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Lujia Feng
Clemson University

Durul Ulutan
Clemson University

Laine Mears
Clemson University, mears@clemson.edu

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Lujia Feng, Durul Ulutan, Laine Mears
Automotive Engineering Department
Clemson University
Greenville, SC, USA

***Abstract*— As an important part of a sustainability strategy, energy usage in an automotive manufacturing plant is an important topic that has recently gained significant attention. Researchers mostly focus on energy conservation through increasing the efficiency of such facilities, optimizing energy supplies, and scheduling efficient production sequences. However, attention is seldom focused on holistic energy modeling at the level of process assembly lines. In this study, the problem of energy consumption during the automotive vehicle final assembly (FA) process is discussed. An energy classification in the final assembly department is generated to give more transparent understanding of the energy consumption in each category. Typical energy models of every energy category are presented to demonstrate the potential energy savings through a combined approach. Finally, considering the current status of most manufacturing plant metering systems, a three-level metering system is proposed to support the hybrid (i.e., discrete and continuous, deterministic and stochastic) modeling approach.**

Keywords—energy consumption; automotive manufacturing; final assembly; energy modeling.

I. Introduction

Among the four major energy end users (i.e. industrial, residential, transportation and commercial activities), industry consumes more than one third of the total, and ranks as the highest energy consumer overall. As an important part of industrial activities, manufacturers consume a significant amount of energy every year [1]. Many manufacturers, like cement [2], automotive [3], aluminum [4], and chemicals are widely studied on their energy usage at the plant level [5]. However, due to the complexity of the manufacturing processes and the lack of use of smart meters in those processes [6], lower level research, such as process line or machine level research, is limited.

According to recent studies, automotive assembly plants in the USA spent $3.6 billion on energy in one year [3]. Efforts are made to study the optimal energy supply strategies [7], the influential parameters in affecting the energy consumption [8], and energy demand features of the whole plant [9]. However, the energy usage within the assembly area of the manufacturers is seldom studied. For most plants, the final assembly department usually consists of various automated, semi-automated, and non-automated processes, making the energy study of the final assembly even more challenging [10]. However, it typically ranks second in specific energy use behind the paint shop.

Nomenclature

E	Energy
N	Number
P	Power
t	Time
L	Length/Distance
m	Weight
v	Speed
η	Efficiency
F	Force

Subscript

Lighting	Lighting fixture
High	High bay lighting
Low	Low bay lighting
Sub	Sub-assembly workstation
Main	Main line
i	Indicator
Grip	Gripper
HVAC	Heating, ventilation, and air conditioning
Misc.	Miscellaneous

II. Background

As a discrete part manufacturing area [11], the energy consumption in the automotive vehicle final assembly shop can be investigated from two perspectives: discrete and continuous. Many similar studies that discuss various modeling strategies for systematic discrete part manufacturing systems exist, and the most relevant ones are summarized in this section.

Discrete and continuous modeling approaches are the two main branches of the energy modeling in discrete part manufacturing system. Unlike the continuous models focusing on the energy dynamics, discrete models have the energy consumption in “numbers of product” [12], and they usually assume the energy consumption of one product has no significant difference from another product. According to Sun Qingchao and his colleagues [13], the discrete energy modeling approach is good for discrete part manufacturing systems. It can be used to obtain the overall energy consumption per parts by combining the usage from "Direct Energy" – the energy directly related to the manufacturing processes, and "Indirect Energy" – the energy associated with the manufacturing environment. The authors are ambiguous about the differences between the direct and indirect energy, and deliberately separate the continuous energy consumption based on the production time of each part. Alessandro Cannata's [14] team took one step further, and assumed that the discrete part manufacturing plant and the machines inside can be represented as discrete states – idle, working, and set-up phase, and so on. The continuous modeling of energy used on HVAC [15], lighting [16] and conveyors [17] are studied separately by researchers. Cannata's approach can perform well if the energy consumption from the working environment is neglected, and the power characteristics for every machine in the whole assembly shop are established. However, it is very unlikely for manufacturers to have power load meter or information for every machine. Considering the large contribution of the heating, ventilation and air conditioning system (HVAC) in the plant, it is not reasonable to ignore the energy usage of HVAC.

Y. Seow and S. Rahimifard [18] developed the concept of discrete part manufacturing energy modeling by using the commercial energy software together with an advanced comprehensive metering system. They built a detailed "embodied product energy" model with product specifications. However, their model requires a large amount of data input from an expensive monitoring system, which is lacking in most of the manufacturing plants.

