Modelling Electrical Energy Consumption in Automotive Paint Shop

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Abstract. Industry players are seeking ways to reduce operational cost to sustain in a challenging economic trend. One key aspect is an energy cost reduction. However, implementing energy reduction strategy often struggle with obstructions, which slow down their realization and implementation. Discrete event simulation method is an approach actively discussed in current research trend to overcome such obstructions because of its flexibility and comprehensiveness. Meanwhile, in automotive industry, paint shop is considered the most energy consumer area which is reported consuming about 50%-70% of overall automotive plant consumption. Hence, this project aims at providing a tool to model and simulate energy consumption at paint shop area by conducting a case study at XYZ Company, one of the automotive companies located at Pekan, Pahang. The simulation model was developed using Tecnomatix Plant Simulation software version 13. From the simulation result, the model was accurately within ±5% for energy consumption and ±15% for maximum demand after validation with real system. Two different energy saving scenarios were tested. Scenario 1 was based on production scheduling approach under low demand situation which results energy saving up to 30% on the consumption. Meanwhile scenario 2 was based on substituting high power compressor with the lower power compressor. The results were energy consumption saving of approximately 1.42% and maximum demand reduction about 1.27%. This approach would help managers and engineers to justify worthiness of investment for implementing the reduction strategies.

1. Introduction

In a recent economic downturn trend environment, the industrial player must be smart enough to control their expenses and utilize their resources optimally. In order to sustain in their business, the company must find a solution to reduce their operational cost so that they can survive and keep maintaining their reputation in front of customer view. One aspect that has big potential for cost reduction is an energy consumption cost.

In general, there are some barriers that limit the industrial player to extensively explore on improving energy efficiency. Such barriers are the limitation of capital investment, technical risks, challenging in collecting energy related data, very little information about efficiency opportunities and the cost of identifying and assessing opportunities. This study tries to analyse energy consumption level in automotive industry by using simulation-based model approach and observe the effectiveness of energy saving methods through virtual analysis. In automotive manufacturing plant, energy is used throughout the plant for many different end-uses. The common types of energy used are electricity, steam, gas and compressed air. About two-thirds of total expenditure on energy is spent on electricity [1]. In automotive assembly process plant, generally, consists of body shop, paint shop, assembly shop [2]. Paint shop is a
general name called for area where the painting process is conducted. Inside the paint shops there are several main processes such as pre-treatment, electro-coating, sanding, sealant, primer coating, base coating and top coating [3]. Meanwhile, in some processes like pre-treatment and electro-coating there are several sub-processes.

In regards of portion energy consumption, paint shop is considered the highest consumer of energy which estimated around 50-70% of total energy consumed [4]. Pre-treatment, paint application and curing are the main processes in the area that use major energy, while the detail distribution depends on the system’s design and the technology built in [4].

In a relation with the high energy used in the paint shop area, many studies on energy consumption can be found using paint shop as a case study. Guerrero et al. [10] introduced a model to optimize painting process by reducing the number of unnecessary repaints, and reported that this method successfully reduced the energy consumption by 4%. Rohdin et al. [5] studied the effect of controlling air flow in the spray booth line in order to reduce energy caused by large quantities of air used to maintain the air quality. Chen and Zang [6] investigated energy consumption reduction through effective scheduling of machine start up and shutdown. Trakultongchai [11], used simulation model approach to study on process improvement. Effect of car sequencing to the energy consumption was studied by Zhang et al. [7]. Earlier, Cronrath et al. [4] came out with environmental discrete event simulation approach for energy analysis to overcome barriers that facing in implementation of energy analysis study.

Several researchers have conducted energy analysis study using various simulation tools available nowadays. Simulation modelling has gain interest to researcher due to its ability to model real system environment without affecting actual system. Al-Ajmi and Handy [12] used plant simulation as a design tool for to analyse energy consumption performance in proposed building design as well as evaluating the effect of varying certain design parameters. Fysikopoulus, et al. [13] conducted an empirical study of energy consumption at body-in-white subassembly. Meanwhile, thermodynamic simulation model has been used by Feng and Mears [8] for analysis of energy consumption by Heat, Ventilation and Air Conditioning (HVAC) system in automotive paint shop.

