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Energy Consumption Profiling - A Case Study in a Batch Manufacturing Facility

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ABSTRACT

The energy consumption, its data collection and analysis in manufacturing facilities are of high importance for future production decisions. However, it is not always a straight forward task as data analysis relies on the quality and quantity of the collected data. Depending on these factors, extra measurements for additional data collection may be necessary that require purchasing and installing additional gauges, meters and transmitters. In this work, data analysis is conducted for a healthcare batch production facility which produces topical skincare products. The collected data represents the total consumption of the electric energy in the production facility including the production area, in addition to other facility consumers such as computers, lighting as well as heating, ventilation and cooling (HVAC). The data analysis is performed in order to separate the energy consumption of the production area from the energy consumed by other daily resources. The latter is identified as the base load consumption. A mathematical model for the estimation of the energy consumption of the base load on 15-minute basis is applied. After splitting the energy consumption of the production area from the base load, additional analysis is performed to quantify the energy consumed for producing a single product without the need to install any additional measurement devices. The quantity and profile of the energy consumption of the product are introduced and compared to the manufacturing data collected from the batch production records to identify the production steps that consume most of the energy for the product. By following the proposed methodology, the planning and future scheduling of batch production processes can be used to minimise energy consumption.

Keywords

Data analysis, mathematical modelling, energy quantification, batch production.

1. INTRODUCTION

As electrical energy is mostly used in the industrial sector, attention is required to properly utilise it to decrease the environmental effect associated with its generation. The main reason for such concern is that for each one kilowatt-hour of electricity produced by using fossil fuels, 900 g of CO_2 are released into the environment [1]. Having a proper measurement of the electric demand of any electric-consuming facility can help in decreasing the environmental load. Overestimating the required electric load will result in a waste of energy on the demand side and greater emissions than needed in the case of using fossil fuels for generation of electricity. Accurate electric load estimation and forecasting are key elements in the decision-making process for both power plants and industrial consumers. Due to the importance of electric load estimation and forecasting, many authors have published review papers on the models and methods applied for electric load forecasting [2]–[5]. A major emphasis is placed on the energy analysis and estimation of the energy data for residential, office buildings and industrial facilities [6]–[9].

Batch production is a major production method which is used in case of low volume and high value-added intermediates such as specialty chemical, paints and pharmaceutical products [10]. Although batch production can easily utilise the available resources, it requires sophisticated tools for planning how to share the resources required for each batch manufactured. A major step in planning the shared resources for a batch production system is to determine the required resources for each batch manufacturing process. Although these resources can include equipment, utilities, manpower, raw materials and storage tanks, the main resource studied is this paper is electric consumption [11]. The main reason for focussing on electrical energy analysis for batch production environments is that approximately 50 percent (%) of the manufacturing industry are batch processes [12]. This signifies the importance of electrical energy analysis in batch production environments. In addition, few researchers have considered the cost of electric energy in batch industries although the electricity cost accounts for 10-50 percent (%) of the final product cost [13]. Different applications of electric energy analysis have been applied to batch production processes that include the steel industry [14], [15] and batch processing machines in the glass industry [13]. In this paper, a healthcare batch production facility is studied to estimate the electric base load of the plant on 15-minute basis. The estimated base load is used to determine the required electrical energy for manufacturing different batches of the same product. Further analysis of the estimated electrical energy for this product is performed leading to more accurate results.

2. METHODOLOGY

Products are manufactured in large mixing vessels equipped with two large electric motors; one for the main vessel agitator and the second is for the vessel homogeniser. Each vessel has a heating/cooling jacket to achieve the required temperature

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depending on the recipe requirements. Hot and cold water are circulated through the external jacket of each mixing vessel via two circulation pumps; one for hot water while the second is dedicated for cooling water. In addition, each vessel is connected to a vacuum pump to maintain the required pressure during manufacturing.

