A Statistical Approach Linking Energy Management To Maintenance and Production Factors

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ABSTRACT

This research has addressed a quantitative approach for improving energy management through applying statistical techniques aimed at identifying and controlling factors linked to energy consumption rates at manufacturing plants. The paper presents analysis and results of multiple linear regression models used to establish the significance of a number of energy related management factors in controlling energy usage. Regression models constructed for this purpose proved the existence of statistically valid relationships between electrical energy consumption and maintenance and production management factors, namely, failure rate and production rate, where R^2 values of the magnitude of 65% were obtained. Furthermore, an economical treatment based on the derived regression models was formulated and demonstrated that effective management practices associated with proper maintenance, cost accounting and reporting systems can result in highly significant savings in energy usage.

Practical Implications

The results of this study represented a real-life example of using quantitative analysis techniques for controlling and improving energy consumption rates in an actual manufacturing setup using data collected from live records. One of the most important factors that were found to impact energy consumption in energy-intensive plants was the failure rate of production equipment. Repetitive failures of production machines lead to increased machine warming and re-startup energy, thus increasing energy consumed per unit of production. Since machine failure rates are highly dependent on the quality of the maintenance system in general, this study has uncovered a clear linkage between maintenance quality and energy consumption rates. In this context, maintenance policies should be designed based on, among other factors, energy consumption and energy costs. By using accurate cost data of related cost elements involved in a manufacturing system, production and maintenance managers will be able to set an “optimum” level of production line availability that minimizes the overall maintenance and energy consumption costs.

Introduction

Healthy economic development leads to more industrial production and exploration of energy resources as increasing levels of industrialization results in higher levels of energy consumption. However, most energy resources are limited and may cause environmental pollution. Therefore, to overcome this problem, a trend towards reducing energy consumption for the same industrial output and thus achieving same or even better economic return has been under extensive research and exploration. This trend is called increasing the efficiency of energy use or rational use of energy as it involves energy management. This research deals with improving energy management methodologies through examining the impact of energy-related factors that can be used to improve energy consumption rates in manufacturing plants.

The motivation behind this research lies in the fact that energy costs represent a significant portion of the overall production costs and thus have a detrimental impact on product prices and marketability. Energy costs range from 2% of production costs as in electronics and printing industries, to 35% as in iron and aluminum industries, and can even reach 65% of production costs as in oil refineries and similar industries [1]. Since energy represents a purely variable or semi-variable cost item, energy management has gained increased importance even if the cost share of energy is only 2% to 3%, as the share of energy within the variable costs category can reach 50% or more, and therefore, energy becomes a controllable factor hat has a significant effect on the expenses of businesses.

Improving energy management and realizing savings in industry may be achieved on several scales depending on strategies upon which managers can act [2]. First, energy can be saved with no additional investments, mainly by acting management initiatives to improve manpower competencies and management systems and practices. Second, medium-level investments can be made to modify certain processes within the framework of the given technology 'state of the art' of the manufacturing plant. Third, energy can be dramatically saved through a complete overhaul of the production system technologies; a scheme that must be carefully studied and economically justified.

Following the first energy management strategy, this research provides a quantitative approach for improving energy consumption rates that can realize energy savings with no extra-ordinary investments. The importance of this purely management approach for improving energy usage stems from that fact this method mostly depends on appropriate management practices, good cost accounting and reporting systems, and effective feedback and decision making with no major investments. Under this energy improvement scheme, reported energy savings in the magnitude of 15% to 20% can be realized [2].

Across these main energy usage improvement tracks, research in energy management and conservation has witnessed international attention and proliferated especially after the oil crises in early seventies when governments around the world encouraged research activities that aim at optimizing energy usage [1]. Vast amounts of literature exist that deal with so many different aspects of energy and its rational use especially in energy intensive manufacturing plants, in which authors investigated energy efficiency indicators, comparisons, and policies across industrial sectors and across countries, for example [3,4,5,6,7]. While others have focused on the development of economic and mathematical models relating physical process parameters to generate optimal operation points of production equipment and energy generating plants, for example [8,9].

