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Key Variable Analysis and Identification of Energy Consumption in an Automotive Manufacturing Plant

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***Abstract*— Energy consumption during the process of automotive vehicle production has seen increasing attention with a current world focus on sustainability. Energy analysis helps researchers better understand life cycle energy consumption of vehicles, and assists manufacturers to set effective energy conservation goals. Previous studies have been focusing on the machine-level energy modeling and analysis, but higher-level energy characteristics are less well understood. In particular, the investigation of influential variables on plant level energy consumption is believed to be essential, but previous studies have proved insufficient. This paper is intended to analyze and identify the key variables in plant level energy consumption of an automotive manufacturing plant. In this paper, the authors summarize three main categories of key variables, and provide guidance for further plant and higher level energy modeling and conservation.**

Keywords*— energy modeling; key variables; automotive manufacturing plant

I. Introduction

It is reported the automotive vehicle industry in the U.S. spends about $3.6 billion on energy annually [1]. Energy is indispensable in everyday production, however a major concern for sustainable development strategy. In recent times, energy conservation has evolved from not only an environmental protection strategy, but also a strategy for minimizing cost. Manufacturers are facing pressures from the public, governmental policies, and the market to reduce energy consumption. The tradeoffs among the energy usage, monetary cost, and environmental emission are multifaceted and were studied in [2].

According to [3] and [4], the manufacturing system can be divided into four time phases and five organizational levels. The four phases (product design, process design, process adjustment, and post-processing) and five levels (device/unit process, production line, facility/plant, multi-factory, and global supply chain) can be considered independently, but have some relationships that should be considered in forming a sustainability strategy. In this paper, the authors focus on modeling of the energy use of the post-processing phase in the time domain, and plant and lower levels in the organizational domain.

Many efforts have been made in energy modeling of the manufacturing plant, and the importance of plant-level key influential variables is widely recognized. They can be used to provide guidance for energy saving measurements, set comparison criteria between two similar plants, and refine plant level energy models to be more informative and robust. However, the analyses of plant level energy consumption influential variables have never been systematically developed. This paper is dedicated to investigating the key variables in the manufacturing system by using the automotive assembly plants as demonstration.

The authors review the relative work of energy modeling in Section II. Typical examples of energy models and their key influential variables in the production processes of automotive manufacturing plants will be illustrated in Section III. In Section IV, plant level data will be applied to examine the significance of various variables, and organize the key influential ones into three categories. Finally, the conclusion of this research will be summarized and further application of this work will be discussed in Section V.

II. Background Review On Energy Modeling

A. Energy Consumption In Production Processes

There are three main departments in the automotive assembly plant – body shop, where the vehicle panels are formed and welded together to form a body-in-white structure; paint shop, where the paint and sealant are added for corrosion protection and attractive appearance; and final assembly shop, where all the components of the vehicle including powertrain marriage to body are assembled together.

Extensive welding techniques are applied in the body shop. Spot welding is one of the traditional joining technologies used in the automotive manufacturing plant. J. D. Cullen *et al*. studied the energy use in the spot welding specifically in the automotive industry [5]. They used an artificial intelligence approach to correlate the energy consumption of the automotive spot welding with welded material type, material thickness, number of weld, weld nugget size, and tip width. Hao Liu and Qianchuan Zhao modeled the energy consumption of the welding process as two parts – energy consumed in generating welding spot and welder idle time [6]. Laser beam welding is another popular technology used in automotive manufacturing. For laser welding CO_2, excimer, and the Nd: YAG (neodymium in yttrium aluminum garnet) lasers are used. A further development of laser welding has led to the introduction of remote laser welding (RLW), which uses large focal length optics, high-power laser sources and mirrors to translate the laser beam into a large 3D working volume at high speeds [7]. Unlike laser beam welding, which use the laser as heat source, gas metal arc welding (GMAW, MIG) forms an electric arc between the wire electrode and work piece, by using the inert or active gas as the heat source. Both welding techniques join the materials through metal melting. The theoretical energy of metal melting can be modeled through the material properties and welding process. The energy of welding also depends on the efficiency of energy conversion from primary energy (*e.g.,* electricity, gas chemical energy) to thermal energy. M. Gao and his colleagues introduced a series of CO_2 laser-gas metal arc (GMA) hybrid welding experiments on the mild steel [8]. They discussed how the laser power, arc current and the distance between laser and arc can affect the melting energy.

