Industrial Power Study: An Approach

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Industrial Power Study: An Approach

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Abstract

A power study was carried out to attain power profiles for the machines used by a Medical Device Manufacturing company in Ireland, on a particular value stream (VS) for two products, in order to; (a) understand the machines' electrical consumption during productive and idle states, and (b) ascertain the utility services such as compressed air, coolant, process water (deionised water) and dust extraction consumed at each machine station during productive and idle states. The resultant machine profiles and utility services analysis were used to determine the energy usage baseline for the value stream and the Significant Energy Users (SEUs) for each product line. The study demonstrated that energy reduction during idle periods of time could be significantly reduced with either no-cost or low cost measures.

1 Introduction

The industrial sector has more than doubled its energy consumption in the last 40 years reaching 2556.74 Mtoe, corresponding to 30% of world's energy [1]. Energy-intensive sectors including chemicals, primary aluminium, cement, iron and steel, pulp and paper, glass and glass products currently account globally for 20% of industrial value added, 25% of industrial employment and 70% of industrial energy use. Hence, energy cost will be vital to the competitiveness of energy-intensive industries [2]. Energy efficiency improvements could mitigate these high energy costs while addressing energy security and environmental concerns. In order to carry out energy efficiency improvements, it is first necessary to determine a means to measure the energy usage of systems and processes to set a baseline and then establish a means toward control of energy consumption and costs [3].

Previous work focusing on energy consumption reduction in industry has mainly been centred on energy efficient machine developments, with strong emphasis on measuring and modifying single machine components. Large efforts have been placed on tooling design and the optimisation of individual machine energy efficiency particularly in precision machining [4] [5] [6]. For example, Salonitis [7] reduced process steps, carried out better process planning and improved grinding wheels to obtain significant energy reduction in grinding operations. Götze et al [8] presented an integrated approach for evaluating energy and cost effectiveness of machine tools based on energy flow measurement, predictive energy consumption simulation of drive systems and life-cycle costing. Diaz et al. [9] demonstrated the development of a specific energy characterization model to predict the electrical energy consumed by a 3-axis milling machine tool during processing, in order to adopt green practices (i.e. reduce energy consumption) by upgrading and regrinding the cutting tools used for processing. Some research has focused on identifying and analysing energy usage in industrial sites, particularly focusing on energy usage from a process perspective for single machines or process type [10] [11] [12] [13] [14]. Fysikopoulos et al [15] proposed the estimation of energy consumed by a laser drill by using sub-systems that are “always on” and those that are “periodically on”. In addition, a smaller portion of the work has also explored the optimisation of scheduling or reducing inter-arrival times between batches for a single machine, in order to reduce energy consumption at idle times [16] [17] [18] [19].

In general, past efforts to monitor and analyse energy usage in manufacturing have been done as an accounting exercise, or by using theoretical estimates of energy consumption utilised by the different subsystems of equipment and the technical services associated [20]. An extensive literature review demonstrated little exploration of energy usage and efficiency from a product or production system perspective. Neugebauer et al [21] focused on system influences that affect energy consumption in production by exploring the energy efficiency of machine tools and efficiency systems. Although, they analysed energy consumption from a product definition, particular emphasis was placed on tooling upgrades. Thiede et al [22] proposed the optimisation of a process chain in order to secure the best electrical energy use under simulation of a factory environment. Rahimifard et al [23] and Seow [24] proposed a product-oriented view of energy consumption. Although they divided energy usage into Direct and Indirect categories and developed an Embodied Product Energy (EPE) Model, they did not consider the energy usage of a diverse product going through the same system or workcell. With that, most of the work carried out was based on simulation results rather than an actual facility. The work of Slonitis and Ball [25] provided an overview of energy efficiency approaches focused on production and machine tool level and their relationship. The work proposed by the authors builds on the methodologies outlined here.