Electrical energy data was obtained for every 15-minute interval between April 2017 and April 2018. The electric energy data does not distinguish the energy used in manufacturing the products from other normal electric consumers such as computers, lights, kitchen and HVAC. A possible solution is to install additional measuring devices, on the mixing vessels for example, however, this solution is expensive. This represents a challenge to separate the energy used for manufacturing and to quantify the electric energy required for manufacturing products. As the recorded energy represents the total electrical energy consumption for the production facility, the energy required for manufacturing can be estimated as the difference between the total electrical energy consumption and the base load electrical consumption. The base load electrical consumption is identified as the electrical load including all the electric consumers except the electric consumers attached to the mixing vessels in the manufacturing area. In this case, the integration between the electrical energy data and the data collected from the batch manufacturing records can be used to identify the base load consumption for the production facility. The batch manufacturing book records each manufactured batch start and end times. These times are coupled with the data for the plant energy consumption to identify the energy consumed when the manufacture of these batches occurred. The remaining energy values represent the energy consumption when manufacturing was not taking place. The energy values when there was no manufacturing are called *"No manufacturing"* energy values, which is abbreviated as NM. The NM used in the estimated base load excludes the weekends as no manufacturing occurs during weekends. The estimated base load curve using the average values of NM for each 15-minute interval over the course of the years data is defined as "approach 1" and is presented in Figure 4. The following steps can summarise approach 1.

1. Identify each 15-minute period between 00:00 to 23:45 that there is no manufacturing taking place over the period between April 2017 and April 2018.
2. Average the energy values for each of these 15-minute time periods for the studied year.

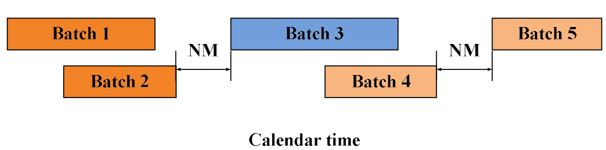

Figure 1. Illustration of the model used for identifying NM

The model used to identify the NM was then modified to search for the cases when there is only a single batch is manufactured. This case is identified as a *"single-batch manufacturing"* or SBM case. For SBM, the observed energy values represent the base load energy consumption in addition to the energy required for producing that specific batch of the product. By calculating the area between the curves of the estimated base load and the total energy consumption at the time of manufacturing the studied batch, the energy required to produce the single batch under study is calculated. The following steps can summarise the "single-batch manufacturing model" from the modified NM model.

1. Identify cases where there were instances of single batch manufacturing.
2. Average the energy values for each of these 15-minute time periods.
3. Subtract the yearly NM base load from the SBM cases identified to calculate the energy consumption for specific SBM cases. Calculating the area between the NM curve and the SBM curve leads to the same estimate of the energy consumption for specific SBM cases but with considering 15-minute interval.

SBM cases are identified in the case of having NM before and after the start and end time of any batch as shown in Figure 2. This guarantees that there are no batches manufactured at the same time.

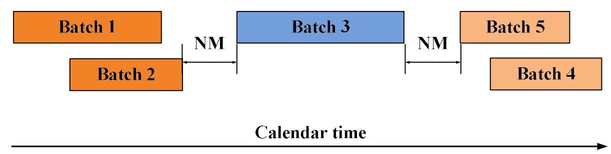

Figure 2. Illustration of the model used for identifying SBM

After all single-batch manufacturing cases are identified for different products, one product was chosen for further study. To have the same base for comparing the results, the time of the day at which the studied batches are manufactured need to be similar.

In this study, the batches produced between 00:00 and 07:00 are selected. The energy consumption of a selected batch estimated using the "single-batch manufacturing model" and the base load energy consumption estimated using approach 1 are on the same graph as shown in Figure 5. The energy consumption for producing the selected batch is estimated by calculating the area between the two curves. In the next stage, the methodology for estimating the base-load is updated by taking the average of the NM values for two weeks before and after the date at which the studied batch is manufactured. This differs than approach 1 used in base-load estimation for which the average of the NM is taken for one year. The purpose of such method is to have greater confidence in the base load estimation as there was a noticeable change in energy consumption over the investigated period due to an upgrade to the plant's HVAC system. This upgrade led to a significant decrease in the actual energy consumption in the plant after a certain date. Calculating the base load by taking the average of the NM values two weeks around the date of manufacturing a specific batch is defined as "approach 2". The following steps can summarise approach 2.

1. Identify cases between 00:00 and 07:00 where there were instances of single batch manufacturing.
2. Identify each 15-minute period between 00:00 to 07:00 that there is no manufacturing taking place two weeks before and after the cases identified in step 1.
3. Average the values for each of these 15-minute time periods.