In recent development, Tecnomatix Plant Simulation (TPS) is increasingly been used in the energy analysis study. It is due to introduction of energy analyser function inside the Plant Simulation software version 11 [9]. Trebuna and Popovic [14] used Tecnomatix to develop digital factory model and demonstrate the power consumption capability of the software. It is almost similar with the study by Cronrath [4].

This paper aims at reporting a tool to model and simulate energy consumption at paint shop area by conducting a case study at XYZ Company, one of the automotive companies located at Pekan, Pahang. The model is conducted based on discrete event simulation approach by using energy analysis function of Tecnomatix Plant Simulation software version 13. The painting process covered in the study is starting from pre-treatment until final touch up process while the energy analysed is based on electrical control panels directly connected to the process equipment’s in paint shop area. Objectives of this study were; (i) to develop energy simulation-based model for paint shop area, (ii) to validate energy consumption at the paint shop area, and (iii) to evaluate energy saving potential through different scenarios using simulation model.

This paper is organized as follows. First Section serve as an essential introduction to research. Second section describes the research methodology and its rationale. Next section provides an overall result and discussion of research finding. Last section concludes the study and suggestion for future work.

2. Methodology
The methodology carried out in order to fulfil the objectives stated in the study. Generally, the methods can be divided into four stages which relate to the particular objective, namely: (i) Data collection, (ii) Initial model development, (iii) Model validation, and (iv) Simulate alternative scenarios, as discusses as follow:
2.1. Data Collection and Initial Model Development

Several information and parameters have been defined as the necessary input data in this study. The data can be classified into 3 type of data; process flow data, energy data and validation data.

The gathered data under process flow category were overall paint shop layout (required to develop the mimic model that almost similar with the actual system), Process flow information (required to know the sequence of processing for the paint shop process), Time study (processing time & cycle time), and Production working hours (required to simulate the system).

The focus of energy to be analyzed in this study is the electrical energy. In line with that, the elements that use electrical power are identified and the power measurements are made on each of the elements. The measurement conducted using AC clamp meter to measure Phase Current (A) and Line Voltage while Power Factor, PF value is taken directly from the electrical element specification. Equation (1) is then been used to calculate Phase power, $P_n$ for each phase where for 3-phas system there will be Red-phase Power, $P_{red}$, Yellow-phase Power, $P_{yellow}$ and Blue-phase Power, $P_{blue}$. Summation of each phase power will result the Total Power, $P_{total}$ used by each of the element as specify in equation (2).

$$P_n = \frac{\text{Line Voltage}}{\sqrt{3}} \times \frac{\text{Phase Current (A)}}{1000} \times PF$$

$$Total \ Power \ (kW), P_{total} = P_{red} + P_{yellow} + P_{blue}$$

The $P_{total}$ value calculated is the main input parameter for simulation model. For validation purpose, the latest 5 months electricity consumption (EC) and maximum demand (MD) data are collected from Tenaga Nasional Berhad (TNB) smart meter. EC is the total amount of energy been used for a month period and it is measured in kWh while MD is the highest level of electrical demand recorded during a 30-minute interval in a month and it is measured in kW. The interval time to determine MD may vary by different energy provider and country. The type of tariff implemented at the company is determined to calculate the electricity cost.

Next step after all the relevant data have been collected is to start building the simulation model of the system. At first, it is defined as initial because adjustment and modification might be needed after run test and validation process. Under this phase, three main activities have been defined which are constructing model conceptual and assumptions, programming the model and validation and analysis of the model.

2.2. Model Validation

To ensure the simulation model is valid, the total EC and MD value from the simulation result are being compared with the actual data recorded from the company. The confidence interval set for the simulation model is 95% for EC and 85% for MD. Lower value set for MD because of the study scope did not cover in details the operation sequence and running time for every single energy consumer which is needed to accurately simulate MD value. Thus, the error within 5% for EC and 15% for MD are considered valid. After the result validated, the scenario for energy saving measure is being simulated and the amount of energy saving is being presented in term of amount and cost saved.

2.3. Simulate alternative scenarios

In this study, two different scenarios are evaluated in order to analyse the energy consumption reduction by implementation of the alternative scenarios. The scenarios chosen for evaluation were based on current situation at XYZ Company.

The technique applied in scenario 1 is considering low demand situation where the production running below its actual capacity. The processes which recorded the high amount of energy consumption had been chosen which is in this case Primer and Top Coat processes. Both processes are consequent where the part from primer operation will go into top coat operation. In this scenario, the production...
time for both processes are reduced into half than normal working hours. In the first half, the Primer process will operate first and in the second half, Primer will be shut down and Top Coat will begin operation.