Review of the literature has indicated that most research activities have focused on examinations and analyses of energy factors that are directly related to energy consumption or generation. This research paper is concerned with a methodology for improving energy management through examining and controlling factors that are indirectly related to energy consumption in manufacturing facilities. These factors belong to maintenance and production management and therefore can be improved through low-cost management improvement initiatives.

This research article aims exploring the use of statistical linear regression methodology for improving energy management techniques at energy-intensive manufacturing plants through identifying, validating, and controlling statistically significant control factors that can influence energy consumption rates. Besides, the use of statistically significant regression models to formulate an economic treatment has been presented; such a model can be used to demonstrate the economic impact of improving control factors of energy consumption. As a result, this paper concludes by a set of recommendation for effectiveness management practices that will lead to energy savings.

General Methodology

The research was based on the posture that relationships do exist between energy consumption, on one hand, and other management variables relating to maintenance and production on the other hand. As such, the construction of statistical models like linear regression can serve as a vehicle to verify or otherwise refute the presence of relationships between interacting variables. Therefore, the technical approach adopted here consisted of three major steps. First, multiple linear regression models were constructed that represented anticipated relationships between energy consumption and related control variables. These models were then tested for validity and adequacy using statistical tools such a hypothesis testing, ANOVA analysis, and coefficient of determination, R^2. Finally, based on derived regression models, an economic treatment was derived that reflected the economic implications of investments in improving energy consumption.

This methodology was applied to and tested using data pertaining to an aluminum profile manufacturing plant in West Bank; in particular, data pertaining to powder coating and extrusion production lines were used as test beds.

Formulation of Multiple Linear Regression Models

Linear Regression

Linear regression analysis is a statistical tool used by researchers when investigating relationships of a behavioral or economic nature [10]. In other words, it can be used to examine sample data and draw conclusions about the functional relationships that exist among variables, whereby such relationships are expressed in a form of mathematical functions that demonstrate how the variables are interrelated.

In multiple linear regression, a response variable (Y) is related to a set of control variables using the following linear model:

$$Y= \hat{a}_0+ \hat{a}_1X_1 + \hat{a}_2X_2 + \hat{a}_3X_3+\ldots..+ \hat{a}_kX_k + \varepsilon$$

Where Y is a linear function of *k* control variables $X_1, \ldots, X_k$, and ε is an error term.
The construction of a multiple linear regression model essentially requires the estimation of the parameters $\hat{a}_0$, $\hat{a}_1$, $\hat{a}_2$, $\hat{a}_3$, …. $\hat{\imath}_k$ of the model. Using sample data representing variables, model parameters can be estimated using the coefficients b_0, b_1,…b_k of the regression equation associating response variable ($\hat{Y}$) with its control variables $X_1, \ldots, X_k$:

$$\hat{Y}= b_0+ b_1X_1 + b_2X_2 + b_3X_3+\ldots..+ b_kX_k$$

Variables Selection

The major focus in this research was on empirical investigation of the relationships between electrical energy consumption (EC) and a set of energy control variables. In this study, the latter set of variables included *failure rate and production rate* as independent variables. The specific definitions and units of measurements of these variables were defined as given below.

- <u>Failure Rate (FR):</u> It represented stoppages of the production line that occur as a result of electrical, mechanical, or production failures. This factor is measured by the number of failures or stoppages per month. These stoppages essentially included breakdowns only and not planned stoppages.
- <u>Production Rate (PR):</u> It is measured by the amount of aluminum produced and given in units of tons/month.
- <u>Electricity Energy Consumption (EC):</u> It is measured in kWh per ton of aluminum production. It is computed as the gross volume of production in tons divided the consumed electricity in kWh.

The above factors were selected as control variables impacting energy consumption based on two criteria. The first was the presence of physical or logical influence of these factors on energy consumption rate. For example, as number of breakdown increases, energy consumption per ton would increase as a result of the extra energy requirements for production startups. Similarly, it is predicted that as production rates in tons/unit time are changed, it is logically sound to conclude that energy consumption rate in kWh/ton would change accordingly. Second, these control variables were selected based on the experience and understanding of the researcher and the judgment of a number of plant managers of selected energy intensive industries such as aluminum and stone cutting industries. Furthermore, to justify the presence of such informative relationships between these factors, scatter diagrams were used which clearly indicated the validity of initial selection of control variables.