It is important to highlight that in all figures, the y-axis which should represent the energy consumption in kWh is normalised to anonymise the data.

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3. RESULTS AND DISCUSSION

The NM energy values for each 15-minute interval are plotted using boxplots in Figure 3. In this figure, each boxplot represents the spread of recorded values over a year at each 15-minute period from 00:00 to 23:45. Some boxplots are skewed and have outliers at different times. This is due to the large variability in the values of NM energy values. Possible justifications for such variability are the randomness of the daily activities related to people in the production facility, seasonal effect on HVAC system and other activities such as cleaning and packaging which are not recorded in the batch manufacturing records.

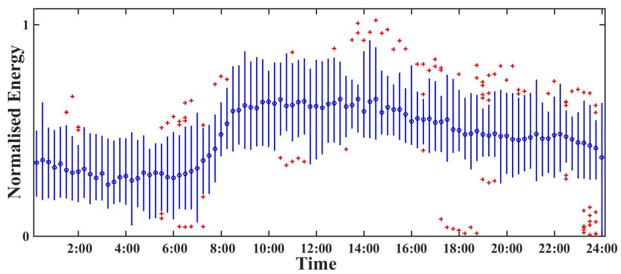

Figure 3. Boxplot of NM values for 15-minute intervals

The estimated base-load is calculated by taking the average of the values of NM for each 15-minute period for one year as defined as approach 1. Although the values of NM at each period vary as shown in Figure 3, the methodology was followed to estimate the base-load. This can be justified by comparing the behaviour of the estimated base load shown in Figure 4 with the actual activities taking place at the facility. The energy consumption starts to increase at the early morning (around 07:00) due to the arrival of staff until reaching its maximum value between 13:00 and 14:00. After that time, the energy consumption decreases until reaching very low values at night. The main reason for such decrease in the energy consumption is that the number of personnel in the facility at night is much lower than the number during the day. So, a major part of the electric consumers such as lights and computers are switched off. After the electrical load decreases at night, it increases again in the morning of the next day in a cyclic manner.

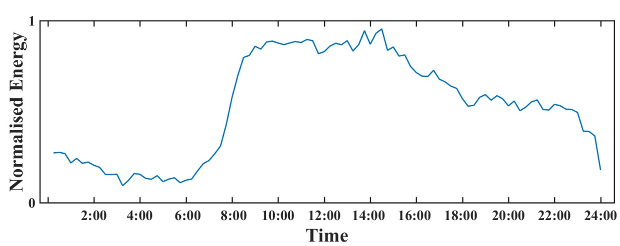

Figure 4. Estimated base-load for 15-minute interval

The energy consumption of a single product can be estimated by following the methodology in Section 2. After identifying all the single-batch manufacturing cases, only one product is selected for further study which is given code of “P1”. The criteria for selecting the batches of a product for further study is mentioned in Section 2.

To calculate the energy consumption for producing each studied batch for product “P1”, three batches of product “P1” referred to as A, B and C are selected. The total energy consumption at the manufacturing time of each batch is plotted against the values of the estimated base-load energy consumption using approach 1 as shown in Figure 5. The energy consumption for each batch is estimated by calculating the area between the two curves between the start and end time of manufacturing each batch.

The shape of the curves of the actual energy consumption (the blue curves in Figure 5) for batches A, B and C are not identical. Other activities such as cleaning or packaging are also occurring and the energy used to complete these activities could be a possible cause of this variability. The energy values are recorded every 15 minutes and aligning the start and end of each manufacturing step exactly to these 15 minutes intervals is not possible.