The welded vehicle body will be transported to the paint shop. This area is responsible for vehicle painting and sealing, and consumes as much as 60% of total plant energy [1]. Roelant *et al*. studied the cost and environmental impact from the automotive painting shop by creating a mathematical model to simulate painting processes [9]. Authors also discuss the most energy intensive part of the paint shop in [10].

Final assembly shop completes the vehicle with other sub-assembled components such as engine/powertrain, seats, window, electronic harnesses and components, and trim parts. In this department, there are many more energy consumption sources than in the previous two departments. The energy analysis and modeling techniques for assembly are reviewed and summarized in paper [11].

Another considerable energy consumer in the manufacturing plant is the building energy. To maintain a safe and comfortable working environment, the brightness and temperature of the plant are maintained through lighting and HVAC (heating, ventilation and air conditioning) system. In an automotive manufacturing plant, lighting is believed to constitute approximately 15% of the total electricity consumption [1]. Automatic control systems with light or motion sensors are proven to be more efficient in energy conservation. HVAC not only consumes electricity, but also hot water/steam, chilled water and sometimes natural gas. Ivan Korolija *et al*. developed regression models to predict the building annual heating and cooling demand [12]. According to their research, the building heating/cooling energy is related to the amount of heat gain and loss such as the transmission heat gains/losses through building envelope, solar gains, internal heat gains (such as manufacturing processing heat), and heat gains/losses in through the heat exchangers and air ventilation systems. The importance of the building shell itself, and the interaction between the production process and its environment was addressed in [13] and [14]. In these two papers, the energy consumption of technical building services is also taken into consideration. They illustrate how it is used to ensure the production conditions in terms of temperature, moisture and air purity through heating, cooling and conditioning of the air; and how it is affected by the local climate of the production site and machine waste heat.

Energy models in production processes are critical in understanding the energy consumption at a lower level; however, they are independently studied and can hardly be directly integrated to gain overall understanding of the plant level energy use.

B. *Studies On Plant Level Energy Use*

Unlike the models of production processes, research on plant level energy study the plant as a system, and takes the variables from lower level as inputs.

Energy performance models typically study the plant energy consumption per vehicle. One approach for energy modeling of automotive assembly plant is from Gale A. Boyd's work in 2005 [15]. Boyd developed a performance-based indicator for the US Department of Energy known as the Energy Performance Indicator (EPI) to score energy performance in megawatt-hour energy used per vehicle produced. It is an inexpensive and convenient tool to compare one plant with other similar automotive manufacturing factories – the EPI score represents energy performance of the plant through percentage of ideal values. Yogesh Patil *et al*. developed a Lean Energy Analysis (LEA) method, which models electricity and natural gas use in automotive manufacturing plants [16]. The main contribution of this paper is the generation of energy signatures, defined as the basic shape of a statistical regression. It is used to represent the baseline energy use in each plant. This paper reported that the energy signature is represented by the manufacturers' unique energy equations derived from their own independent variables. S. Kara and S. Ibbotson [17] started from the life cycle analysis point of view, proposing the methodology in assessing the embodied product energy (EPE). They used two different roofing systems (fiber composite and galvanized steel roof systems) as demonstration examples, and developed 10 different manufacturing supply chain scenarios, and considered the embodied energy of raw materials supplied. Discrete models have the energy consumption in "numbers of product", and usually assume the energy consumption of one product has no significant difference from another product. Evolved from the traditional EPE models, discrete event simulation models [18, 19] took this concept one step further by describing the production procedures. They modeled the energy from two aspects – direct energy (DE) and indirect energy (IE). DE is defined as the energy used directly in the manufacturing process (*e.g.*, welding, machining); ID is defined as the energy consumed to maintain the working environment (*e.g.*, lighting, heating and ventilation). DEs were modeled by using physical models of multi-machine and single machine levels, while IEs were calculated as the average energy consumption over the time and number of products stayed in different production zones.