This authors’ research work is not centred on developing energy efficient processes, nor will it provide an in depth analysis of energy efficient solutions for manufacturing systems. This has mainly been discussed in [26] [27] [28]. It will, however, present a methodology to collect concurrent energy and process information data at machine level to develop machine profiles, and demonstrate the implementation of this methodology and subsequent results in a precision manufacturing facility. The aim of this work was to a) understand the machines’ electrical consumption during productive and idle states, and (b) ascertain the utility services such as compressed air, coolant, process water (deionised water) and dust extraction consumed at each machine station during productive and idle states. The data collected allowed for the generation of machine profiles in order to identify value-added energy (energy used to add value to the process i.e grinding) and auxiliary energy (energy used when a machine is left idle). The results will enable decision makers to understand the energy consumption of machines and technical services, and will highlight the opportunities to reduce auxiliary energy.

This paper is structured as follows; Section 2 will cover the methodology overview, Section 3 will discuss the Case Study data gathering and results and Section 4 will address conclusion and future work.

2 Methodology Overview

Discrete manufacturing processes are composed of various inputs and configurations that change in accordance to the product being manufactured. The methodology proposed was developed based on the principal that manufacturing activities are composed of multiple levels; starting with individual equipment where a singular process is carried out, to production lines and value streams (VS) that produce various products, up to the highest level factory or enterprise level. Hence, the energy consumption, both electrical and associated utilities for each machine, theoretically when aggregated provide a holistic view of the consumption at factory level [29]. As discussed earlier, former approaches tended to focus on energy from a machine perspective or tooling perspective. Further developing the concept of “product view” and “process view” energy monitoring proposed by Seow and Rahimifard [30], the aim of this methodology is to aggregate energy consumption (of machine and utilities) by following the production path or steps required to produce a product.

The methodology consists of two aspects; gathering data for machines that represent the various machine types used in the factory and the associated utilities, as well as the analysis of the data collected to generate machine power profiles and energy “signatures”, as displayed in Figure 1.