Meanwhile, scenario 2 is using equipment change method. Under simulation approach, it is easy to simulate the equipment change. In this case, the compressors power change has been modelled and the effect on total energy consumption had been simulated to study the amount of reduction. The change is done by reducing the power input for high power compressor to follow the value of lower power input compressor. In reality, the new equipment must be ready first before it can be tested but in virtual, it is simply done by changing the power setting at simulation model. The result could be used to justify whether the changing is worth or not for implementation.

3. Results and Discussion

3.1. Data Collection

3.1.1. Process Flow, Processing Time and Production Working Hour
Paint shop of the company XYZ consists of eight main processes. It starts with Pre-Treatment and Electro-deposition (PTED) section involving several sub-processes such as hot water cleaning, degreasing, rinsing, conditioning, phosphate, electro-deposition, ultra-filter and oven. Then it goes to ED Sanding, sealant, primer, moist sanding, major rework, top coat and touch. Processing time data is directly taken from time study data provided by the company. This scope study is not going detail on processing time distribution pattern. Our general assumption for manual process, the time follow the data provided in the time study table while for automatic process the time set constantly 5.00 minutes based on production cycle time. The company XYZ is running production in normal working hour, 5 days per week. The start working time is at 8:00 AM and end at 5:30 PM.

3.1.2. Energy Data
Current measurement has been conducted for 58 control panels which have been identified having direct relation with the production process. Although it is not completely covers all energy consuming elements for the whole paint shop like administrative room, air conditioning system and a few control panels that difficult to access, the result is still considered valid because all major systems that have significant effect to energy consumption have been covered. For the example, the total power input result calculated using previous mentioned equations for Top Coat process is shown in Table 1. The top coat involves 11 control panels with different power input along its processes.

3.1.3. Validation data
In order to validate the result from simulation model developed, the current electricity usage for the company XYZ is recorded. The available data provided by the company is the latest 5 month. Table 2 summarized the electricity usage and the cost based on TNB tariff. The company XYZ is using Tariff E1- Medium Voltage General Industrial Tariff. Under this tariff, the cost of RM29.60/kW will be charged for each kilowatt of MD per month and 33.70cent/kWh for total EC.

Table 1. Power Calculation for Top Coat process.

| Main Process       | System Control Panel | Control Panel ID | Line Voltage (V) | Power Factor; PF | Total Power (kW) |
|--------------------|----------------------|------------------|------------------|------------------|------------------|
| Top Coat           | ASU Top Coat Blower 2| TopCoat_CP1      | 430              | 0.75             | 129.75           |
|                    | ASU Top Coat Blower 3| TopCoat_CP2      | 430              | 0.75             | 123.41           |
|                    | ASU Top Coat Blower 4| TopCoat_CP3      | 430              | 0.85             | 60.78            |
|                    | ASU Top Coat Humidifier 1| TopCoat_CP4   | 430              | 0.85             | 5.87             |
|                    | ASU Top Coat Humidifier 2| TopCoat_CP5   | 430              | 0.85             | 5.96             |
|                    | Top Coat Exhaust Fan No 1| TopCoat_CP6    | 430              | 0.85             | 29.58            |
Table 2. Energy consumption records for Company XYZ.

|                   | November | December | January  | February | March   | Average   |
|-------------------|----------|----------|----------|----------|---------|-----------|
| EC (kWh)          | 779,203  | 813,545  | 820,156  | 846,371  | 1,112,628 | 874,380.6 |
| Tariff (RM)       | 0.337    | 0.337    | 0.337    | 0.337    | 0.337   | 0.337     |
| Cost usage (RM)   | 262,591.4| 274,164.7| 276,392.6| 285,227.0| 374,955.6| 294,666.3 |
| MD (kW)           | 3.083    | 2.763    | 3.090    | 3.169    | 3.236   | 3.068.2   |
| MD Tariff (RM)    | 29.60    | 29.60    | 29.60    | 29.60    | 29.60   | 29.60     |
| MD cost (RM)      | 91,256.80| 81,784.80| 91,464.00| 93,802.40| 95,785.60| 90,818.72 |
| Total Cost (RM)   | 353,848.2| 355,949.5| 367,856.6| 379,029.4| 470,741.2| 385,485.0 |

3.2. Initial Model Development

From the data collection result, it is known that 58 control panels are going to be simulated in the model for energy consumption. The control panel may be connected with more than one process or system. For the purpose of modelling, the energy parameter setting for control panel will be set to either one of related process to avoid the multiplication of the result if each process is setting with the power input parameter. Thus, the sub-processes for every main process are mapped with the related energy system control panel. For each process that was mapped with energy control panel, the power input value will be assigned. In our model, we assume that operating power and working power for all the systems are same but in actual certain systems would have slightly lower operating power than working power.