On the other hand, C. Herrmann and S. Thiede [12] came up with a systematic modeling approach to foster energy efficiency in a manufacturing plant on different layers. Additionally, they pointed out in detail that using a simulation model specific to certain processes is an obstacle since it leads to inflexibilities in industrial applications. Later they [19] applied their modeling approach to aluminum die casting and weaving mill, and validated successfully.

Although the automotive final assembly plant systems have features specific to their particular field, they also share some common features with other discrete part manufacturing systems. The breakdown of energy consumption within a final assembly shop and its attribution to the total energy demand of the whole plant is not yet well understood. In the next sections, an energy classification in the final assembly department is generated, and a three-level metering system approach is proposed to support the hybrid modeling approach.

III. Energy Classification and Model Decomposition

A deterministic physical model of every equipment and tool used in the final assembly shop is ideal but infeasible, considering the complexity and the stochastic nature of the manufacturing processes, and high cost of a required monitoring system for such a model. Therefore, a holistic approach with hybrid physical and statistical, continuous and discrete models is proposed in this section.

In order to have an energy consumption model capable of accurately simulating the plant as well as fairly comparing among similar plants, the overall energy usage within the final assembly shop was divided into two major parts – building energy and production energy. The building energy encompasses energy for lighting, as well as heating, ventilation and air conditioning (HVAC), whereas the production energy is the energy used directly related to the production activities (see Fig. 1).

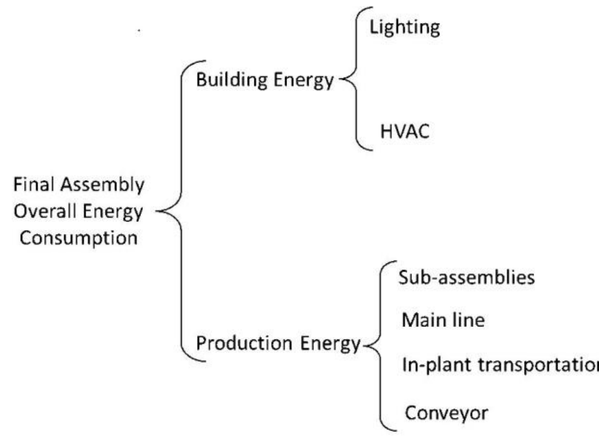

Figure 1. Final assembly energy classification

Generally in such plants, production energy is used in four major categories: sub-assemblies, main assembly line, in-plant transportation, and conveyors. Sub-assemblies are the workstations with individual tasks to assemble the portion of the final product not related to the main part. Main line has the procedures where the sub-assembled parts are assembled to the main part. For example, in an automotive assembly line, the procedures of vehicle door assembly, bumper assembly, and engine assembly are the sub-assemblies, which are processed at individual production cells, or in some cases assembled at a separate location. On the other hand, the main line has the procedures such as attaching doors to the vehicle body, windscreen installation, seat mounting, and so on. In this case, the vehicle body is taken as a main part, and any assembly procedure related to the vehicle body is a part of the main line; otherwise, it is a sub-assembly procedure. In-plant transportation and conveyors are the two major methods used to move parts from one location to another. Typical in-plant transportation includes autonomous guided vehicles (AGVs) and manual operated forklifts, while typical conveyors are belt conveyor, chain conveyors and hanging conveyors.

A. *Lighting*

In an automotive manufacturing plant, lighting is believed to constitute approximately 15% of the total electricity consumption [3]. In the assembly department where relatively higher manual labor is observed, the portion of electricity consumption is believed to be higher than other departments. There are two lighting systems in the assembly shop: high bay lighting and low bay lighting. High bay lighting is generally a portion of building energy to provide a bright environment for the building, whereas low bay lighting is concentrated alongside the workstations. Usually, high and low bay lighting have the same lighting fixture within the same system, but are different from each other. Thus, the energy consumption of the lighting system can be calculated as in Equation 1.

$$E_{Lighting} = E_{High} + E_{Low} = N_{High} \times P_{High} \times t_{High} + N_{Low} \times P_{Low} \times t_{Low} \quad (1)$$

The number and power of the lighting fixtures are highly related to the building structure – availability of daylight, and working environment lumen requirement. Energy efficient buildings have sufficient daylight available to allow shorter artificial lighting time, while fine components assemblies have high lumen requirement that necessitates more lights. Besides the daylight availability, the lighting time also depends on the control system design. Automatic control systems with light or motion sensors are proven to be more efficient than manual controls [3].