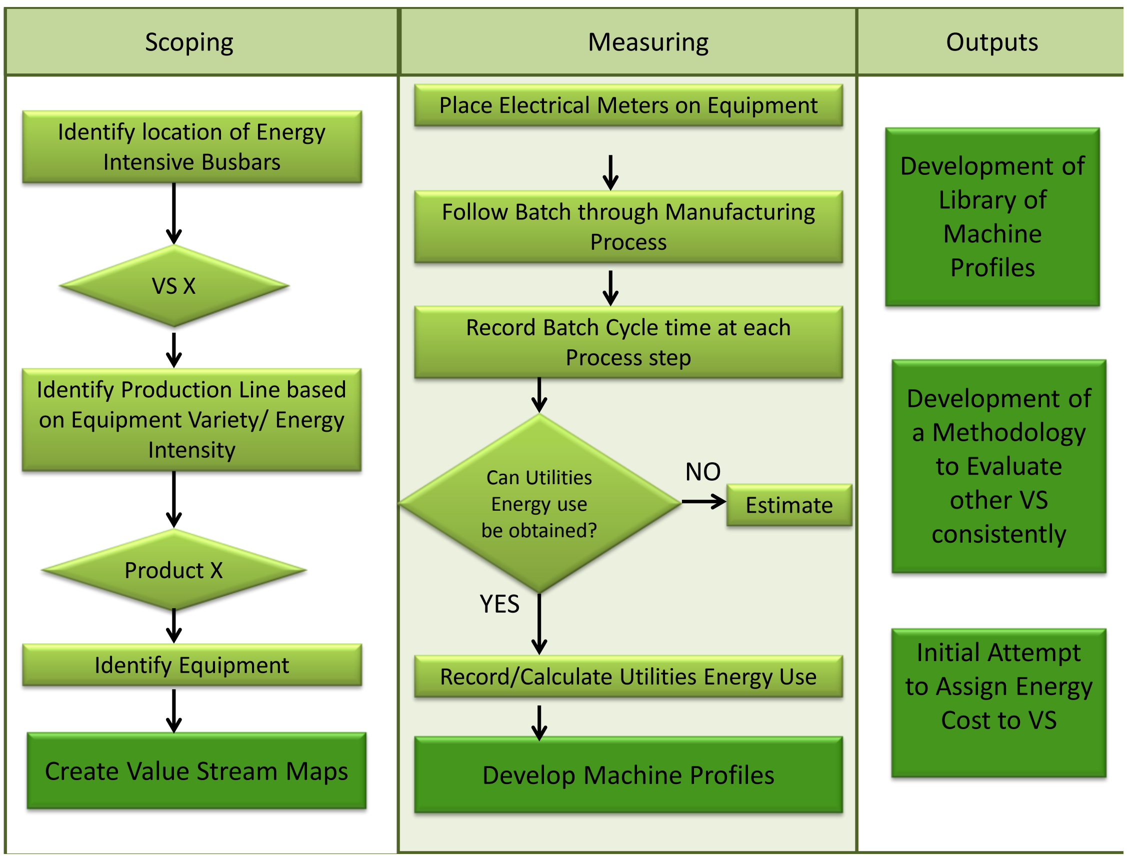

Figure 1 Methodology Overview

Machine current usage across each phase was collected using two Fluke 1735 meters and voltage was obtained from the electrical cabinet displays or distribution boards. Voltage was not collected at machine level since voltage clips could not be attached without interrupting production. Power was calculated across the three phases. The utilities' electrical usage data at VS or Factory level was collected from the Energy Management System (EMS) and the Building Management System (BMS). No sub-metering was available at machine levels; hence calculated values were obtained based on top level data.

The second aspect of the methodology outlined the process used to analyse the raw data to achieve power profiles. All the raw data collected (electrical and process) was graphed and inspected visually. Any unusual data (i.e. machine being stopped due to engineering testing) was removed as the aim was to produce normal operating power profiles for routine production operations. Qualitative information was then sought to account for the anomalies in the data. The electrical data was then sectioned according to batch produced by taking the process data start and end times identified by the operator. An average of the power consumed by each batch was calculated and used as the final average power profile for the batch processing time. The data that represented machine idle time was then analysed and the average idle power was used to determine the duration of the idle time for each machine profile. The resultant was a machine power profile for both idle and operational states.

3 Case Study

A precision medical device manufacturer was selected as the case study site due to the variety of machines used for the processes and the diversity of process steps. The manufacturing process consists of 19 steps depicted in Figure 2. For practical purposes, this paper will only discuss one of the machines analysed, a Grinder. In addition, the energy consumption of the utilities consumed by the Grinder will also be presented.

3.1 Data Gathering

The data collection process preceded with collection and analysis of the factory's electrical consumption busbar data from the EMS. From here, the most energy intensive production area was identified, Value Stream X, and process flow maps, were constructed to identify each piece of equipment utilised. These maps also identify the process sequence used to manufacture each product line in the VS. Two product lines were selected, Product A and Product B since most of the equipment used by these product lines were connected to the energy intensive busbars associated with this VS. A total of ten machines that represented the different machine types used in the VS were metered.