Several assumptions have been made on the simulation model developed, such as: The power input used for operational, working and setting up state is considering same; assuming each station has buffer for part waiting to be processed; the arrival rate for incoming parts is assumed constant; Part entering the system considered like triggering switch to activate the energy usage. For manual processes; the processing time is considered varies in normal distribution based on data from time study; Upper and lower bound is set at 30% from the mean value. For automatic process; the processing time is considered constant and set same as cycle time which is 5.00 minutes; the operation machine is assumed running at 98% availability rate in order to model unexpected downtime that might occur throughout the operation. The peripherals energy consumers such as light and air-conditioning system along the operation are neglected.

3.3. Model Validation Results

The simulation model has been set to run for 20 days in order to get the total energy consumption in a month. The total EC result from simulation is 916,350 kWh in a month while the MD is 2,741.2 kW. To validate the result, the average data of the latest five months usage had been taken for comparison. Table 3 shows the comparison between simulation result and actual data.

Table 3. Comparison between simulation result and actual data.

|                  | Actual  | Simulation | Difference (Simulation - Actual) | Percentage Error |
|------------------|---------|------------|---------------------------------|-----------------|
| EC (kWh)         | 874,380.6| 916,350    | 41,969.4                       | 4.8             |
| MD (kW)          | 3,068.2 | 2,741.2    | -327                           | -10.7            |

From Table 3, the percentage error calculated between simulation and actual result is 4.8% for EC and 10.7% for MD. Thus, the result is considered valid because both EC and MD results are within targeted percentage error.
3.4. Simulating Alternative Scenario

3.4.1. Scenario 1: Reschedule Primer and Top Coat Operation
In a low demand situation as facing by company XYZ recently, one possible approach could be consider for energy saving is to reschedule the operation of primer and top coat process. Conducting this operation strategy could also reduce the requirement of workers where the same operators for primer process are then use to execute top coat process. But, need to be reminded this only works in a low demand and loose production situation only. Table 4 shows the operation time for both processes under normal production and rescheduled production. In a process flow, primer comes before top coat. Therefore, primer processes are being executing first in first half operation time from 8:00 AM till 12:30 AM. During that time, all energy resources for Top Coat is still under shutdown or sleep mode. When the primer process finished, the energy resources at Primer will be shut down and Top Coat starts operation for the second half of operation time.

| Normal Operation | Reschedule Under Low Demand |
|------------------|-----------------------------|
| Primer           | 08:00 AM - 17:30 PM         |
| Top Coat         | 08:00 AM - 17:30 PM         |

Total simulated energy consumption for one month under this operation had been reduced to 641,445 kWh while maximum power input is not changed. Calculation for reduction amount is tabled in Table 5. Total energy consumption reduced in Scenario 1 compare to the current simulated system is 274,905 kWh per month which is equal to RM 92,642.99.

| Current | Scenario 1 | Amount Reduction |
|---------|------------|------------------|
| Consumption (kWh) | 916,350.0 | 641,445.0 | (274,905.0) | (92,642.99) |
| MD (kW) | 2,741.2 | 2,741.2 | - | - |
| Percentage (%) | | | | 30 |

3.4.2. Scenario 2: Changing Compressor Power
In scenario 2, the effect of changing the power input of compressor is being studied. We knew from the simulation results for current system, compressors were among top energy consumers. To study this in real system is very difficult because it involves modification on current system. Thus, production has to be interrupted and some investment cost need to be spent.