B. HVAC

The HVAC department is another big energy consumer in an automotive manufacturing plant. In order to maintain a good working environment, air in the assembly department is constantly exchanged with outdoor air. Some manufacturing plants also control the air temperature and humidity of the department to make sure an ambient working condition exists for the workers, to protect the weather-sensitive equipment, and to guarantee a high quality product. The energy used for HVAC can originate from electricity, as well as natural gas, hot water, and chilled water. Electricity is mostly used to power the ventilation fans and motors. If hot water and chilled water are available for direct use, they are constantly used to heat and chill the inlet air from the atmosphere through heat exchangers. Otherwise, natural gas and electricity are used to run the burner and chiller to generate hot and chilled water on-site. The optimal operation of the HVAC in production plant can be found in the authors' previous study [20].

C. Sub-assemblies

Sub-assemblies can be in various different forms. They are relatively independent procedures where portions of the final product are assembled, which can easily be installed later onto the vehicle body. Many automotive assembly plants receive assembled parts such as the engine, powertrain, seats, and bumpers directly from suppliers, while other plants may have on-site sub-assembly workstations to prepare these portions of the assembly. Most of the energy consumption due to the sub-assemblies is the electricity and compressed air, and the total energy consumed on sub-assemblies can be calculated as the summation of each sub-assembly workstation (Equation 2).

$$E_{Sub} = \sum_{i=1}^{n} E_{sub_i} \quad (2)$$

Energy saving for the sub-assemblies highly depends on the procedures taken in each workstation. For example, the usage of compressed air is related to the method of production and delivery. To increase the energy efficiency of compressed air, the maintenance function can examine the leakage in the delivery system, turn off the compressor according to the production schedule, or even take more energy efficient measures such as replacing compressed air actuators with magnetic or electric [21].

D. Main line

The vehicle body is transported from the paint shop to the final assembly area by conveyor. To have good accessibility during the assembly processes, doors are removed at the start of the assembly shop and transported in parallel with the vehicle body. Similar to many sub-assemblies, the main line has a significant number of harness and hose installation procedures along with many miscellaneous trim items, and the energy consumed for these procedures can be calculated via Equation 3.

$$E_{main} = \sum_{i=1}^{n} N_{robot_i} \times E_{robot_i} \quad (3)$$

One of the important parts of the main line is the material handling. Various types of material handling robots are used to help carry the weight of installed parts, so the workers can work more efficiently and safely. Also, due to the ergonomics-related concerns, the material handling robot helps to hold the heavy parts, while the workers mount them to the right position.

$$E_{robot_{handling}} = [L \times (m_{part} + m_{grip} + \eta \times m_{robot}) \times v]/(\eta_{motor} \times t_{handling}) \quad (4)$$

Equation 4 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 ($t_{handling}$). Increasing the energy efficiency is possible through improvements in each and any of these aspects.

E. In-plant transportation

In-plant transportation is another important part of the assembly shop where the parts are delivered from the storage to the workstations. Energy consumption of the in-plant transportation does not rely only on the transportation tool design, but also on the in-plant transportation planning and scheduling [22]. Recently there are plants that use clean energy, such as hydrogen, in their in-plant transportation, and they have been reported to achieve energy reduction success [23].

F. *Conveyor*

The conveyor is another tool used in the final assembly line to transport bulk materials and parts. It transforms electricity into mechanical energy to move the materials and parts.

$$E_{Conveyor} = \int P dt = \int (F \cdot v) \mathrm{d}t \tag{5}$$

The energy consumption of a conveyor is highly related to its power and time of use. As an example, the energy of the belt conveyor can be calculated as shown in Equation 5. In this equation, the power of the conveyor (P) is calculated as the function of conveyor speed v and the driving force F, which is related to the conveyor slope angle, resistance force, and weight of the parts transported. Conveyor efficiency can be improved through the use of a higher efficiency idler, drive system, and belt/chain.

IV. Metering Suggestions and Hybrid Modeling Approach

Extensive quantification of energy metering in the manufacturing plant is desired but rare. Plants install meters based on the measurement requirements, compatibility with current system, database storage space [24], and cost limitations. Most traditional plants only install metering systems that can monitor and record the energy information at a sampling rate of hourly or daily at high level (such as facility level meters installed by the utility supply companies). Until recent years, most facilities showed a trend of installing lower levels of metering system [25]. In this section, suggestions for lower level metering installation in the final assembly area are provided to support a transparent and flexible energy modeling.

