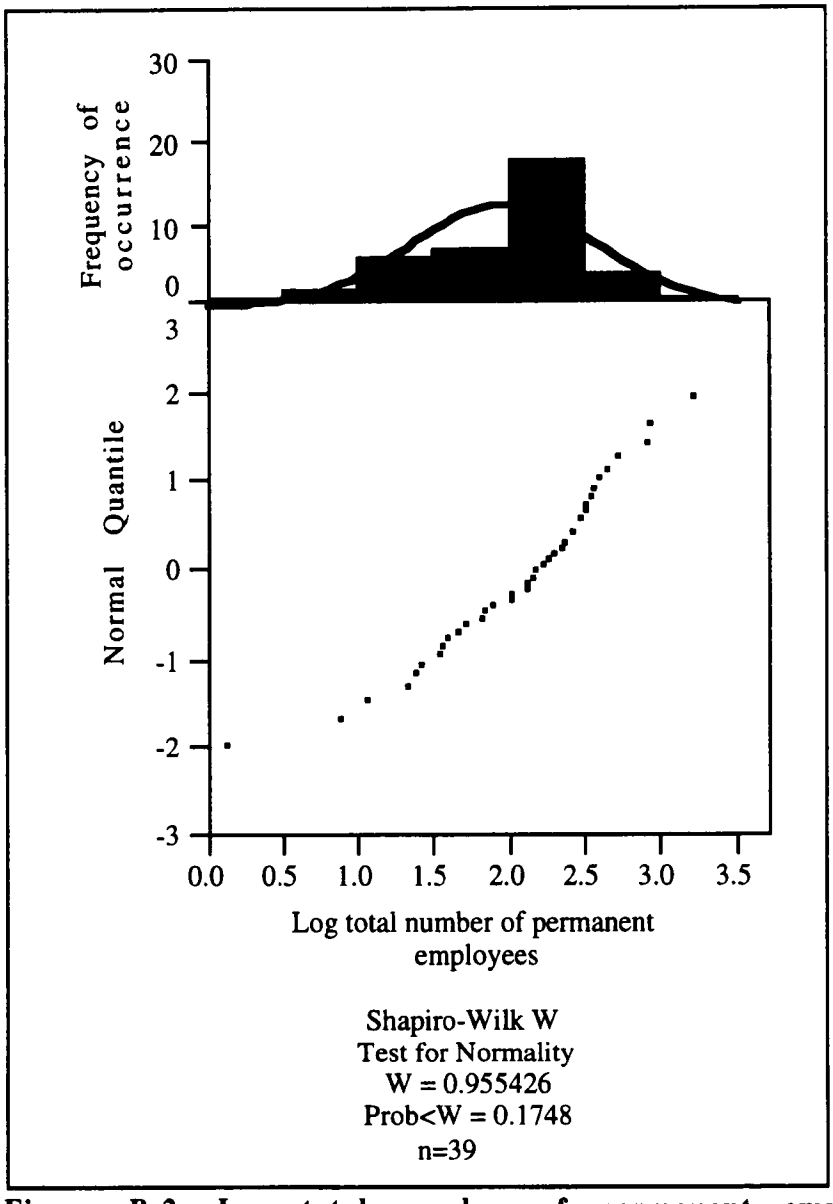

Figure B-2. Log total number of permanent employees for SIC 34 respondents.

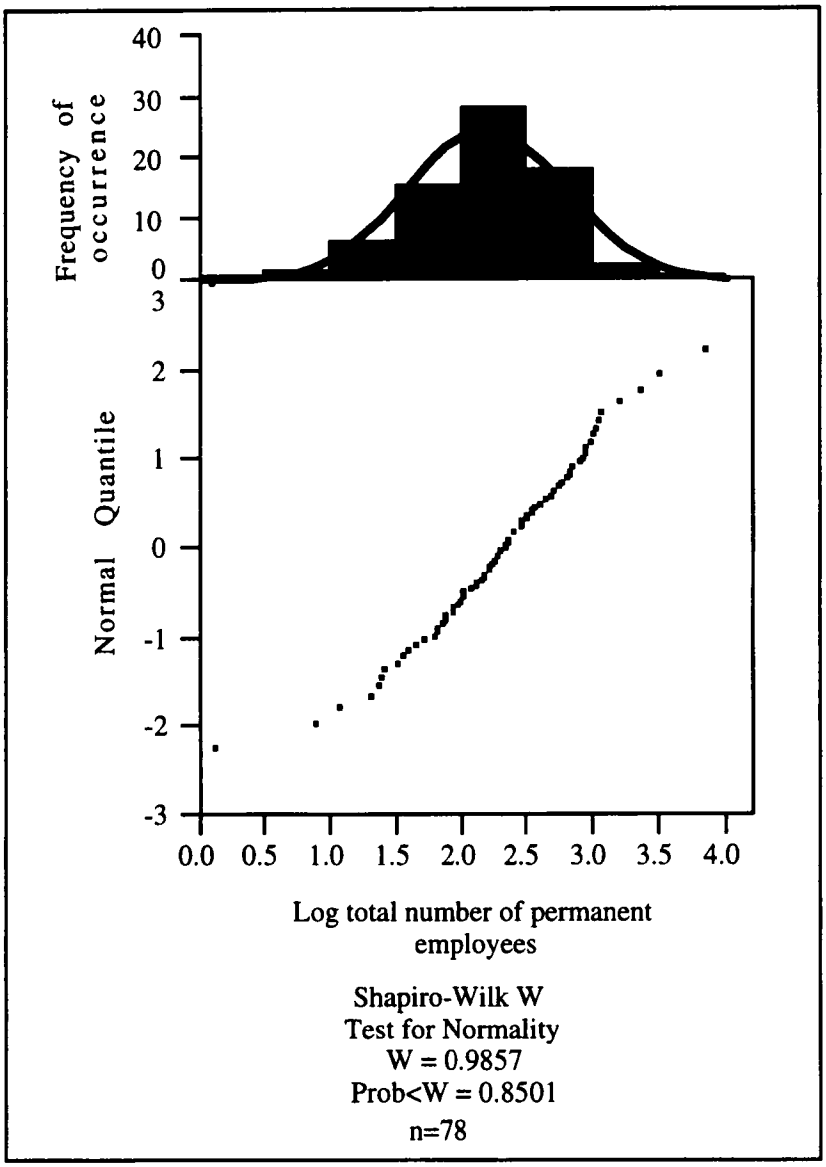

Figure B-3. Log total number of permanent employees for total dataset.

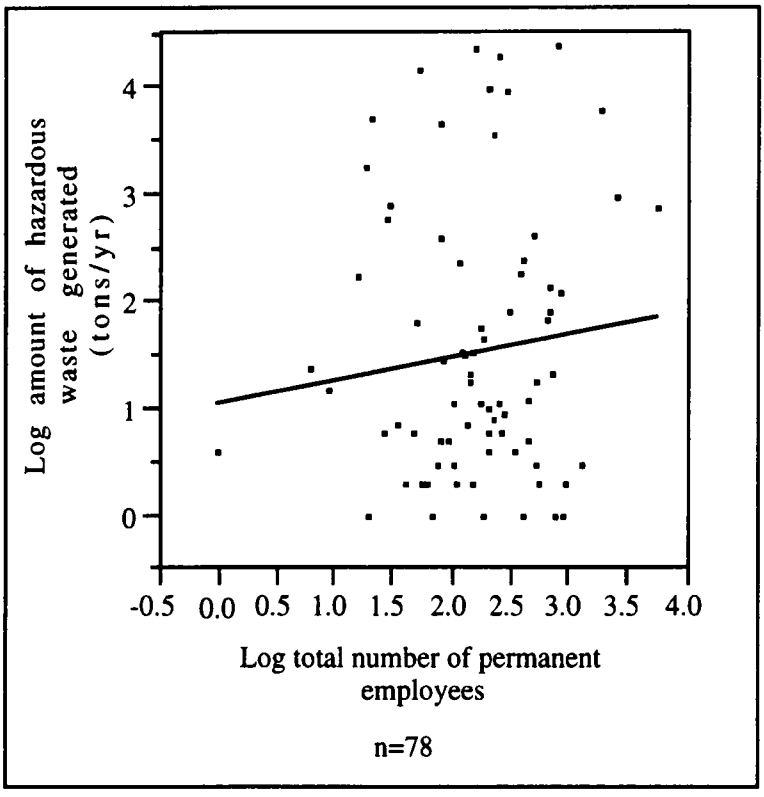

Figure B-4. Log amount of hazardous waste generated versus log total number of permanent employees for the total dataset.