Meanwhile, conducting such studied in virtual environment could be done easily. Table 6 shows current compressors used in paint shop area and their power input respectively. If Compressor No. 21 and Compressor No. 12 been changed to the same type with compressor No. 18 and 20, the power input is expected be reduced to 107.7 kW.

| No. | System       | Control Panel | Power Input (kW) |
|-----|--------------|---------------|------------------|
| 1   | Compressor No.12 | Compressor_CP1  | 117.3            |
| 2   | Compressor No.18 | Compressor_CP2  | 107.7            |
| 3   | Compressor No.20 | Compressor_CP3  | 107.7            |
| 4   | Compressor No.21 | Compressor_CP4  | 133.1            |
| 5   | Compressor No 22 | Compressor_CP5  | 76.1             |
To simulate this, we simply change the input power parameter at our simulation model for compressor No. 21 and 12 from 133.1 and 117.3 respectively to 107.7 kW. After running the simulation, the total energy consumption recorded was 903,337.8 kW. The result is tabled as in Table 7. It has been noticed that the MD value is also affected with the reduction amount of 34.90 kW. Summation of reduction both in energy consumption and MD results the total saving of RM 5,418.15 per month under scenario 2 implementation.

Table 7. Reduction of energy consumption under Scenario 2.

|                | Current kWh | Scenario 2 kWh | Amount Reduction kWh | %  | RM     |
|----------------|-------------|----------------|----------------------|----|--------|
| Consumption    | 916,350.00  | 903,337.80     | (13,012.20)          | 1.42| (4,385.11) |
| MD             | 2,741.20    | 2,706.30       | (34.90)              | 1.27| (1,033.04) |
| Total (RM)     |             |                |                      |    | (5,418.15) |

4. Conclusion

4.1. Conclusion

This study has successfully come out with the automotive paint shop simulation model for XYZ Company that could be used for energy consumption analysis. The model has been developed using Tecnomatix Plant Simulation software version 13 which embedded with the energy analysis function. Comparison with actual consumption data recorded by the company, shows that the model was accurate within ±5% with the average recorded EC and ±15% for the MD data.

In this study, two scenarios on energy saving methods had been tested using the model developed. In scenario 1, it can be noticed that it is possible to reduce the EC simply by managing the production schedule and the way production running. By running half working hours for Primer and Top Coat respectively and consequently, the amount of EC could be reduced up to 30% which is about RM 92,642.99 saving in electricity charges.

Moreover, in the scenario 2, the higher power input compressors which are compressor 12 and 21 had virtually changed to the same power type with compressor 18 and 20. The result of the saving amount is approximately 1.42% in EC and 1.27% in MD which is about RM5,418.15 total reduction in electricity charges.

The simulation result for current system and energy saving scenarios had been summarized as shown in Table 8. It can be concluded that large amount of saving could be resulted from implementation of scenario 1. Meanwhile, for scenario 2 further study on amount of investment and return of investment should be conducted to justify whether the implementation is worth or not.

Table 8. Summary of simulation result for all scenarios.

|                | Current kWh | Scenario 1 kWh | Scenario 2 kWh |
|----------------|-------------|----------------|----------------|
| EC             | 916,350.00  | 641,445.00     | 903,337.80     |
| Reduction      | 274,905.00  | 13,012.20      |               |
| Percentage (%) | 30.0        | 1.42           |               |
| MD             | 2,741.20    | 2,741.20       | 2,706.30       |
| Reduction      | 0.00        | 34.90          |               |
| Percentage (%) | 0           | 1.27           |               |

4.2. Future Work

In this study, the model paint shop being studied is an old fashion type paint shop line which most of the processes are manually conducted by human such as sanding, primer and top coat spray. In modern style, mostly the new paint shop line involves robots to execute the processes. However, this type of paints shop line is still unavailable at company being studied. Other than that, the major limitation in this study is the availability of data. Several assumptions have to be made because of lack of data.
available. This is because company policy state limited access to the outsider in accessing company internal information. Therefore, only data that are provided by the company are allowed to be used in study purpose. Even no single photo is allowed to be captured inside the company.

The same model and approach could be extended further for other type of analysis which has not been covered in this project scope. At least three other topics could be considered for further research as follows:

- Energy efficiency could be related with how well the energy been used to produce one unit of output. Data on processing time, machine availability, reject rate and current production output at least must be well collected to realise this study.
- The capability of Technomatix Plant Simulation is also to analyse different power operation state if details power input for each state is known. By utilizing the operation state, energy optimization study could be conducted. Again, information on failure rate, machine availability, production schedule is crucial in order to conduct energy optimization study.
- An extended study using the same approach could be done on automatic paint shop model that most of processes done by robots. It should be more interesting because this paint shop is expected to consume more energy compare to manual paint shop

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