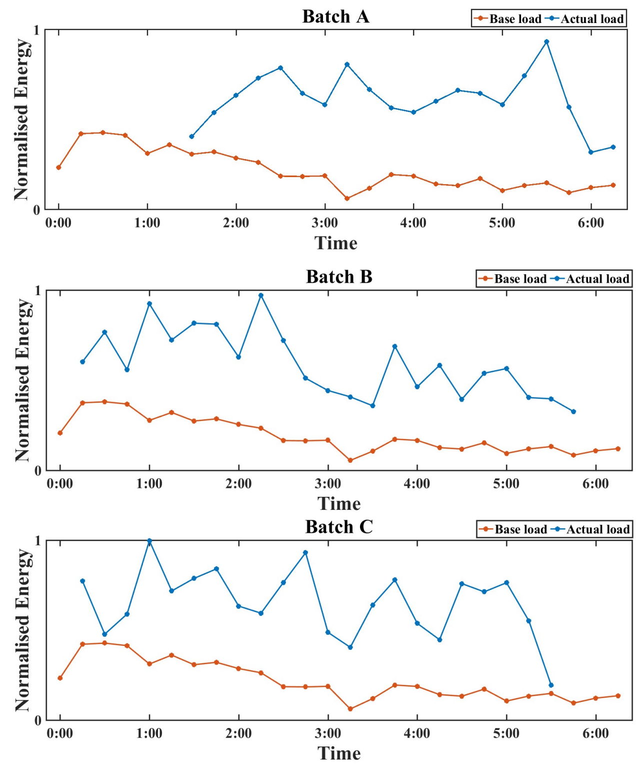

Figure 5 . Total energy Vs. estimated base-load for batches A, B and C of product “P1" using approach 1

The estimated energy consumption for product “P1” differs based on the number of manufacturing hours as clarified in Table 1. As the manufacturing time increases the energy consumption also increases. The energy consumption is normalised by forcing the energy consumption of batch B to equal unity then the estimated energy consumption for other batches is considered as a fraction of B. Batch B is selected to normalise all the energy values as batch B has the highest energy consumption compared to the other two batches.

Table 1. Summary of results for three batches (A, B, and C) of product "P1"

Batch	Total manufacturing hours	Normalised energy consumption
A	4:45	0.90
B	5:30	1
C	5:15	0.94

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After taking the average of the NM values two weeks around the date of manufacturing of batch C as explained in approach 2, a new estimate of the base-load is plotted against the total energy consumption at the manufacturing time of batch C as shown in Figure 6. Batch C was chosen as it had a significant number of NM points surrounding it whereas batches A and B had missing values. Hence, batch C provided more confidence in the estimated base load.

The estimated energy consumption when approach 2 is applied is normalised and equals 0.70, of the energy consumption of batch B, for total manufacturing time of 5:15 hours. This value is lower than the normalised energy consumption for batch C, i.e. 0.94, when approach 1 is applied as shown in Table 1. As there was a significant decrease in the plant electrical load in the second half of the year due to the upgrade of the plant's HVAC, it was expected that the base load estimate following approach 2 would be higher than the estimate using approach 1 leading to less required energy consumption per batch C. This is expected as the observations recorded in the two weeks before and after batch C was manufactured are more reflective of the true base load during that four-week period rather than containing all the yearly data that has large variation as discussed.

In Figure 6, the actual load and the estimated base load are close at the start and the end of manufacturing Batch C. This indicates that the approach of taking the average of NM values around the manufacturing date of the studied batch is more appropriate. Just before the start of batch C manufacturing, the base-load and the actual plant energy consumption should be close as no manufacturing is taking place so, the total energy consumption should equal the base-load value at that time.

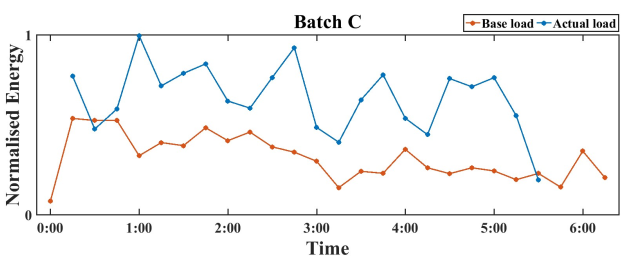

Figure 6. Total energy Vs. new predicted base-load for batch C of product 'P1" using approach 2

Once the manufacturing starts, the values of the total energy consumption will increase due to turning on all the electric devices attached to the mixing vessel dedicated to manufacture batch C. At the end of the manufacturing cycle, the electric consumers are turned off leading to decreasing the total energy consumption to reach again the value of the base-load.

When the difference between the total energy consumption and base-load from Figure 6 is plotted, the energy profile of manufacturing batch C is concluded as shown in Figure 7.