The effort of studies on plant level energy usage was made, but the models proposed were infeasible to be directly applied to other plants due to the lack of integration with low level models. The models reviewed can be used on the studied case, but the question of how can they be applied to other plants or similar systems is not answered. One of the reasons is the research did not identify the key variables for energy consumption through lower level models.

III. PRODUCTION PROCESS KEY VARIABLES

In this section, energy models in production processes and manufacturing buildings for automotive manufacturing plants will be provided. The processes illustrated are significant energy consumers in plant, and they are the examples to analyze the low level essential variables. The analysis procedures of this section can also be repeated on other similar plants for specific variable analysis and identification.

A. Air handler Unit

An air handler unit (AHU) is a subsystem of the HVAC (heating, ventilation, and air condition). It is responsible for the discharge air temperature and humidity control into the certain space area. An AHU controls the temperature and humidity through humidifiers and heat exchangers, such as heating wheel, heating coils, and cooling coils. Energy consumption in can be calculated through the enthalpy difference of inlet and outlet air of AHUs, while the enthalpy of air can be modeled through equation (1).

$$\mathrm{h} = \mathrm{C}_{\mathrm{p,a}}T + W(C_{p,W}T + h_{w,e}) \tag{1}$$

In equation (1), h is enthalpy of moist air in unit kJ/kg; $C_{p,a}$ is air specific heat capacity in $kJ/kg \cdot$ °C; $C_{p,W}$ is water specific heat capacity in $kJ/kg \cdot$ °C; T is temperature in °C; and $h_{w,e}$ is evaporation heat of water in kJ/kg. The energy consumption also related to the air flow rate in kg/s, and time of operation.

In paper [10], the authors discuss the energy consumption in paint shop building and booth. Variable temperature set points of the building and booth was discussed to get the optimal energy conservation strategy in the studied case. This study illustrated how the local weather information, especially the temperature information is essential in energy consumption of automotive paint shop.

The same models can be used to analyze other critical parts of the automotive manufacturing plant. Apart from the building and base-coat booth, clear-coat booth and oven are two places where the same models can be applied.

1) Clear-coat Booth

In paper [10], authors discussed the concept of the booth, where the space is separated from the building to operate paint spraying production process. In that paper, continuous temperature set points were adjusted for testing the optimal operation conditions for building and base-coat booth. Similarly, the clear-coat booth is a separate room within the building, where the clear-coat spray is applied. The energy models of the base-coat booth can be directly applied into the clear-coat booth, since the clear-coat booth has the similar building-to-booth air supply system as the basecoat booth.

In our studied case, the clear-coat booth has a designed tolerance on humidity from 50% to 67%. As the required model inputs, the variables in the model are: 1) inlet air temperature, 2) inlet air humidity, and 3) outlet air humidity. Other inputs are constant, namely the air flow rate and outlet air temperature. Because of the building-to-booth air supply system, the inlet air temperature is actually relatively stable. However, out of the research purpose, it is discussed as one of the variables.

In a space with humidity control, the dehumidification process should be avoided as much as possible, due to its large energy demand in the dehumidification and reheating processes. Thus, in the clear-coat booth where the relative humidity is a variable, higher humidity could have better chance in avoiding the dehumidification process. However, the larger relative humidity (in this case 67%) in the outlet air also requires more energy for the extra moisture heating or cooling, *i.e.,* in a simple heating or cooling process, the extra moisture (the extra 17% on the original 50%) requires more energy to change temperature. “Which energy demand is more dominant?” is a question that needs to be answered. Experiments were designed as TABLE I, and normalized energy demand was calculated to discuss the question.