Table B-1. ANOVA Table for Log Amount of Hazardous Waste Generated versus Log Total Number of Permanent Employees for Total Dataset

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob>F	R^2
Model	1	1.317	1.317	0.837	0.363	0.011
Error	76	119.594	1.573			
C Total	77	120.912				

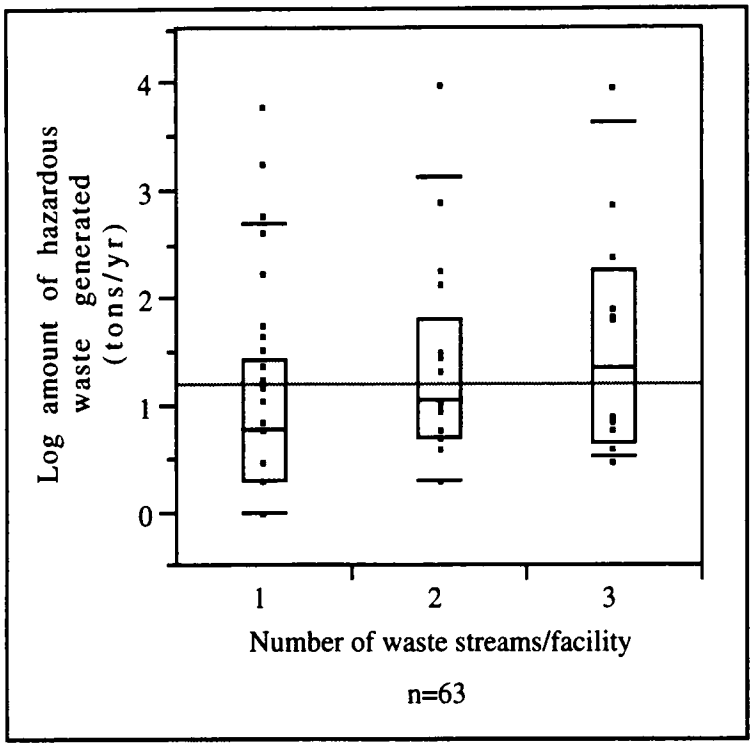

Figure B-5. Log amount of hazardous waste generated versus waste streams/facility for the total dataset.

Table B-2. ANOVA Table for Log Amount of Hazardous Waste Generated versus Waste Streams/Facility for the Total Dataset

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob>F	R^2
Model	2	3.916	1.958	1.934	0.153	0.060
Error	60	60.747	1.012			
C Total	62	64.664				

Table B-3. Average Amount of Hazardous Waste Generated/Waste Stream per Facility for the Total Dataset

No. of waste streams	Reported	log Amount of hazardous waste generated (tons/yr)	Amount of hazardous waste generated (tons/yr)
1	34	0.978	273
2	17	1.371	657
3	12	1.580	859

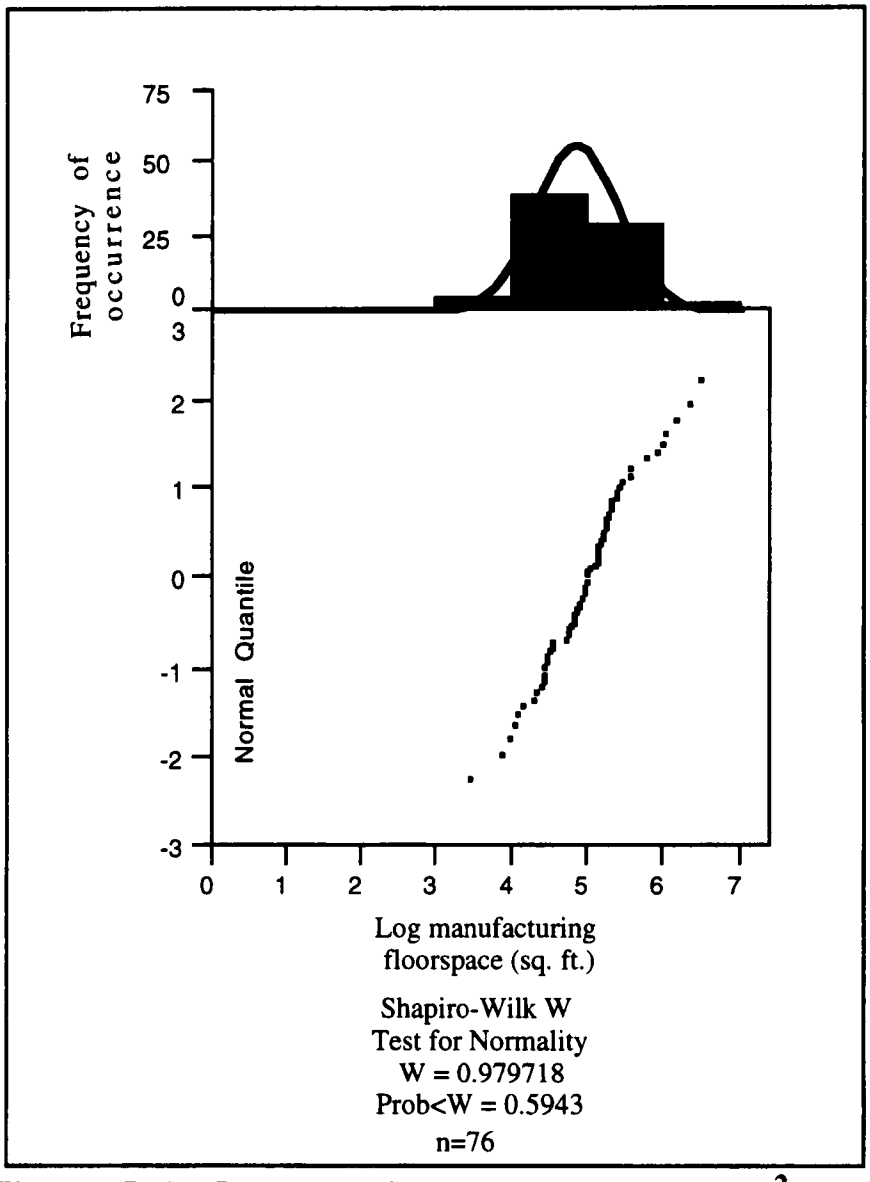

Figure B-6. Log manufacturing floorspace (ft^2) for the total dataset.