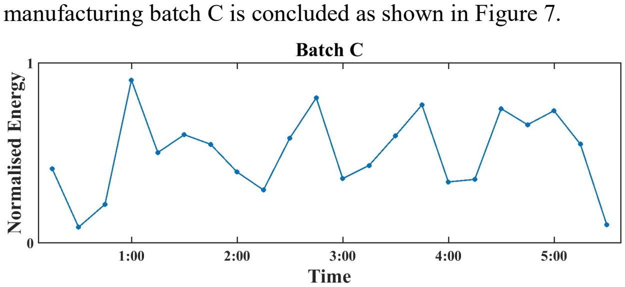

Figure 7. Energy profile of Batch C of Product "P1"

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When the energy profile in Figure 7 is compared with the data in the actual batch manufacturing record of batch C, three of the five peaks in the energy profile correspond to the times when the large electric consumers of the mixing vessel were working on full load. Three of the four minimum values in the energy profile correspond to the times when raw materials were added to the mixing vessels. This indicates that the energy profile of batch C is very close to the actual case when batch C was manufactured.

After the rated power of each electric device, on the mixing vessel used in batch C manufacturing, is multiplied by its working hours then summed as shown in Table 2, the maximum normalised energy consumption for manufacturing batch C equals 0.88. In Table 2, the identity of each electrical device and its rated power are anonymised. The value 0.88 represents the upper limit of the normalised energy consumption when the electric devices work at their rated power. When this value is compared with the values of 0.94 and 0.70 estimated from approach 1 and 2 respectively, it is found that the value from approach 1 exceeds the maximum normalised energy consumption for manufacturing batch C which is not possible. Also, the value from approach 2 is less than the maximum normalised energy value, which is logical as the electric devices shall work within a percentage of their rated power. This indicates the suitability of approach 2 over approach 1 in determining the energy consumption.

Table 2. Maximum energy consumption for Batch C of Product "P1" based on rated power of electric consumers

Component	Normalised rated power	Working time	Normalised consumed energy
Electric component 1	0.004	0:35	0.0024
Electric component 2	0.004	1:25	0.0058
Electric component 3	0.0517	1:03	0.0543
Electric component 4	0.1138	4:00	0.4554
Electric component 5	0.2328	1:33	0.3609

4. Conclusion

The energy consumed per product in a batch production facility can be estimated based on the introduced term NM or *"No manufacturing"* energy values. NM are the energy values at the times when no batches are manufactured. The NM are extracted from the total energy consumption data by eliminating the energy consumed when each batch was manufactured for the studied period. The remaining energy values represent the energy consumed when no manufacturing is taking place. By taking the average of the NM for one year as defined as approach 1, an estimated base-load for the production facility was introduced. The base-load represents the energy associated with all the activities in the production facility excluding the energy required for batch manufacturing. Three batches of the same product are studied, and their energy consumption are estimated by plotting the total energy consumption versus the estimated base-load. The area between the curves represents the estimated energy consumption for the studied batches. By following approach 1,

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the estimated energy consumption for the batch C was higher than the maximum normalised energy consumption for manufacturing batch C. The latter is calculated by multiplying the rated power of each electric consumer with its operating time extracted from the batch manufacturing record of batch C. More accurate results are determined when approach 2 is applied. Approach 2 is based on taking the average of NM values two weeks around the manufacturing date of batch C. In this case, the estimated energy consumption was lower than the maximum normalised energy consumption for manufacturing batch C. This signifies an improvement in the energy estimation based on the average around the manufacturing dates of the studied batch.

When the energy profile of batch C is calculated based on the difference between the total energy consumption at the manufacturing time of batch C and its estimated base load using approach 2, most of the peaks and minimum points corresponded to the actual times when electric consumers were working fully, and raw material were added respectively. This can prove the suitability of the proposed methodology to introduce an energy profile for each product in similar production environments.

5. Recommendations and future work

The energy data of activities such as cleaning and packaging can improve the results by removing the associated energy consumption with such activities from the base load estimate. This is expected to decrease the variation in the estimated base-load. Also, studying the effect of climatic data on the HVAC system may lead to better results. An estimated base-load for each month rather than a full year would have a positive effect on the results. The results of the work can be extended to introduce a better production plan based on the electrical consumption per product by considering scheduling under time-of-use electricity tariff as suggested in different applications [16], [17].

6. ACKNOWLEDGMENTS

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