Models Assumptions

The following assumptions were made:

1. Based on preliminary analysis of data and scatter diagrams, it was decided to use “first order model” for data modeling implying that multiple linear regression models were derived.
2. The control variables selected that influence energy consumption were not intercorrelated among themselves implying that multicollinearity was not present.
3. The random errors (ε) were independent (i.e., uncorrelated) and *normally* distributed with constant variance and zero mean.

The above assumptions represented general requirements that should be secured in order to develop multiple linear regression models. The validity of each of these assumptions together with the problem of multicollinearity was tested as shown in the analysis and results section.

Models Formulation

Based on the selected variables above and model assumptions, the following multiple linear regression models were constructed for the two selected production lines, namely, the powder coating and extrusion production lines.

Model I: Powder Coating Production Line

$$E\,(EC_p|\ FR, PR) = b_{0p} + b_{1p}FR + b_{2p}PR \qquad \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Model II: Extrusion Production Line

$$E\,(EC_x|\ FR, PR) = b_{0x} + b_{1x}FR + b_{2x}PR \qquad \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Where model coefficients were defined as:
b_{0p} = intercept of model I (powder coating line)
b_{1p} = regression coefficient associated with failure rate of model I
b_{2p} = regression coefficient associated with production rate of Model I
b_{0x} = intercept of Model II (extrusion line)
b_{1x} = regression coefficient associated with failure rate of Model II
b_{2x} = regression coefficient associated with production rate of Model II
$E\,(EC_p|\ FR, PR)$ is the *expected value* of Electricity Consumption per ton of powder-coated aluminum output given the independent variables FR and PR.
$E\,(EC_x|\ FR, PR)$ is the *expected value* of Electricity Consumption per ton of extruded aluminum output given the independent variables FR and PR.

Statistical Tests on Regression Model Parameters

To test each model formulated above, the researcher has considered the following hypotheses. Hypothesis I addressed the validity of the presence of a relationship between energy consumption and control variables, and hypotheses II were concerned with identifying which of the control variables was actually significant in explaining the variations of the energy consumption.

Hypothesis I: Testing Model Validity

Model I Hypothesis (Powder Coating)

H_0: $b_{jp} = 0$ for $j = 1,2$
H_1: at least one $b_{jp} \neq 0$

Model II Hypothesis (Extrusion)

H_0: $b_{jx} = 0$ for $j = 1,2$
H_1: at least one $b_{jx} \neq 0$

These hypotheses were intended to test validity of the presence of a relation between energy consumption and any of the independent variables. If the null hypothesis could be rejected, then one would conclude that there were some independent variables that do actually affect electrical energy consumption.

Hypotheses II: Individual Testing of Coefficients of the Multiple Linear Regression Models

Hypothesis II (a): Failure Rate (FR)

H_0: $b_{1p} = 0$ vs. H_1: $b_{1p} \neq 0$ (Model I) and H_0: $b_{1x} = 0$ vs. H_1: $b_{1x} \neq 0$ (Model II)

The null hypotheses assumed that there was no statistically significant relationship between electricity consumption and failure rate (FR).

Hypothesis II (b): Production Rate (PR)

H_0: $b_{2p} = 0$ vs. H_1: $b_{2p} \neq 0$ (Model I) and H_0: $b_{2x} = 0$ vs. H_1: $b_{2x} \neq 0$ (Model II)

The null hypotheses assumed that there was no statistically significant relationship between electricity consumption and production rate (PR).

Results of the Statistical Analysis

Used Datasets

Dataset used in this study were taken from powder coating and extrusion production lines. Monthly historical data on energy consumption and related control variables were collected from various relevant accounting and production records and it covered an investigation period of about 3 years (1998-2000).

Multiple Linear Regression Report

The SPSS (version 8.0) software system was used to analyse obtained data and perform the required tests, and the obtained regression reports provided the following tests and analyses:

1. Analysis of variance (ANOVA) to test overall model validity and gives sum of squares, degree of freedom, F-ratios, and its probability level.
2. The regression equation section of t-tests to estimate regression coefficients, standard errors, t-values, probability level, and the value R^2.
3. Multicollinearity test section to estimate conditional indices and variance inflation factors (VIF).
4. Durbin-Watson test to examine independence of error terms, and residuals' statistics to show normality of error distribution.