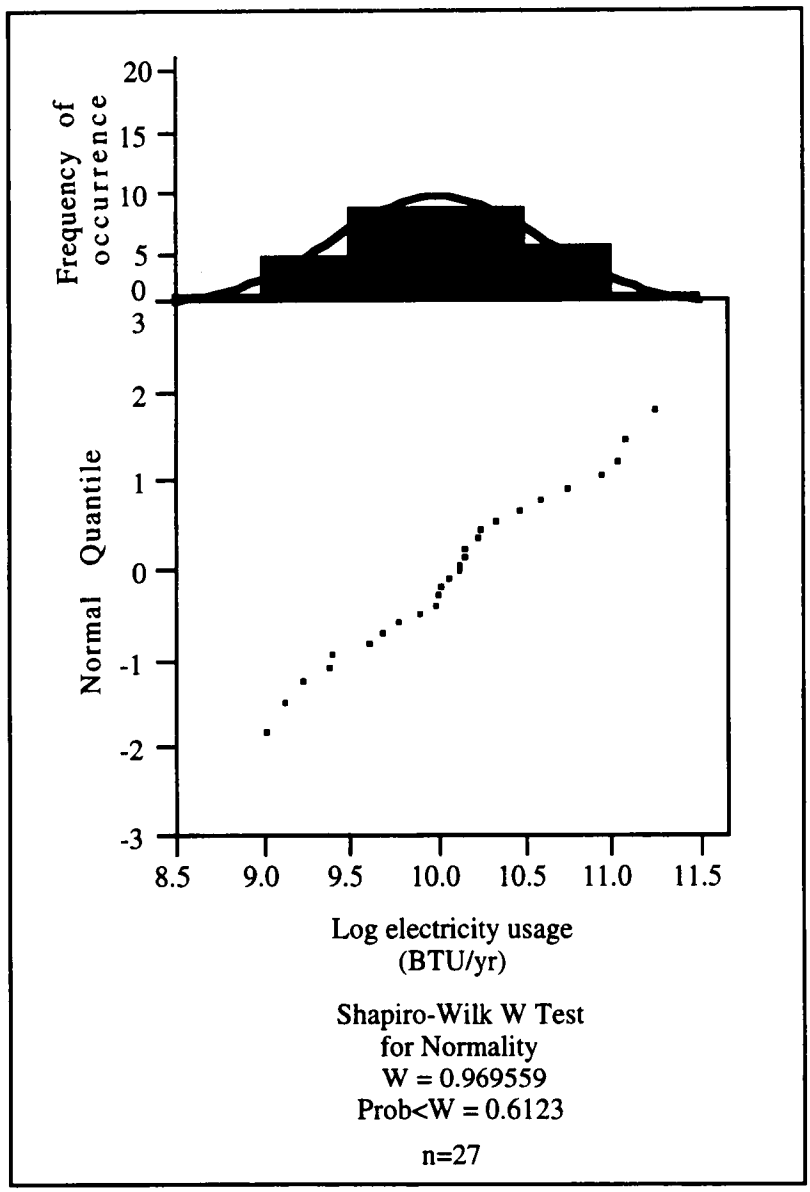

Figure B-7. Log electricity usage (BTU/yr) for SIC 34 respondents.

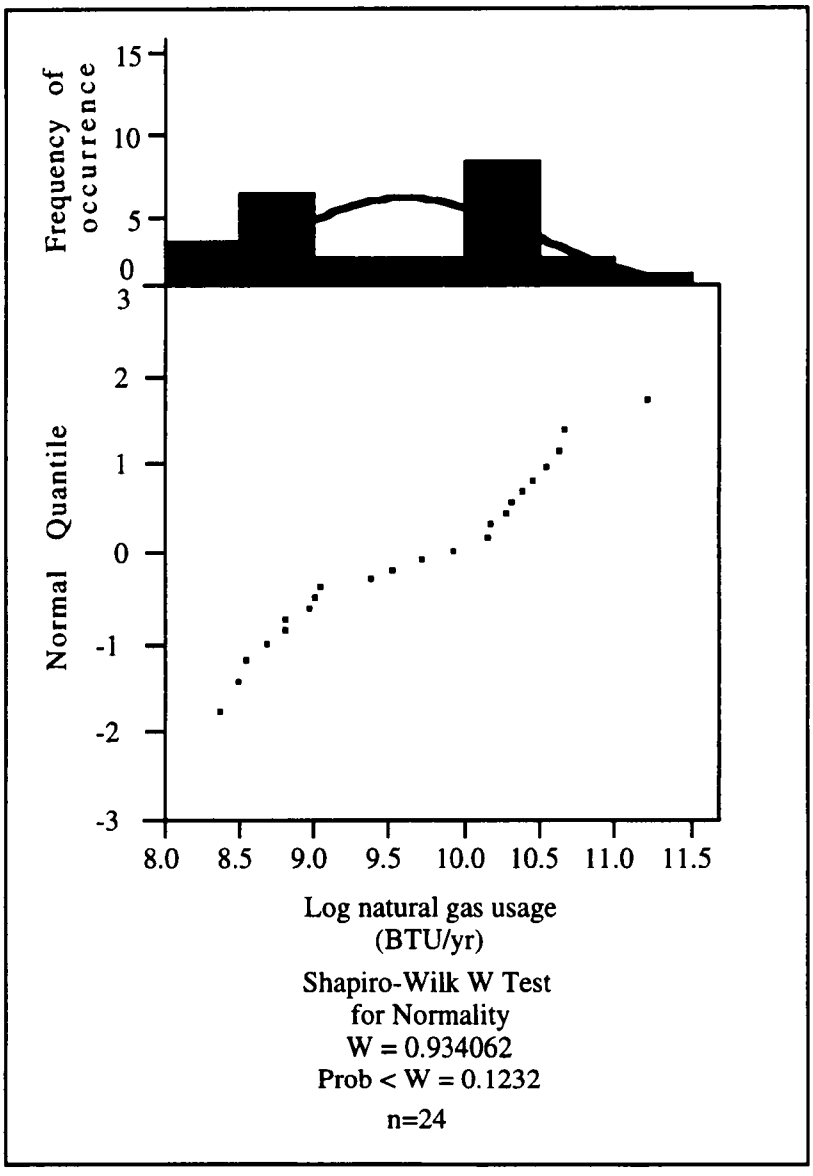

Figure B-8. Log natural gas usage (BTU/yr) for SIC 34 respondents.

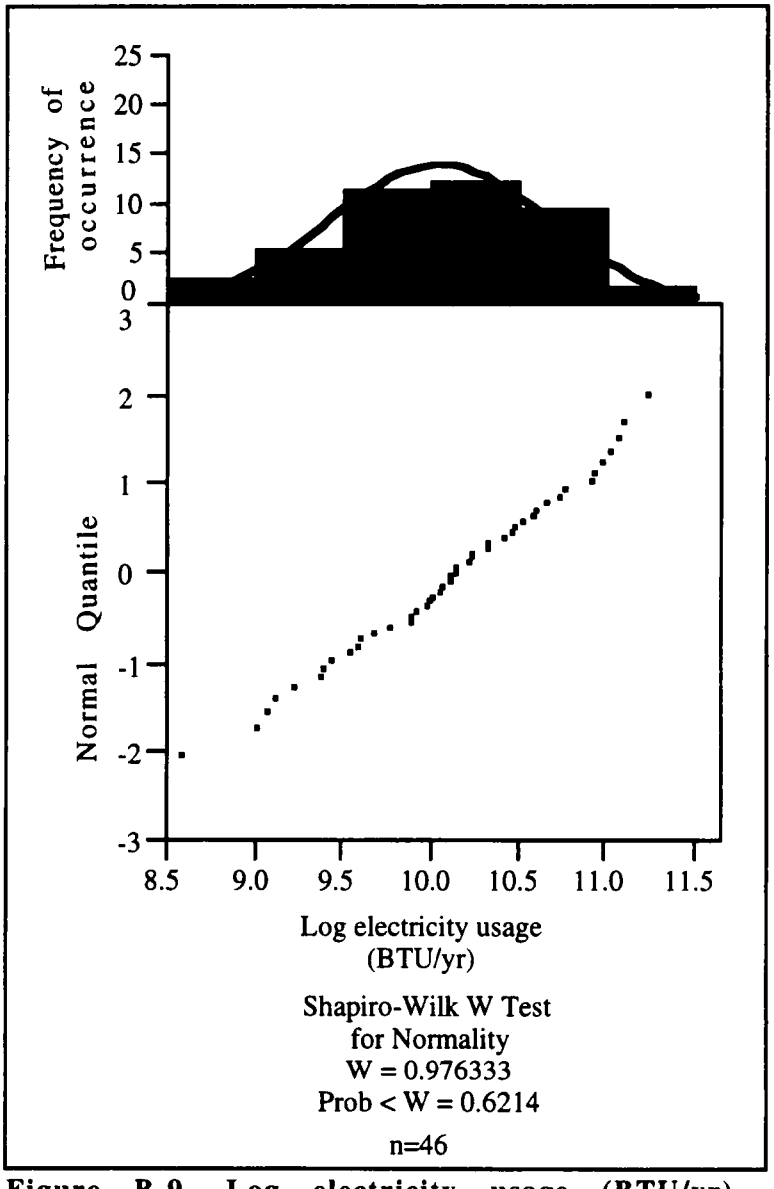

Figure B-9. Log electricity usage (BTU/yr) for the total dataset.