TABLE I. EXPERIMENTAL DESIGN AND RESULTS OF HVAC ENERGY IN CLEAR-COAT BOOTH

No.	Inlet Air Temp. [°F]	Inlet Air Hum. [%]	Outlet Air Hum. [%]	De-humidification or not (1-Yes, 0-No)	Normalized Energy Demand
1	68	49.8	50	0	0.476
2	68	49.8	67	0	0.478
3	68	79.1	50	1	1.803
4	68	79.1	67	0	0.478
5	72	49.8	50	0	0.204
6	72	49.8	67	0	0.205
7	72	79.1	50	1	3.109
8	72	79.1	67	1	1.247

By piecewise comparing the energy demand, TABLE I provides elucidating information to study how energy demands are correlated to the humidity in the outlet air.

In summary:

1. if the dehumidification process is not in the control range [50%, 67%], 50% consumes slightly less energy (experiments 1 and 2, 5 and 6);
2. when both humidification and dehumidification processes are within the control range [50%, 67%], choosing a set point of 50% will consume less energy (reference Experiments 3 and 4);
3. when the dehumidification process is in the control range [50%, 67%], 67% consumes less energy (reference Experiments 7 and 8).

When the process does not need dehumidification, less humidity means less energy used for moisture in the air; when choosing between the process with and without dehumidification, the energy demand is always lower in a process without; when the dehumidification process is inevitable, choosing a higher relative humidity output needs less energy, since there is a lower amount of water condensed. Therefore, the best operation strategy is to set variable set points based on the inlet air condition, instead of a constant set point throughout the year. In other words, the energy consumption of the clear-coat booth is highly related to the local weather temperature and humidity.

2) *Oven*

The paint oven is another considerable energy consumer in an automotive manufacturing plant. The plant has many ovens in the painting process to cure the layers of paint and sealant. Generally, the vehicle in the oven will go through heating up, temperature hold, and cooling down processes. The oven is another relatively separate space from the building. Except for the temperature and humidity control inside the oven, the oven air handler unit can also control their inlet air flow rate. One of the energy conservation strategies is to reduce the air flow rate into the oven during downtime.

At downtime, the previous vehicle has left the oven, and the next vehicle has not entered the oven yet. The air supply houses adjust the airflow speed into the oven, but not shut down, to prevent dust and particulate matter from entering the oven. During this period of time, the energy can be saved from two sides – thermal energy and electrical energy. Except for the energy saving for heating and cooling, the electrical energy for fan speed reduction is also substantial.

According to the thermal energy model, the airflow affected the heating and cooling energy linearly. Based on the specification of the fans used, the electrical energy is also influenced. In this way, the energy of the oven is closely related to the vehicle production speed.

B. *Welding*

Welding is a main process in the body shop, which joins two parts together. General spot welding energy consumption can be written as Equation (2):

$$E_{weld} = E_{ps} N_{spot} x + (1-\alpha) P_{idle} T \tag{2}$$

where N_{spot} is the number of welding spots per product, x is the number of products to be produced, α is the ratio of welding engaged time to the total uptime, P_{idle} is the no-load power when the welder is in idle stage, and T is the total uptime.

Figure 1 shows two spot welding schedules under different production rates. The green regions are the down time, while the red regions are the welding engaged time, and yellow regions are the idle time.

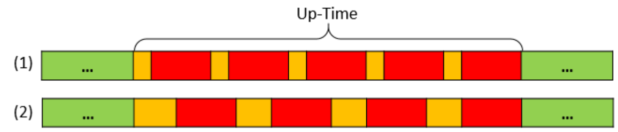

Figure 1. Spot Welding Schedule

These two scenarios have the same uptime, but during the uptime, the upper (1) schedule has one more part processed than the lower schedule.