Results and Interpretations

Extrusion Production Line Model

The ANOVA analysis in the regression report, shown in Table 1 below, gave a computed value for the F-ratio of 27.85 while the corresponding table value of 3.34 at 0.05 level of significance (ل) and (2,28) degrees of freedom showed that the multiple linear regression was significant and valid. The R^2 value reached 0.666, thus indicating that the regression was 'strong' as about 67% of the variation in electrical energy consumption could be explained by the control variables. The coefficients b_o, b_1, and b_2 were 508.86, 33.38, and -0.70, respectively; and the results of the ***t*** test indicated that regression coefficients b_1 and b_2 were statistically significant and not equal to zero (as given by hypotheses II) at 0.05 level of significance and 28 degrees of freedom (table t value = $t_{.025,28}$=2.048). Therefore, the regression equation of electrical energy in kWh/ton consumed by the extrusion production line can be given by:

$$E\ (EC_x|\ FR, PR) = 508.86 + 33.38\ FR - 0.70\ PR \quad \ldots\ldots\ldots\ldots\ldots\ldots(3)$$

It should be noted that the assumptions made were valid for this model with respect to multicollinearity and residuals' distribution. As seen from analysis, the Durbin-Watson computed test value was 1.873 while the table value is 1.66 implying that residuals were actually independent, and furthermore, the residuals' average was zero with standard deviation of approximately 1.0. The variance inflation factor VIF of 1.696 indicated that multicollinearity was not a problem in this application (i.e., VIF<4) [10] that clearly demonstrated that production rate and failure rate were not significantly interacting factors.

Table 1: Summary Analysis Results of the Extrusion Production Line Model (ل =0.05)

Analysis Item	**FR**	**PR**	**R^2**	**Significance**	
Model Summary	33.38	-0.705	0.666	< 0.01	
	Computed F value		**Table F value**		**Significance**
ANOVA Summary	27.85		3.34		0.000
	1. Multicollinearity Test (interaction) using:			**2. Residuals Test Using:**	
Testing Assumptions	Variance Inflation Factor (VIF) 1.67			Durbin-Watson Factor 1.873	

<u>Powder Coating Production Line Model</u>

As shown in Table 2, a computed value for the F-ratio of 17.33 was obtained and the corresponding table value of 3.34 at 0.05 level of significance (ل) and (2,28) degrees of freedom implied that the multiple linear regression model was again significant and valid. The R^2 value was 0.553, thus indicating that the regression was also moderately 'strong' as more than 55% of the variation in electrical energy consumption could be explained by the production rate and failure rate control variables. The coefficients b_o, b_1, and b_2 took the values 305.10, 26.45, and -1.17, respectively; and the results of the ***t*** test indicated that regression coefficients b_1 and b_2 were statistically significant. Therefore, the regression equation of electrical energy in kWh/ton consumed by the powder coating production line could be given by:

$$E\ (EC_p|\ FR, PR) = 305.10 + 26.45\ FR - 1.179\ PR \quad \ldots\ldots\ldots\ldots\ldots\ldots(4)$$

Again the assumptions made earlier were valid since the Durbin-Watson computed test value was 1.32 which was larger than table value of 1.12 implying that residuals were not necessarily dependent, and in addition, the residuals' average was zero with standard deviation approximately equal 1.0. A VIF value of 1.30 implied that multicollinearity was not a problem, thus, indicating again that no interaction between production rate and failure rate was noticed.

Table 2: Summary Analysis Results of the Powder Coating Production Line Model

Analysis Item	**FR**	**PR**	**R^2**	**Significance**	
Model Summary	26.45	-1.179	0.553	< 0.01	
	Computed F value		**Table F value**		**Significance**
ANOVA Summary	17.33		3.34		0.000
	1. Multicollinearity Test (interaction) using:			**2. Residuals Test Using:**	
Testing Assumptions	Variance Inflation Factor (VIF) 1.309			Durbin-Watson Factor 1.320	

One additional observation to emphasize is given in order. As it might appear a misleading result, the coefficient of production rate was negative implying that as production rate increases, energy consumption rate decreases. To explain this result, and as given earlier, production rate is measured in tons/month while energy consumption is measured in kWh/ton of aluminum production which implies that as more tons are produced per month the average kWh/ton will decrease. Indeed, an increase in production volume per month would be due to higher utilization of machine work time, better production scheduling and material handling, improved operators' efficiency, and the like. For steady energy consumption per month, increasing amount of production would necessarily decrease kWh/ton, and thus, a negative coefficient in the energy consumption equation.