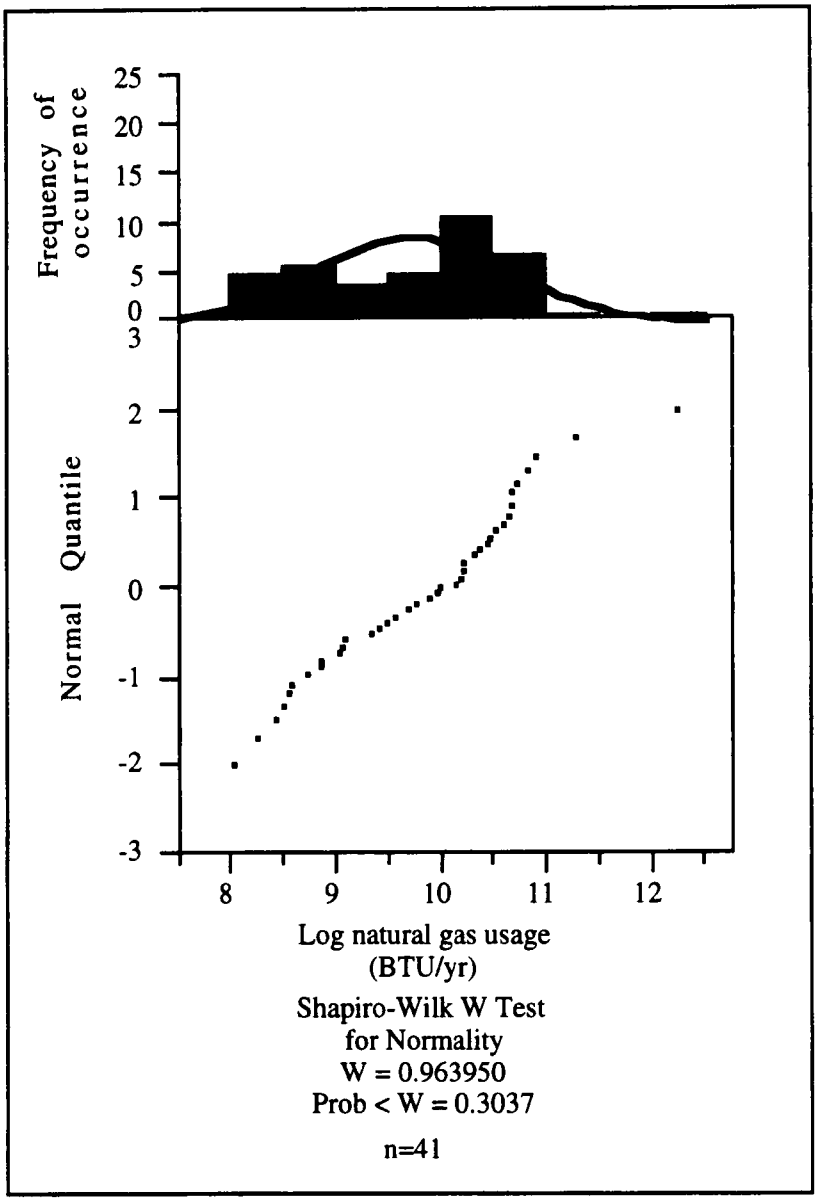

Figure B-10. Log natural gas usage (BTU/yr) for the total dataset.

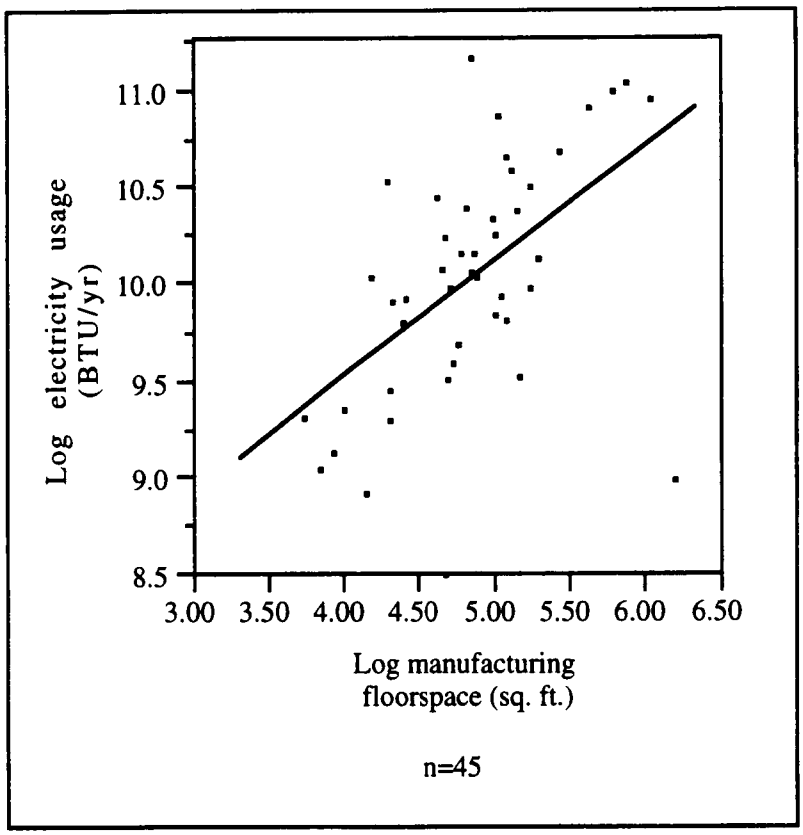

Figure B-11. Log electricity usage (BTU/yr) versus manufacturing floorspace (ft^2) for the total dataset.

Table B-4. ANOVA Table for Log Electricity Usage (BTU/yr) versus Log Manufacturing Floorspace (ft^2) for the Total Dataset

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob>F	R^2
Model	1	4.897	4.897	17.339	0.000	0.287
Error	43	12.146	0.282			
C Total	44	17.044				

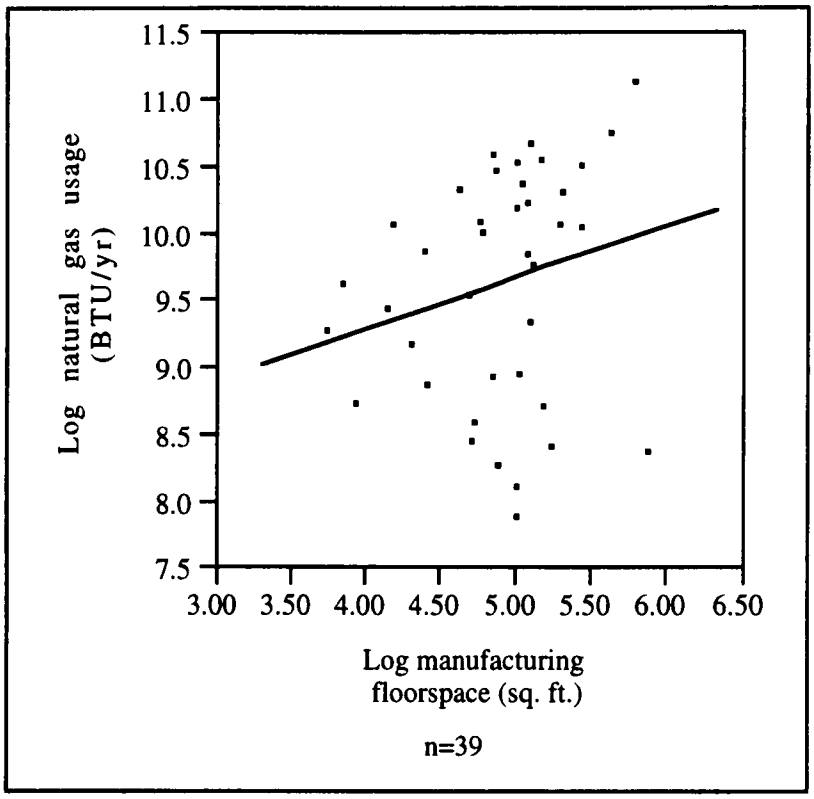

Figure B-12. Log natural gas usage (BTU/yr) versus log manufacturing floorspace (ft^2) for the total dataset.