Assume the production time is T, which is also the uptime for spot welding. During this period of time, x parts were processed in this particular spot welding procedure, and the average engagement time for each part is t. Thus,

$$\alpha = \frac{x \cdot t}{T}. \tag{3}$$

Therefore, α in Scenario (1) is larger than Scenario (2) in Figure 1.

If the quantity of produced parts was reduced by 20% of the original ($x' = 80\% \cdot x$), the welding engaged ratio becomes

$$\alpha' = \frac{x' \cdot t}{T} = \frac{0.8 \cdot x \cdot t}{T}. \tag{4}$$

Therefore,

$$\begin{aligned} E'_{weld} &= E_{ps} \cdot N_{spot} \cdot x' + (1-\alpha') \cdot P_{idle} \cdot T = \\ & E_{ps} \cdot N_{spot} \cdot 0.8 \cdot x + (1 - 0.8 \cdot \alpha) \cdot P_{idle} \cdot T = \\ & 0.8 \cdot \left[E_{ps} \cdot N_{spot} \cdot x + (1-\alpha) \cdot P_{idle} \cdot T\right] + \\ & 0.2 \cdot P_{idle} \cdot T = 0.8 \cdot E_{weld} + 0.2 \cdot P_{idle} \cdot T. \end{aligned} \tag{5}$$

Let $0.2 \cdot P_{idle} \cdot T = c$, where c is a constant, we get

$$E'_{weld} = 0.8 \cdot E_{weld} + c. \tag{6}$$

Generally, Equation (6) can be further written as

$$E = c + \alpha \cdot x. \tag{7}$$

where α is the coefficient, c is a constant, and x is the production rate.

It can be concluded that the welding energy is linearly related to the production ratio (*i.e.,* number of parts produced in certain uptime period).

C. *Material Relocation*

The production affects the energy consumption not only in terms of number of parts produced in certain period of time, but also in terms of vehicle type.

As mentioned in [11], heavy parts handling usually involves in robotic material handling. Generally, robotic material handling energy is summarized in following equation.

$$E_{handling} = \left[L \times \left(m_{part} + m_{grip} + \eta \times m_{robot}\right) \times v\right] / (\eta_{motor} \times t_{handling}) \quad (8)$$

This equation indicates the energy consumption of the robot handling material, and the variables involved in this equation are the length of the moving material (L), speed of moving (v), weight of the part (m_{part}), weight of the gripper ($m_{gripper}$), robot specifications such as the weight of the robot arm (m_{robot}) and the angle of the robot arm (η), as well as the motor efficiency (η_{motor}) and handling time ($t_{handling}$).

From this equation, the energy of material handling was affected by part variation due to the different vehicle models through the parts' weights m_{part}. For a certain autonomous material handling robot, the time of handling, efficiency of the motor, handling route, speed, robot weight, grip weight and robot efficiency are all designed and constant. The equation can be simplified as

$$E_{handling} = \alpha + \beta \cdot m_{part} \, . \quad (9)$$

where α is a constant, and β is the coefficient. In this case,

$$\alpha = \frac{(m_{grip} + \eta \times m_{robot}) \times v \times L}{\eta_{motor} \times t_{handling}} \, . \quad (10)$$

$$\beta = \frac{L \times v}{\eta_{motor} \times t_{hanlding}} \, . \quad (11)$$

Notation: length of the moving material (L), speed of moving (v), weight of the part (m_{part}), weight of the gripper ($m_{gripper}$), robot specifications such as the weight of the robot arm (m_{robot}) and the angle of the robot arm (η), the motor efficiency (η_{motor}), and handling time ($t_{handling}$).

In summary, the material relocation energy is related to the part's weights associating with the vehicle types.

Air handler unit, welding, and material relocation have been presented as three examples to show how the local weather, production speed, number of parts produced, and types of products can affect the energy consumption. These examples provide good information in terms of influential features in production processes, and they are the foundations for the plant level key variables identification.