Three layers of meters are recommended. The highest-level meters monitor the energy input into the assembly department. Most plants already have this level of meters. The second level meters can be installed to measure the energy that is:

- supplied to the HVAC system: electricity used in fans, hot and chilled water used for heating and air conditioning,
- consumed by the conveyor: most of the conveyors in the assembly shop are connected to each other and share the same voltage, but due to different weights each conveyor carries and the complex buffer systems, it is difficult to simulate them separately.
- delivered to the main line and sub-assembly workstations.

The third level of meters can be installed to measure the load profile of energy intensive machines and robots. It is well known that the energy consumption of machines and robots are highly related to their production status. Power load profiles or power characteristics are useful in calculating the energy consumption in each production cycle. Unlike the other two, the third level meters do not necessarily need to be used to monitor the power continuously. Due to the large amount of machines and robots in the assembly area, one can sample the same types of machines and robots and test the full production cycles to obtain the power load profiles from time to time (during the maintenance period) in case of degradation.

In this way, one can calculate different levels of energy consumption with transparency and apply it to different but similar systems for comparison and benchmarking. Therefore, directions can be provided for best practice and energy consumption reduction.

$$E_{overall} = E_{HVAC} + E_{Lighting} + E_{conveyor} + E_{Transp.} + E_{Robots} + E_{misc.} \tag{6}$$

Equation 6 is used to demonstrate the energy distribution in final assembly. By comparing the energy consumption among the similar systems or in the same system but different periods of time, the energy managers will be able to tell the most energy inefficient/efficient area. For example, let's assume that Plant A has more energy consumption compared with Plant B, and they also find the main difference is caused by the energy consumption on the robot. The energy manager can look into the physical models of the robots and find out whether:

- Plant A has a higher level of automation and using more quantity of robots than another plant;
- The robots in plant A have lower efficient motors, or lower energy-efficient design;
- The parts carried by the robots in plant A are generally heavier than plant B (e.g. assembly larger vehicles); and so on.

Basically, the plant manager can check through physical variables related to energy (Equation 7) in calculating robot energy consumption.

$$E_{Robot} = f(N_{Robot}, \eta_{Motor}, m_{Part}, \ldots) \tag{7}$$

By using the deterministic equations for each energy usage in the final assembly shop as demonstrated in Equations 1-5, together with the statistical energy consumption knowledge from the metering, energy managers and specialists can have a more transparent understanding of energy consumption. At the end, they can come up with more efficient energy improvement strategies.

V. Conclusion and Future Work

Energy consumption in the automotive manufacturing plant is an important topic due to its implications on total plant operational costs and therefore the cost of the output product. Energy consumption of the final assembly shop in automotive manufacturing plants is not fully understood. In this study, a systematic energy classification in the final assembly department is generated to provide a more transparent understanding of the energy consumption in each category. Typical energy models of each energy category are presented to demonstrate the potential energy savings from different parts of the process. Finally, considering the current status of most manufacturing plant metering systems, a three-level metering system approach is proposed to support the hybrid (i.e., discrete and continuous, deterministic and stochastic) modeling approach.

Future work will include a case study with an example from an actual automotive manufacturing plant, as well as developing further on the smart metering system to have a real time energy model to monitor and alarm the energy usage within the final assembly. The same approach can also be developed to apply to different manufacturing systems for an energy saving and simulation tool.

REFERENCES

[1] W.H. Golove and L. J. Schipper. Long-term trends in US manufacturing energy consumption and carbon dioxide emissions. Energy. vol. 21, no. 7-8, p. 683-692, Jul-Aug 1996.

[2] F. Mielli. Energy efficiency strategies for the cement industry. 2011 IEEE-IAS/PCA 53rd Cement Industry Technical Conference, CIC 2011.

[3] C. Galistsky and E. Worrell. Energy efficiency improvement and cost saving opportunities for the vehicle assembly industry: An energy star guide for energy and plant managers. Lawrence Berkeley National Laboratory, 2008.

[4] H. Kita, H. Hyuga and N. Kondo. A rationalization guideline for the utilization of energy and resources considering total manufacturing processes - an exergy analysis of aluminum casting processes. Synthesiology (English Edition), vol. 1, no. 3, p. 199-208, 2009.

[5] J. R. Duflou, J. W. Sutherland, D. Dornfeld, C. Herrmann, J. Jeswiet, S. Kara, M. Hauschild and K. Kellens. Towards energy and resource efficient manufacturing: A processes and systems approach. CIRP Annals - Manufacturing Technology, vol. 61, p. 587-609, 2012.