Table B-5. ANOVA Table for Log Natural Gas Usage (BTU/yr) versus Log Manufacturing Floorspace (ft^2) for the Total Dataset

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob>F	R^2
Model	1	1.349	1.349	1.858	0.181	0.047
Error	37	26.888	0.726			
C Total	38	28.237				

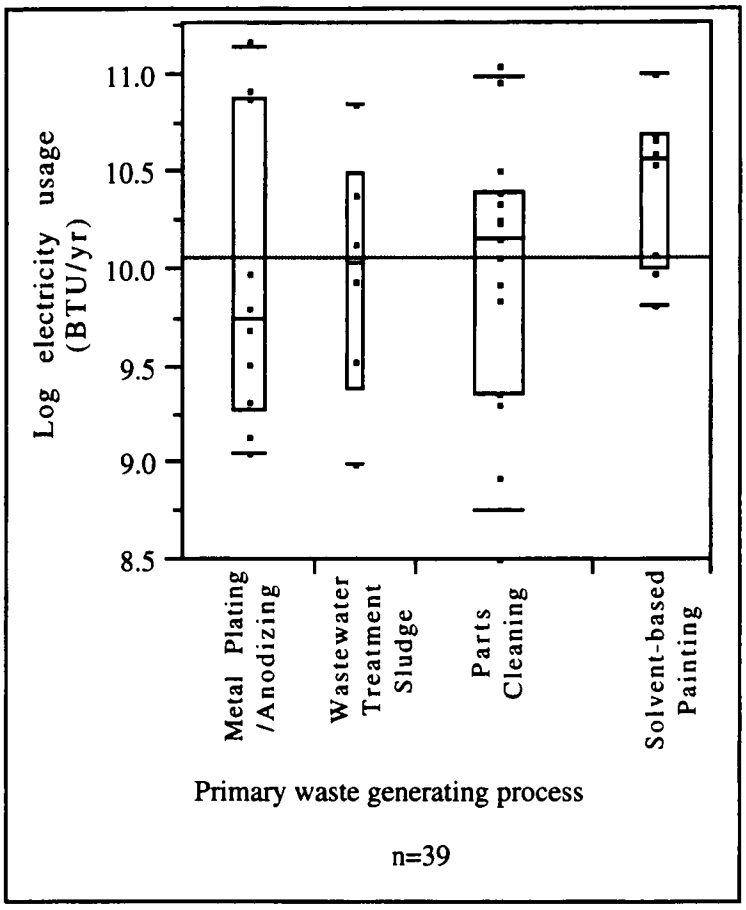

Figure B-13. Log electricity usage (BTU/yr) versus primary waste generating processes for total dataset.

Table B-6. ANOVA Table for Log Electricity Usage (BTU/yr) versus Primary Waste Generating Processes for the Total Dataset

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob>F	R^2
Model	3	1.288	0.429	0.961	0.421	0.076
Error	35	15.644	0.446			
C Total	38	16.933				

Table B-7. Average Electricity Usage (million BTU/yr) for the Primary Waste Generating Processes for the Total Dataset

Process	Number	log average quantity of electricity used	Quantity of electricity used
Metal Plating/Anodizing	10	9.940	32,790
Wastewater Treatment Sludge	6	9.968	19,895
Parts Cleaning	15	9.987	23,819
Solvent-based Painting	8	10.416	36,734

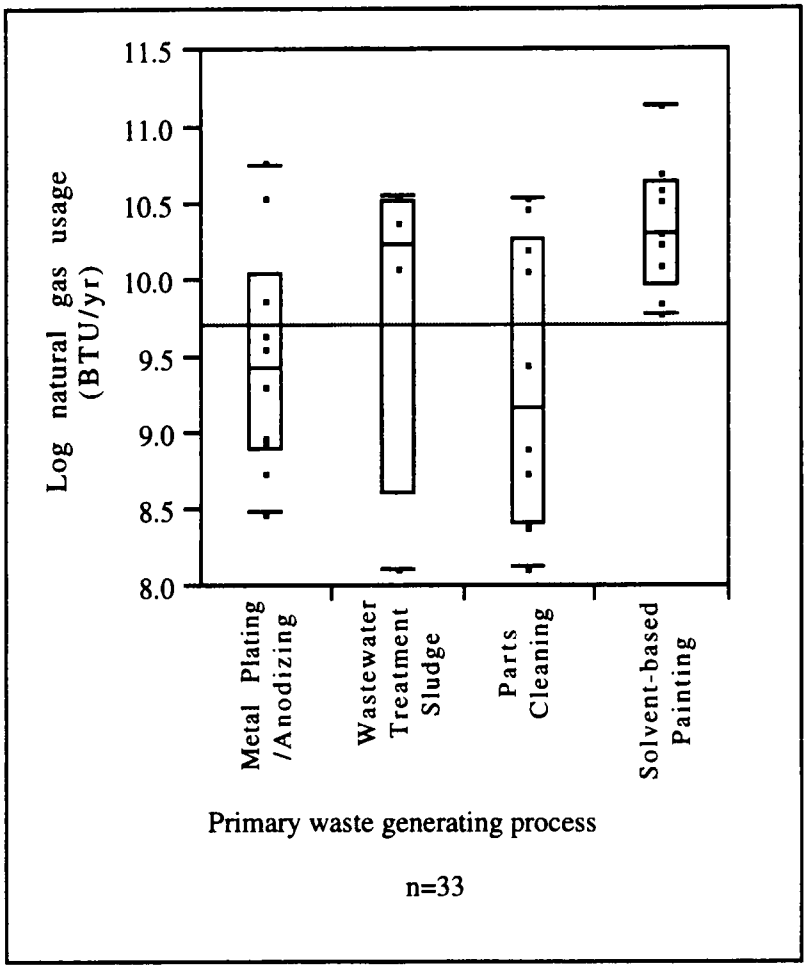

Figure B-14. Log natural gas usage (BTU/yr) versus primary waste generating processes for the total dataset.

Table B-8. ANOVA Table for Log Natural Gas Usage (BTU/yr) versus Primary Waste Generating Processes for the Total Dataset

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob>F	R^2
Model	3	5.821	1.940	3.066	0.044	0.241
Error	29	18.352	0.633			
C Total	32	24.173				

Table B-9. Average Natural Gas Usage (million BTU/yr) for the Primary Waste Generating Processes for the Total Dataset

Primary waste generating process	Number	log average quantity of natural gas used	Average quantity of natural gas used
Metal Plating/Anodizing	10	9.474	11,327
Wastewater Treatment Sludge	4	9.780	17,992
Parts Cleaning	10	9.324	9,627
Solvent-based Painting	9	10.356	36,050

Table B-10. Tukey-Kramer HSD Test for Log Natural Gas Usage (BTU/yr) for the Primary Waste Generating Processes for the Total Dataset

	Solvent-based painting	Wastewater Treatment Sludge	Metal Plating/ Anodizing	Parts Cleaning
Solvent-based painting	-1.022	-0.727	-0.114	0.036
Wastewater Treatment Sludge	-0.727	-1.533	-0.976	-0.826
Metal Plating/Anodizing	-0.114	-0.976	-0.969	-0.819
Parts Cleaning	0.036	-0.826	-0.819	-0.969