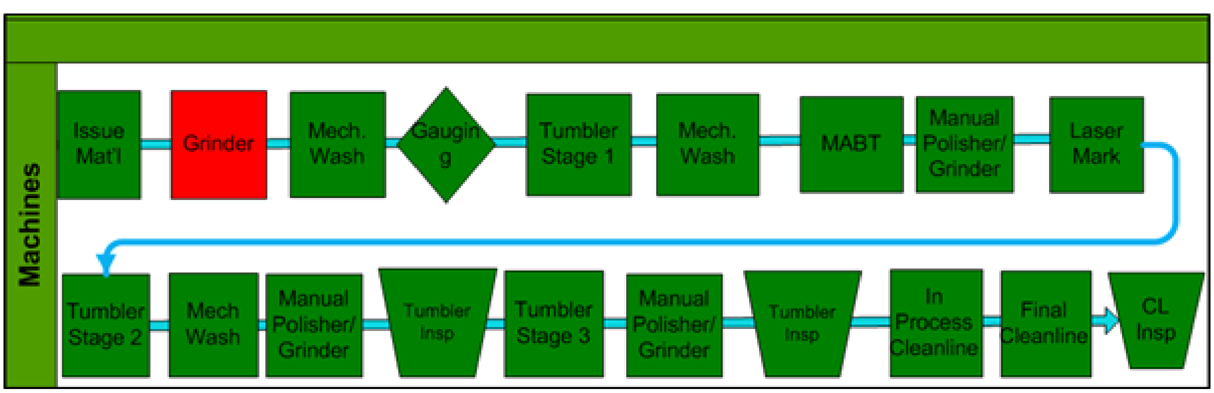

Figure 2 Process Map for Product A

In addition to machine electrical consumption, data was collected on the utilities (Compressed Air, Dust Extraction, Water, Waste Water or Effluent system, and Coolant system) used by the machines via the EMS. Sub-metering at machine level was not available for all services; hence estimations were carried out to determine the use of such during each process.

Compressed air (CA) electrical usage was determined based on gathering data from electrical meters at compressor level, flow measurement for the total quantity produced, and by utilising findings from a previous study conducted by a third party [31]. The study looked at a day's compressed air usage by each of the main machine or equipment types that utilise compressed air. The study made several assumptions; a) all machine types consumed the same amount of compressed air, b) the total compressed air consumption used by a machine repeats each day.

An energy to compressed air factor was determined by dividing the total energy consumption of the compressors by the total CA, resulting in an average value of 0.11753 kWh/m^3. This ratio was used throughout the process steps to determine the CA energy usage at machine level. It is worth noting that any leakages in the distribution system were not accounted for. CA consumption at machine level was averaged over a day and then assumed to be constant regardless of machine state, as the system was not modular and did not ramp down regardless of the CA demand.

Dust extraction electrical consumption was calculated based on a previous study conducted in 2012 by a third party [32] that outlined the machines associated with each dust extraction system as well as one-off measured flow rates. From the results of this study, it is unclear if data was available for times of non-operation, however, based on the fact that the system runs at constant volume for 5.2 days it can be assumed that there is no significant changes in system requirement if machines are in idle mode or operation. Hourly electrical data for a month's period was collected to determine the average power used by the systems DUST X and DUST Y that served the VS. By combining the data collected from the energy meters, and the one-off flow rate measurements stated in the study, it was possible to determine the kWh/m^3 used by each system

The energy consumed by the Coolant systems was determined by measuring the electrical consumption of one of the units. All the grinders utilised by the VS were connected to that particular unit, hence the electrical use was proportionally allocated to each grinder.

The effluent or waste water treatment plant intakes the used water once the tumblers have completed the manufacturing process. For the purpose of quantifying the energy usage of this system, one of the effluent systems, EFFL A was metered. This unit was selected as it corresponded to the tumblers being monitored.

While the electrical data was being collected by power loggers, production operators were requested to complete a log of when they started and finished a batch. This would provide a relationship between machine state (idle or in production) and energy use.

3.2 Results

From the data gathered and analysed, it was possible to generate machine power profiles and energy "signatures". These serve as a basis for understanding the electrical energy consumption of the machines and utilities associated with the machines. These profiles provide information of energy consumption, as well as a distinction between value-added energy (energy consumption when machine is performing an activity that adds value to the product, i.e. milling) and the auxiliary energy (energy used during idle times or for activities that do not generate value to the product). By understanding the energy use per machine, it is possible to calculate energy consumption across similar machines and estimate the cost of electrical energy consumed by the VS. The machine profile obtained for the grinder (GRND01)) will be discussed in this section.

The majority of the grinders utilised in the VS were either Haas Multigrind CB or Hass Multigrind HT. They have a voltage rating of 400 V/50 Hz fused with 80 A. During the time the study was conducted, eleven of these machines were process validated to carry out grinding and milling operations for Product A and were utilised for production based on their availability. They remained in an ON state for a 24/7 basis, unless rigorous maintenance activity was required. The machines required coolant for operation. The majority of them were connected to a centralised cooling plant. However, GRND01 had its own cooling system that had been installed directly next to the machine.