IV. Plant level Key Variables

From the previous section, key variables in production processes were discussed. With these examples, it can be concluded that the sensitive variables from the physical model include the: 1) weather information, 2) Product information, and 3) production information. They are summarized into TABLE II.

TABLE II. Key Variable Category Table

Weather Information	Product Information	Production Information
• Temperature • Humidity • HDD (Heating Degree Days) • CDD (Cooling Degree Days	• Type • Weight • Size (e.g., wheelbase)	• Productivity • (Non-) Working days • Working shifts

These three variable categories can be further expanded into: daily average temperature, CDD (cooling degree days), HDD (heating degree days), daily average relative humidity, type I vehicles produced daily, type II vehicles produced daily, day of the week, working and nonworking days, and working shifts. However, not every variable is influential enough to be included in the plant level energy model. Some variables can also be excluded easily. For example, *CDD* and *HDD* are the two terms used widely in building energy calculations, but when analyzing the electricity, which is only used for cooling, *HDD* can be removed. Other variables identification relies on the correlation and coefficient analysis. Correlation analysis is one way to discover if the variable is significant enough to be considered. TABLE III presents the correlation analysis results of plant consumed electricity and 8 candidate variables. In this table, *daily average humidity* with correlation value 0.08 can be first excluded from the plant level key variables. It is proven to be critical in energy consumption of the paint clear-coat booth, but not for the overall plant energy consumption due to the trivial size of the clear-coat booth. Apart from the *daily average humidity*, *weekdays* has the second lowest correlation, which suggests insignificance.

TABLE III. Correlation Analysis

No.	Variables	Electricity
1	Vehicle Type I	0.65
2	Vehicle Type II	0.55
3	Daily Avg. Temp.	0.43
4	CDD	-0.47
5	HDD	-0.35
6	Daily Avg. Hum.	0.08
7	Weekdays	-0.26
8	Non-Working Days	-0.43

Besides the correlation analysis, multivariable linear regression coefficient analysis was used to help determine the key variables. TABLE IV is the statistical result of the coefficient analysis on potential input variables. If we define the variables with p-values less than 0.05 are significant, the results are consistent with the correlation analysis.

TABLE IV. Linear Regression Coefficient Analysis

Variables	Coefficient	t-Value	p-Value
Intercept	309147	12.95	0.000
Vehicle Type I	57.60	22.49	0.000
Vehicle Type II	23.07	6.26	0.000
Daily Avg. Temp.	124.2	1.78	0.076
CDD	-13297	-14.06	0.000
Daily Avg. Hum.	396	1.62	0.106
Weekdays	-2108	-1.14	0.225
Non-Working Days	-51562	-3.49	0.001

TABLE IV suggests input variables – vehicle type I, vehicle type II, CDD, and non-working days are the key variables in the plant level of automotive manufacturing plant.

V. Conclusion and Discussion

This paper pointed out the significance of key variable identification in energy analysis of automotive manufacturing plant. Examples of considerable energy consumers in the plant were illustrated to help determine the sensitivity of variables in both production processes and plant level. Among many variables, this paper showed that the weather, product, and production information are three main key factors in manufacturing energy consumption. This result can be used to improve the product life cycle energy assessment, and assist manufacturers to set effective energy conservation goals. In addition, based on the result of this work, further studies can be developed to build more informed plant level models, such as time series model with exogenous inputs for energy forecasting. Energy comparison among different plants is also believed to be more meaningful with the consideration of differences from key variables. Plants can eliminate the difference by normalizing the energy consumption based on the influential variables. For example, plants can compare the ratio of energy consumption over CDD to determine the "efficiency" of vehicle production, while reducing the effect from the weather difference between two locations.

Regarding future work, it is promising to expand the three categories into other consumable recourses, such as potable water consumption and materials used in plant. In addition, the key variables in one plant are potentially influencing the other manufacturing plants, especially for these plants with supplier and consumer relationship. It would be very interesting to investigate the energy and other resources' influential variables among multiple factories.

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