Note: Positive values demonstrates pairs of means that are significantly

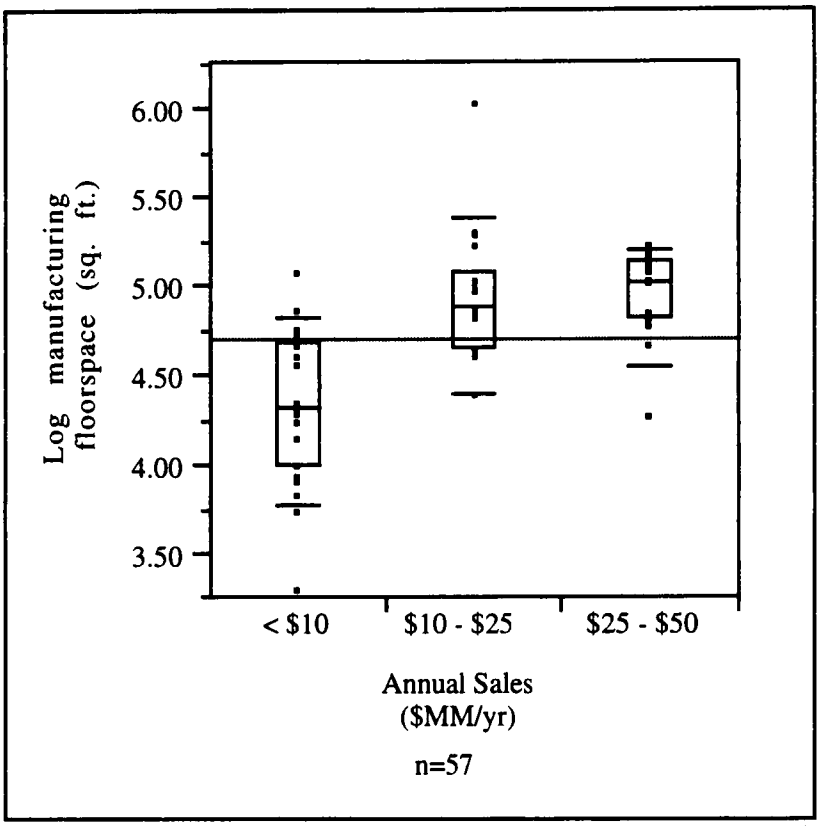

Figure B-15. Log manufacturing floorspace (ft^2) versus annual sales ($million/yr) for the total dataset.

Table B-11. ANOVA Table for Log Manufacturing Floorspace (ft^2) versus Annual Sales ($million/yr) for the Total Dataset

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob>F	R^2
Model	2	5.014	2.507	18.674	0.000	0.408
Error	54	7.249	0.134			
C Total	56	12.263				

Table B-12. Mean of Log Manufacturing Floorspace (ft^2) for the Three Largest Levels of Annual Sales for the Total Dataset

Sales level ($ MM/yr)	Number	Log manufacturing floorspace (ft^2)	Manufacturing floorspace (ft^2)
< 10	23	4.333	30,145
10 - 25	18	4.930	143,472
25 - 50	16	4.946	99,741

Table B-13. Tukey-Kramer HSD Test for Average Log Manufacturing Area (ft^2) for the Three Largest Levels of Annual Sales ($million/yr) for the Total Dataset

	$25 - $50	$10 - $25	< $10
$25 - $50	-0.312	-0.288	0.325
$10 - $25	-0.288	-0.294	0.319
< $10	0.325	0.319	-0.260

Note: Positive values demonstrates pairs of means that are significantly different.

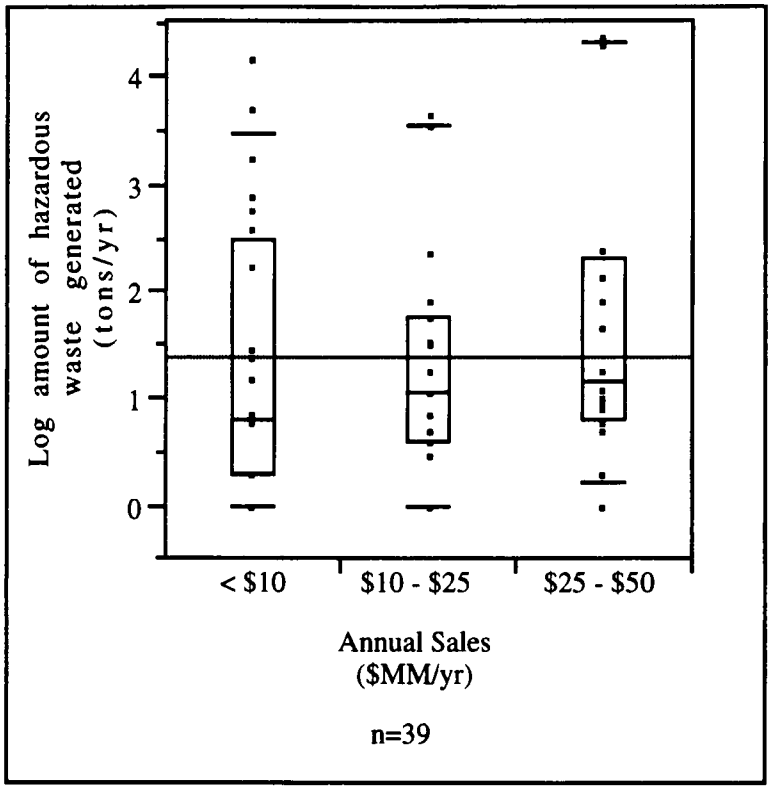

Figure B-16. Log amount of hazardous waste generated (tons/yr) versus annual sales ($million/yr) for the total dataset.

Table B-14. ANOVA Table for Log Amount of Hazardous Waste Generated (tons/yr) versus Annual Sales ($million/yr) for the Total Dataset.

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob>F	R^2
Model	2	1.311	0.655	0.457	0.636	0.016
Error	56	80.332	1.435			
C Total	58	81.643				

Table B-15. Mean of Log Amount of Hazardous Waste Generated (tons/yr) for the Three Largest Levels of Annual Sales for the Total Dataset

Sales level ($ million/yr)	Number	log average amount of hazardous waste generated (tons/yr)	Amount of hazardous waste generated (tons/yr)
< 10	24	1.312	975
10 - 25	19	1.283	456
25 - 50	16	1.633	2,744

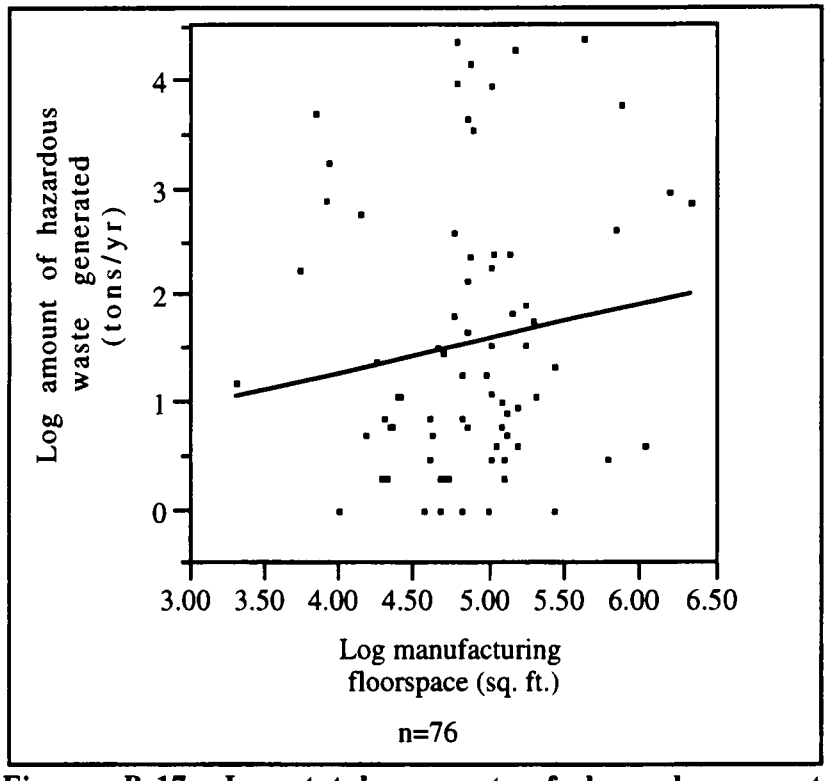

Figure B-17. Log total amount of hazardous waste generated (tons/yr) versus log manufacturing floorspace (ft^2) for the total dataset.