For the purpose of this study, GRND01 (a Multigrind HT) was used to construct machine power profiles. The normal operation of the machine starts with a batch of a maximum of 12 parts (maximum batch size) being loaded into the machine manually by the operator on to six stands that are attached to a conveyor. Batch sizes might vary slightly (1 or 2 parts less) depending on product being rejected or scrapped from previous operations in the Foundry VS. The machine feeds each stand, one at a time, to carry out the grinding operation. The stand remains inside the machine until the process ends, and the machine repeats the operation for each stand (total of 6). Operators then manually unload the batch.

The Fluke meter was attached to GRND01 from 25 November 2013 at 14:39:00 and was removed on 26 November 2013 at 11:09:30. The Fluke meter captured current measurement data for three batches; Batch 1, Batch 2 and Batch 3. Figure 3 illustrates the entire power logged. The batch processing time is apparent, along with the loading and unloading of the batches and the stand change over. Of the three batches captured, Batch 1 contained 10 parts and Batch 2 & 3, 12 parts. It is also possible to see, that an unusual event occurred between 21:30-22:00. Upon investigation with the production team lead, it was noted that the machine was interrupted for process engineering verification.

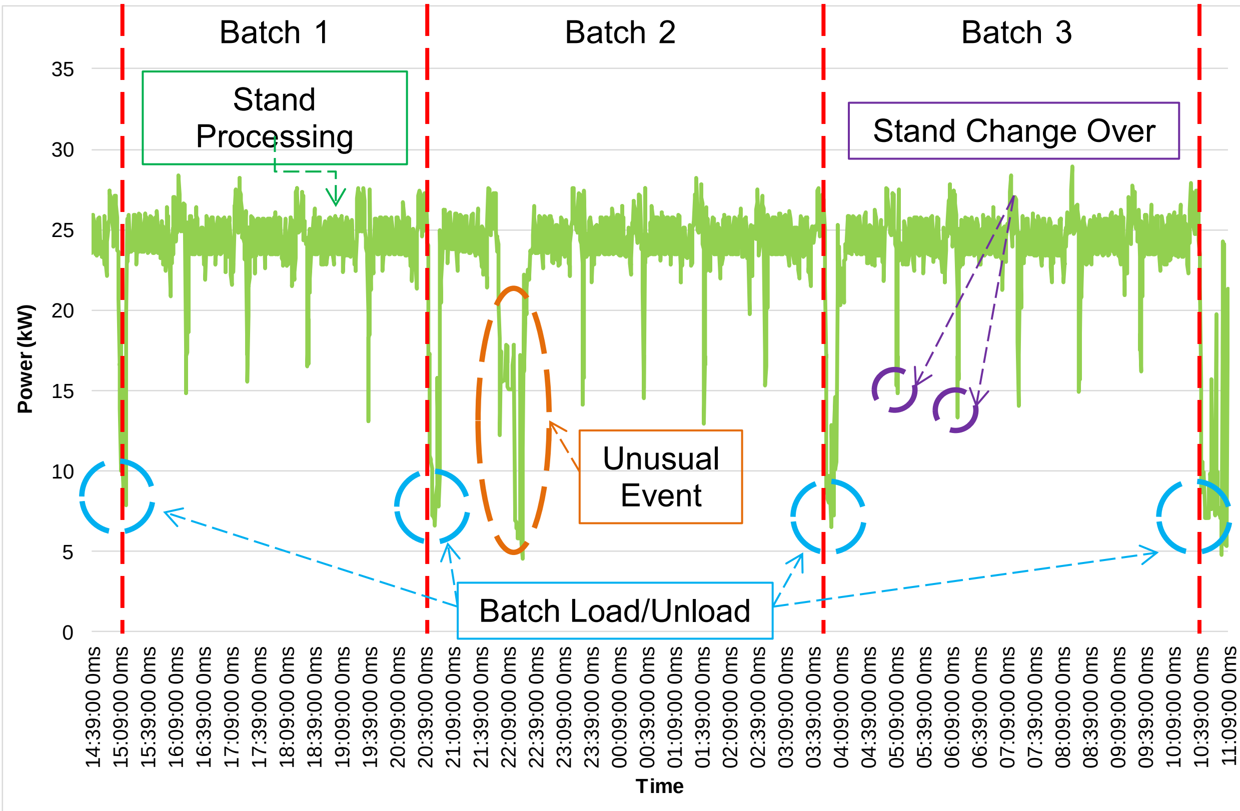

Figure 3 GRND01- Power logged while manufacturing 3 batches

There are three distinct sub-profiles under normal operating conditions; stand processing (two parts), stand change over, and the loading and unloading of a batch. Since the grinder only processes the actual total quantity of parts in the batch, the power profile can be considered as the sum of sub-profiles dependent on the number of parts in the batch. The number of parts in the batch determines the number of stands processed (with 6 being the maximum quantity), and it follows the number of changeovers that are required during the batch process. Each batch is loaded and unloaded once regardless of parts per batch. It takes approximately 2 minutes to load parts, and 2 minutes to unload them Figure 4 shows the power signature for each stand in Batch 1, along with the average power signature for a stand in the batch. The processing time for each stand is 63.5 minutes (3810 seconds).

Figure 4 GRND01 Power Signature

Figure 5 and Figure 6 show the power signature per stand and the power signature per stand changeover respectively. It takes the machine two minutes to transition one stand from the work area to the unload cell.