Economic Modeling and Analysis

As explained in the introduction section, one strategy for improving energy usage is through management improvement initiatives that aim at decreasing energy consumption rates. This research has established valid relationships between energy consumption rates and factors relevant to maintenance and production management. As such, by virtue of the established statistical equations, the effective management of these factors will result in improving energy consumption rates. For examples, effective preventive maintenance programs, availability of suitable parts, and competencies of maintenance personnel will lead to reducing machine breakdowns and consequently reducing failures rates. Similarly, proper setups of production line and improved production planning will allow increasing production rates and therefore reduce energy consumption per unit production.

The objective of the economic treatment presented below is to formulate a methodology using the empirical equations established earlier, and demonstrate, through an illustrative case study, the economic implications of improving the values of energy control variables. A 'net energy return' formula will be constructed that shows relationship between investments in improving energy control variables, namely, failure rate and production rate, and energy savings.

Economical Model Assumptions

The economic analysis was based on the statistical models developed earlier whereby the following assumptions were made:

1. The equations developed using statistical analyses were directly used as a basis for evaluating the economic implications on energy management caused by the selected control variables. The effects of control variables, Production Rate (PR) and Failure Rate (FR), were assumed and verified independent and are additive.
2. The model was based on evaluating incremental (i.e., per unit) savings in energy usage resulting from incremental improvements in the values of control variables.

3. The model considered gained benefits as a result of improving failure rate and production rate without considering the time-value of investments or the restored opportunity that would have been lost if these factors were not improved.

Economic Model Formulation

The linear regression model derived for the powder coating production line was used as a vehicle to demonstrate the significance of economic analysis. The model is statistically significant and adequate since control variables (i.e., FR and PR) explain more than 55% of energy variations as shown earlier.

Since the coefficients (b_{1p}=26.45, b_2p=-1.17) in the equation are *fixed* constants and represent the rate of change of energy consumption with respect to failure rate and production rate respectively, any changes in the values of these variables can be used to determine the corresponding change in electrical energy consumption rate. For example, the incremental rate of change of electrical energy consumption with respect to failure rate is ΔEC/ΔFR, and equals (b_{1p}); therefore,

$$\Delta EC = b_{1p} \,.\, \Delta FR \qquad \text{(kWh/ton)} \qquad (5)$$

Similarly the incremental change of electrical energy consumption rate with respect to production rate is ΔEC/ΔPR, and equals (b_{2p}); thus,

$$\Delta EC = b_{2p} \,.\, \Delta PR \qquad \text{(kWh/ton)} \qquad (6)$$

Consequently, the expected total incremental change in energy consumption rate due to changes in failure and production rates can be written as:

$$\Delta EC = b_{1p}.\Delta FR + b_{2p}.\Delta PR \qquad \text{(kWh/ton)} \qquad (7)$$

The equation above provides a basis for evaluating the economic implications of incremental improvements in energy control variables. Under the stated assumptions, using annual net return (gross annual savings - total annual investment), one can construct a 'return function' using energy gross savings and costs of quantities on right-hand side of the above equation. If we denote the expected gross annual savings of energy reductions by S, the annual cost of improvements in energy control variables by C and the expected annual net return by R, then the following relationship becomes valid:

$$R = S - C \quad (\$) \qquad (8)$$

To express these variables in terms of the variables in the regression model, one would need to define a set of cost parameters for each production line as follows:

C_{fr} = annual cost of reducing FR by one unit ($)
C_{pr} = annual cost of increasing PR by one unit ($)
C_{elect} = unit cost of electrical energy ($/kWh)
P = annual production of aluminum (tons)

Thus, the total annual cost of improving energy control variables can be expressed using the following equation:

$$C = \Delta FR.C_{fr} + \Delta PR.C_{pr} \quad (\$) \quad (9)$$

and the expected total annual savings resulting from reductions in electrical energy consumption can be expressed as:

$$S = \{[b_{1p}.\Delta FR + b_{2p}.\Delta PR].P\}C_{elect} \quad (\$) \quad (10)$$

Therefore, the expected annual net savings can be expressed as:

$$R = \{[b_{1p}.\Delta FR + b_{2p}.\Delta PR].P\}\ C_{elect}. - [\Delta FR.C_{fr} + .\Delta PR.C_{pr}] \quad (\$) \quad (11)$$

Once cost parameters defined above are estimated, it will be possible to compute the expected annual energy return resulting for any level of improvement in the values of the energy control variables.