Table B-16. ANOVA Table for Log Total Amount of Hazardous Waste Generated (tons/yr) versus Log Manufacturing Floorspace (ft^2) for the Total Dataset

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob>F	R^2
Model	1	2.394	2.394	1.521	0.221	0.020
Error	74	116.487	1.574			
C Total	75	118.881				

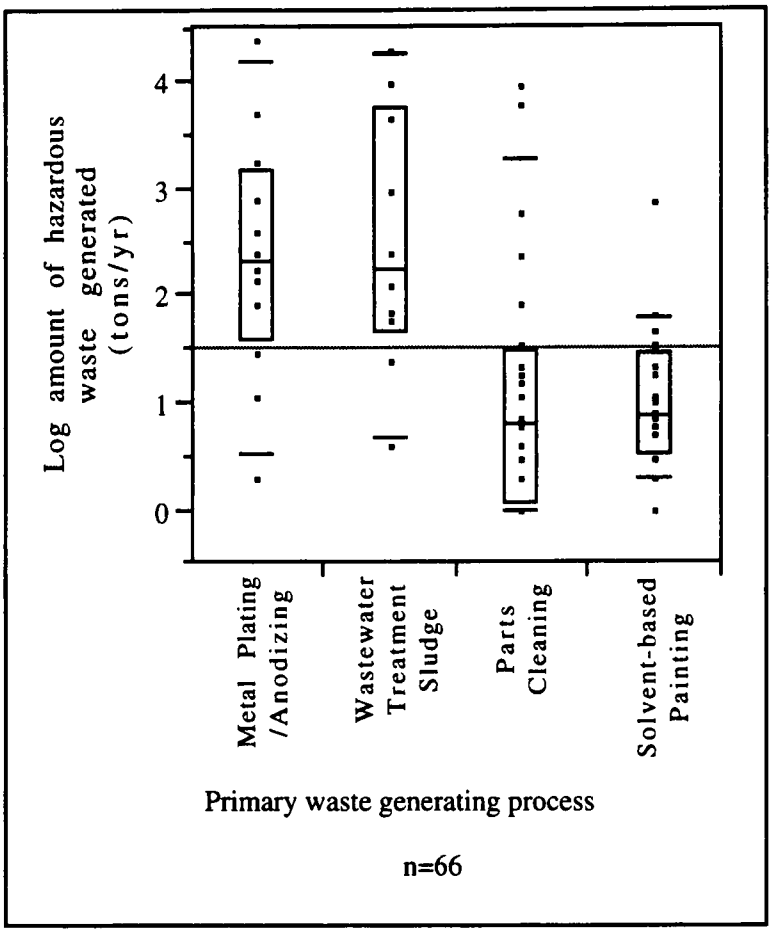

Figure B-18. Log total amount of hazardous waste generated (tons/yr) versus primary waste generating processes for the total dataset.

Table B-17. ANOVA Table for Log Total Amount of Hazardous Waste Generated (tons/yr) versus Primary Waste Generating Processes for the Total Dataset

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob>F	R^2
Model	3	27.692	9.231	8.718	0.000	0.297
Error	62	65.643	1.059			
C Total	65	93.335				

Table B-18. Mean of Log Amount of Hazardous Waste Generated (tons/yr) for the Primary Waste Generating Processes for the Total Dataset

Primary waste generating process	Number reported	Log average amount of hazardous waste generated (tons/yr)	Average amount of hazardous waste generated (tons/yr)
Metal Plating/Anodizing	12	2.360	2,755
Wastewater Treatment Sludge	10	2.496	3,358
Parts Cleaning	24	1.087	674
Solvent-based Painting	20	1.009	52

Table B-19. Tukey-Kramer HSD test for Log Amount of Hazardous Waste Generated (tons/yr) for the Primary Waste Generating Processes for the Total Dataset

	Wastewater Treatment Sludge	Metal Plating /Anodizing	Parts Cleaning	Solvent-based painting
Wastewater Treatment Sludge	-1.215	-1.028	0.386	0.435
Metal Plating/Anodizing	-1.028	-1.109	0.312	0.359
Parts Cleaning	0.386	0.312	-0.784	-0.744
Solvent-based Painting	0.43451	0.35904	-0.74415	-0.85905

Note: Positive values show pairs of means that are significantly different.

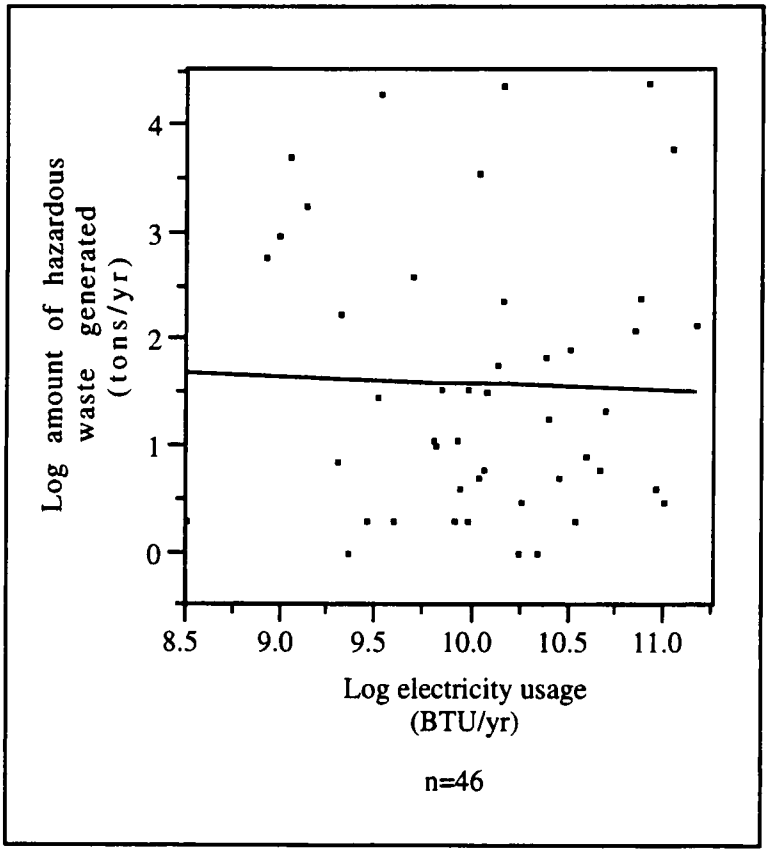

Figure B-19. Log amount of hazardous waste generated (tons/yr) versus log electricity consumption (BTU/yr) for the total dataset.