[6] E. O'Driscoll, D. O. Cusack and G. E. O'Donnell. Implementation of energy metering systems in complex manufacturing facilities - A case study in a biomedical facility. Procedia CIRP, vol. 1, p. 524-529, 2012.

[7] L. Feng, L. Mears, Q. Zhu, C. Beaufort and J. Schulte. Plant level energy supply analysis and optimization in energy, economy and environment. ASME 2014 International Manufacturing Science and Engineering Conference, Detroit, MI, USA. 2014.

[8] G. Boyd. Benchmarking weather sensitive plant level manufacturing energy use. International Journal Global Energy Issues, vol. 32, p. 1-5, 2009.

[9] G. Boyd. Motivating auto manufacturing energy efficiency through performance-based indicators, SAE World Congress Detroit, Michigan, p. 3-6, 2006.

[10] M. Omar. The Automotive Body Manufacturing Systems and Processes. John Wiley & Sons, 2011.

[11] T. Devoldere, W. Dewulf, W. Deprez, B. Willems and J. R. Duflou. Improvement potential for energy consumption in discrete part production machines. Proceedings of the 14th CIRP Conference on Life Cycle Engineering, Tokyo, Japan. 2007.

[12] C. Herrmann, and S. Thiede. Process chain simulation to foster energy efficiency in manufacturing. CIRP Journal of Manufacturing Science and Technology, vol. 1, no. 4, p. 221-229, 2009.

[13] Q. Sun, H. Yang, C. Wang and H. Zang. Energy consumption monitoring system in discrete manufacturing plants. Proceedings - 2013 4th International Conference on Digital Manufacturing and Automation, ICDMA, p. 541-544, 2013.

[14] A. Cannata, S. Karnouskos and M. Taisch. Energy efficiency driven process analysis and optimization in discrete manufacturing. IECON 2009 - 35th Annual Conference of IEEE Industrial Electronics (IECON 2009), p. 4449-54, 2009.

[15] C. Su, and K. Yu. Evaluation of differential pressure setpoint of chilled water pumps in cleanroom HVAC systems for energy savings in high-tech industries. 2012 IEEE/IAS Industrial & Commercial Power Systems Technical Conference, p. 9-16, 2012

[16] Y. Lian. Lighting energy-saving design for industrial factory building. Applied Mechanics and Materials, vol. 484-485, p. 737-741, 2014.

[17] Qing He, Dong Daqian, He Zirui and Ju Jingjie. A new computer aided design system of belt conveyor. Advanced Materials Research, Manufacturing Science and Engineering, vol. 97-101, p. 3667-3670, 2010.

[18] Y. Seow and S. Rahimifard. A framework for modelling energy consumption within manufacturing systems. CIRP Journal of Manufacturing Science and Technology, vol. 4, no. 3, p. 258-264, 2011.

[19] C. Herrmann, S. Thiede, S. Kara, and J. Hesselbach. Energy oriented simulation of manufacturing systems – Concept and application. CIRP Annals - Manufacturing Technology, vol. 60, no. 1, p. 45-48, 2011.

[20] L. Feng and L. Mears. Analysis of HVAC energy in automotive paint shop. ASME 2015 International Manufacturing Science and Engineering Conference, Charlotte, NC, USA. 2015.

[21] N. Alkadi and K. Kissock. Improving compressed air energy efficiency in automotive plants - Practical examples and implementation. SAE 2011 World Congress and Exhibition, 2011.

[22] M. E. Lübbecke and U. T. Zimmermann. Engine routing and scheduling at industrial in-plant railroads. Transportation Science, vol. 37, no. 2, p. 183-197, May 2003.

[23] BMW Manufacturing News Center. "BMW Manufacturing Expands Use of Hydrogen Fuel Cells." 13 Mar. 2013. Access on 15 Mar. 2015. <https://www.bmwusfactory.com/bmw_articles/bmw-manufacturing-expands-use-of-hydrogen-fuel-cells/>.

[24] F. A. Aziz, S. N. Khalid, M. W. Mustafa, H. Shareef and G. Aliyu. Artificial intelligent meter development based on advanced metering infrastructure technology. Renewable and Sustainable Energy Reviews, vol. 27, p. 191-197, 2013.

[25] E. O'Driscoll, G. E. O'Donnell. Industrial Power And Energy Metering - A state-of-art Review. Journal of Cleaner Production, vol. 41, p. 53-64, 2013.