An Illustrative Case Study

As said before, the economic treatment presented in this paper is for illustrative purposes and was not meant to be comprehensive. As such, data given below are approximate and intended to provide an understanding of the extent of economic impact of improving energy control factors.

Estimating cost parameters associated with control variables requires detailed and carefully planned data gathered from accounting files. In this context, one would need to allocate the total investment cost to control variables according to some logical criteria. Here it was resorted to estimating these cost coefficients using basic accounting data available for the years 1998-2000 for the powder-coating production line whose electrical energy consumption equation was given by equation (4):

$$E(EC_p| FR,PR) = 305.10 + 26.45\ FR - 1.170\ PR$$

According to accounting records of the year 2000, about 96,400 \$ were spent on improving the overall operational efficiency of the aluminum profile manufacturing plant, of which 14% (13,490 \$) was dedicated to the powder coating line operations. Therefore, the total costs of improvement in production rate and failure rate during 2000 were 13,490 \$. Using process flow analysis, it was determined that approximately 72.3% of expenditures were on spent on improving failure rate while 27.7% were needed for improvements in production rate. Process flow analysis assisted in identifying investments relating to improving production rate and those relating to failure rate. In this analysis, cause-and-effect diagrams were used to uncover underlying reasons that actually improved both failure rate and production rate. For example, an investment of about 3000 \$ were spent on improving handling system were considered as investments for improving production rate, while expenditures made to improving spare part quality were considered as investments for reducing failure rate.

Levels of improvement in the two factors involved in the model above recorded a change between 2000 and 2001 as follows: the average failure rate had dropped from 6.91to 4.14 failures per month and average production rate had improved from 146.52 to 170.43 tons per month. Therefore, the values of the coefficients C_{fr} and C_{pr} were computed and amounted to 4496.6 \$/failure 288.55 \$/ton, respectively. Using actual C_{elect} at 0.16 \$/kWh and a total production volume of 2040 tons of powder coated aluminum for the year 2001, and according to expected annual net energy return equation given above, the total annual energy return for 2001 amounted to approximately 20,000 $, yielding *a simple* rate of return of about 150%.

Discussion and Conclusions

The analysis and results of this research has established important and statistically valid relationships between energy consumption rates and maintenance and production factors, and economic implications of improving these energy control factors showed economic viability of investments in improving energy factors. In light of the analysis and results of this research, the following remarks can be made:

1. This research presented a methodology for evaluating the improvements in energy usage that can be added to the management tool set that energy managers can use in their attempts to reduce energy consumption rates. Although the focused was made on failure rate and production rate as control variables, other variables may be related to energy consumption rates in a particular setup, and therefore can be added to the statistical model while carefully watching for model assumptions especially multicollinearity.
2. The results established significant relationships between energy consumption and related control variables, thus, warranting additional efforts for integrating energy management systems and other management aspects inside the production facility such as maintenance and production management. This management integration process would make available new data and allow exchanging them among systems to optimize the overall operations.
3. The economic treatment presented showed a positive economical impact on energy savings that resulted in desirable net returns. For more concrete economic analysis, one would need to consider the impact of cash flows analysis; and using predetermined accurate cost data, it would be possible to determine the economically optimal operating point for energy control factors.
4. Economic analysis also revealed the necessity of a detailed costing system that would provide accurate data to be used in the derived model. This costing system will integrate energy factors as well as other management factors pertaining to maintenance, production, quality, and others.

Acknowledgment

The author would like to thank his students for their assistance in collecting a portion of the data needed, namely, Raya Khayat, Taghred Jearah, and Rola Taha. Thanks are extended to the factory management that enabled us to use their data, namely Eng. Osama Aqqad.

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