Table B-20. ANOVA Table for Amount of Hazardous Waste Generated (tons/yr) versus Electricity Consumption for the Total Dataset

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob>F	R^2
Model	1	0.076	0.076	0.046	0.831	0.001
Error	44	72.429	1.646			
C Total	45	72.504				

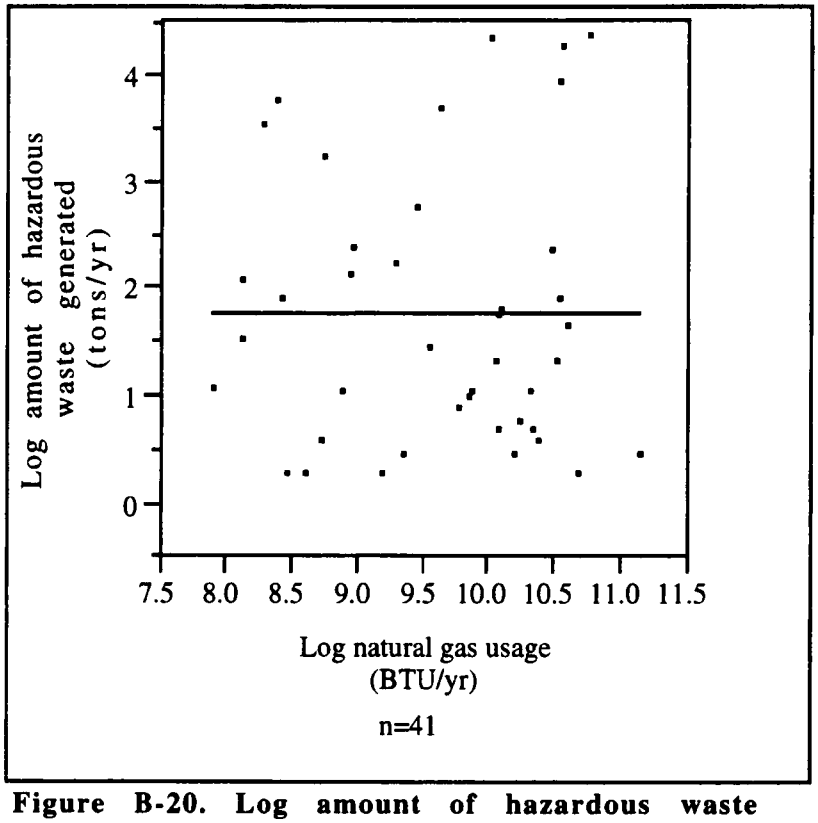

Figure B-20. Log amount of hazardous waste generated (tons/yr) versus natural gas usage (BTU/yr) for the total dataset.

Table B-21. ANOVA Table for Log Amount of Hazardous Waste Generated (tons/yr) versus Natural Gas Usage (BTU/yr) for the Total Dataset

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob>F	R^2
Model	1	0.001	0.001	0.000	0.978	0.000
Error	39	63.769	1.635			
C Total	40	63.770				

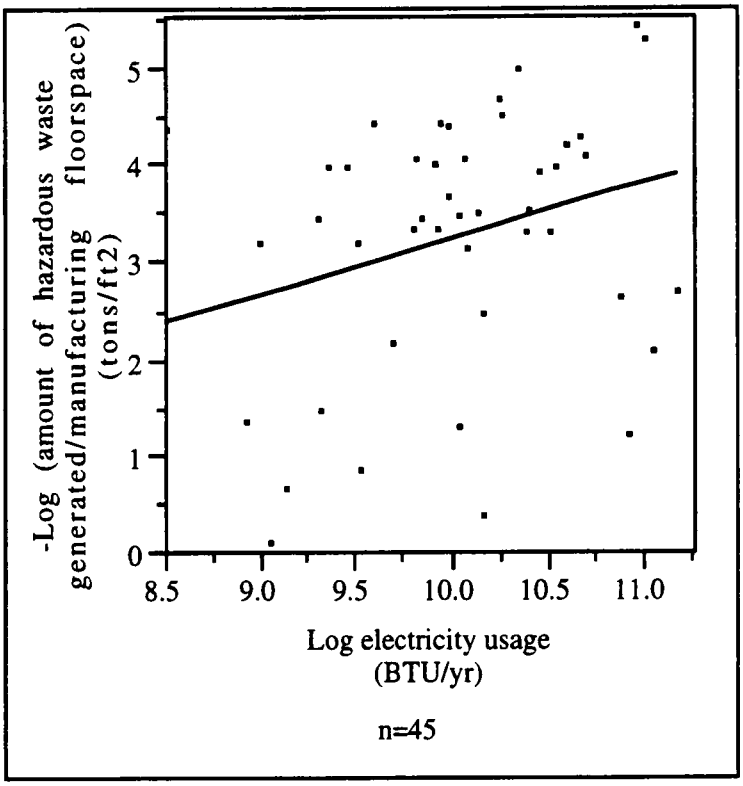

Figure B-21. -Log (amount of hazardous waste generated/manufacturing floorspace) (tons/ft^2) versus log electricity usage (BTU/yr) for the total dataset.

Table B-22. ANOVA Table for -Log (Amount of Hazardous Waste Generated/Manufacturing Floorspace) (tons/ft^2) versus Log Electricity Usage (BTU/yr) for the Total Dataset

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob>F	R^2
Model	1	5.565	5.565	3.375	0.073	0.073
Error	43	70.895	1.649			
C Total	44	76.460				

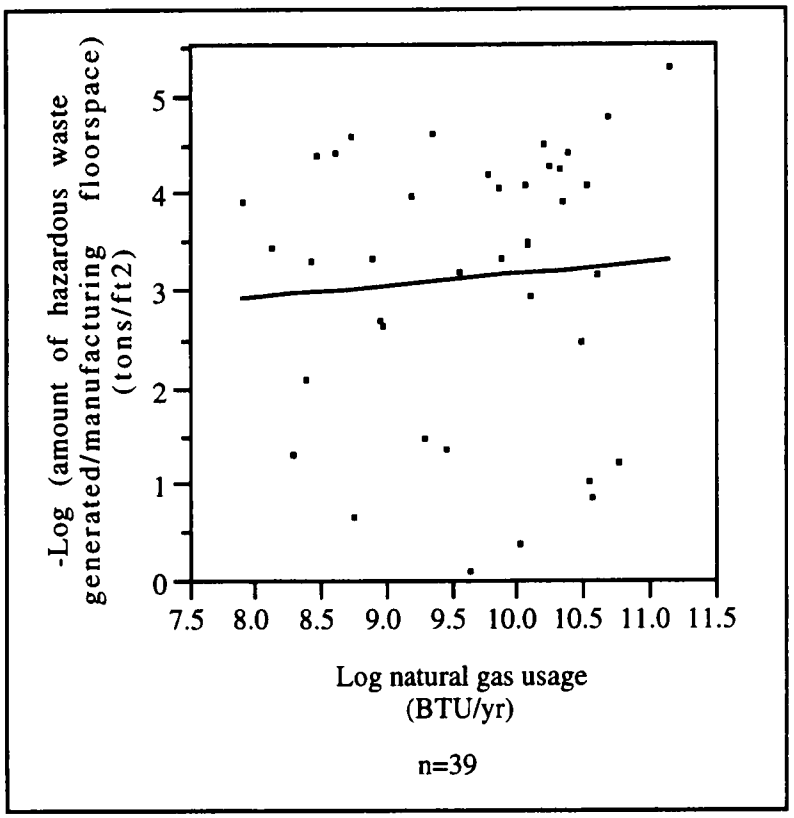

Figure B-22. -Log (amount of hazardous waste generated/manufacturing floorspace) (tons/ft^2) versus log natural gas usage (BTU/yr) for the total dataset.

Table B-23. ANOVA Table for -Log (Amount of Hazardous Waste Generated/Manufacturing Floorspace) (tons/ft^2) versus Log Natural Gas Usage (BTU/yr) for the Total Dataset

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob>F	R^2
Model	1	0.405	0.405	0.203	0.655	0.005
Error	37	73.857	1.996			
C Total	38	74.261				

VITA

Todd Mitchell Thomas was born on September 16, 1966, in Asheville, North Carolina. After graduating high school in 1984 from Dobyns-Bennett in Kingsport, TN, he attended Tennessee Technological University where he received a Bachelor of Science degree in Industrial Engineering in 1989. After approximately two years of professional work, he began full-time pursuit of a Master of Science in Engineering at the University of Tennessee specializing in industrial pollution prevention. To this end, while in school Mr. Thomas was a graduate research assistant and worked in both the Waste Minimization Assessment Center, and the Energy Analysis and Diagnostic Center. In his work, he performed numerous pollution prevention audits and participated on several EPA supported projects Upon graduation in December 1994, he will begin work as a Waste Reduction Engineer for The University of Tennessee's Center for Industrial Services.