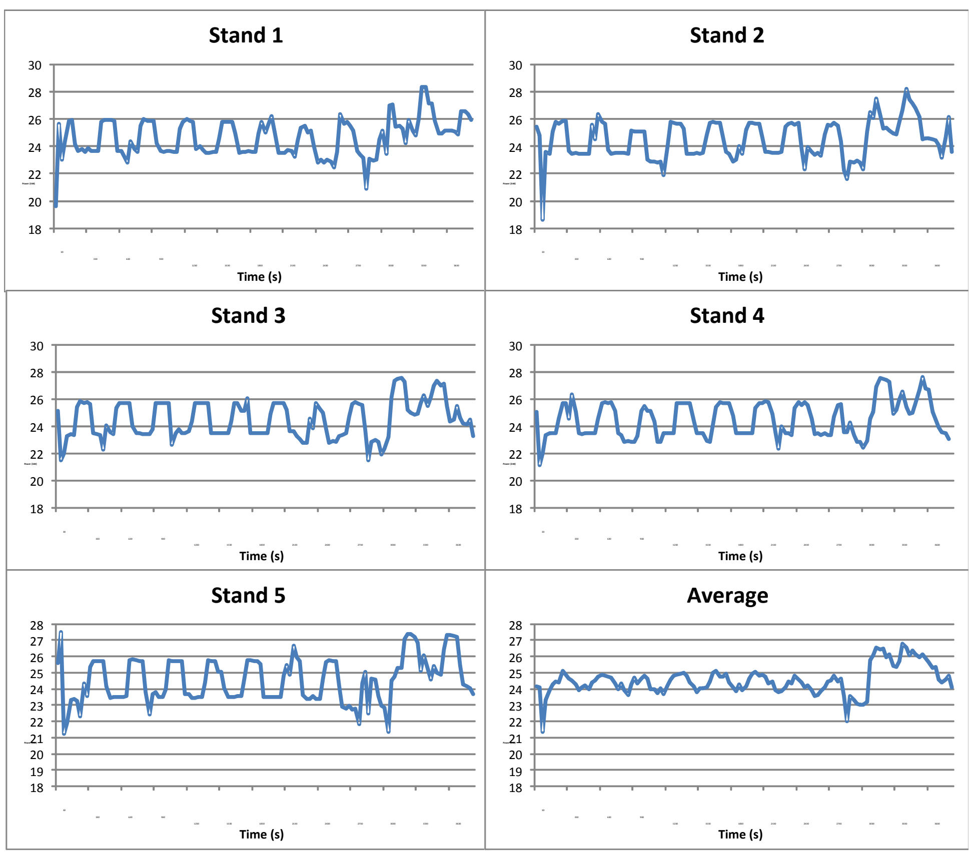

Figure 5 Power Signature of Each Stand for Batch 1

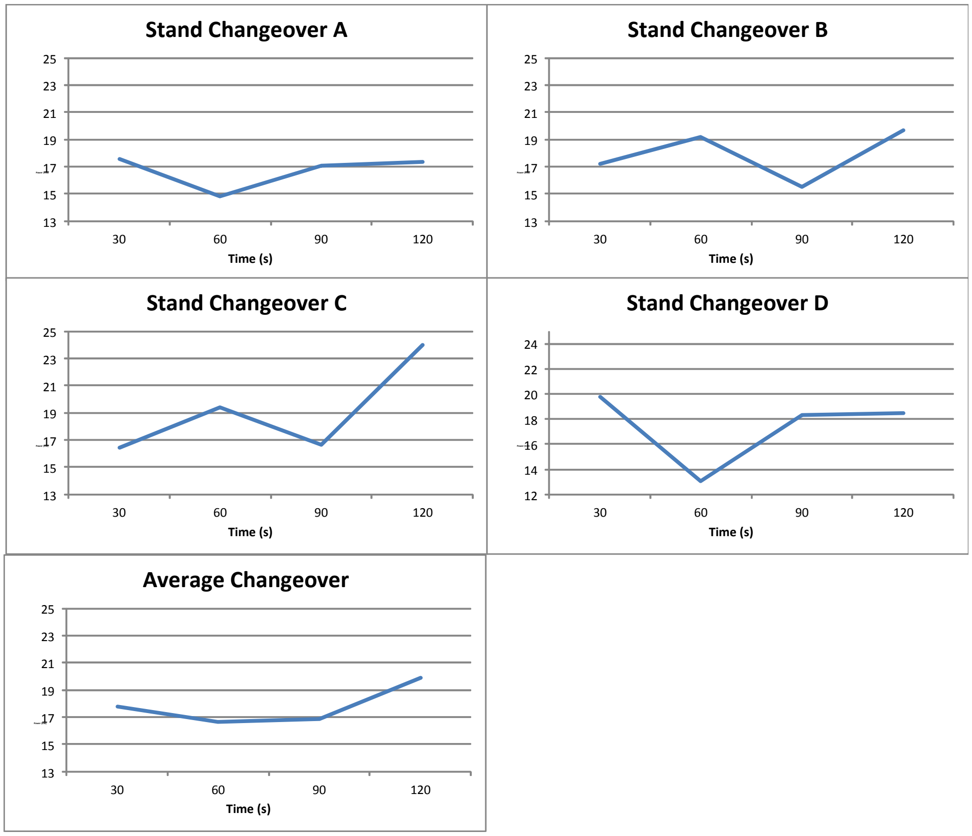

Figure 6 Power Signatures of each Stand Changeover for Batch 1

A similar decomposition of the energy profile (Power Signature for Stand and for Changeover) was carried out for the remaining data as shown on Table 1 , and an average was taken to demonstrate the final profile for a full batch (see Figure 7). During the logging period, no extended idle period was logged. Therefore the minimum power has been set as the fixed energy recorded during the 24-hour period. It would be recommended to re-meter this machine when there is extended periods of non-production to attain a more accurate fixed power.

Table 1 Processing Time and Energy Analysis of GRND01

Parts Processed	Batch Processing Time (s)	Batch Processing Time (min)	Total Fixed Energy (kWh)	Total Variable Energy (kWh)	Total Energy (kWh)	Energy Per Part (kWh/Part)
1 Stand /2 Parts	4,620	77	9.61	18.82	28.44	14.22
2 Stand /4 Parts	8,580	143	17.85	37.29	55.14	13.78
3 Stand /6 Parts	12,540	209	26.09	55.75	81.84	13.64
4 Stand /8 Parts	16,500	275	34.33	74.21	108.54	13.57
5 Stand /10 Parts	20,460	341	42.57	92.67	135.24	13.52
6 Stand /12 Parts	24,420	407	50.81	111.13	161.94	13.50

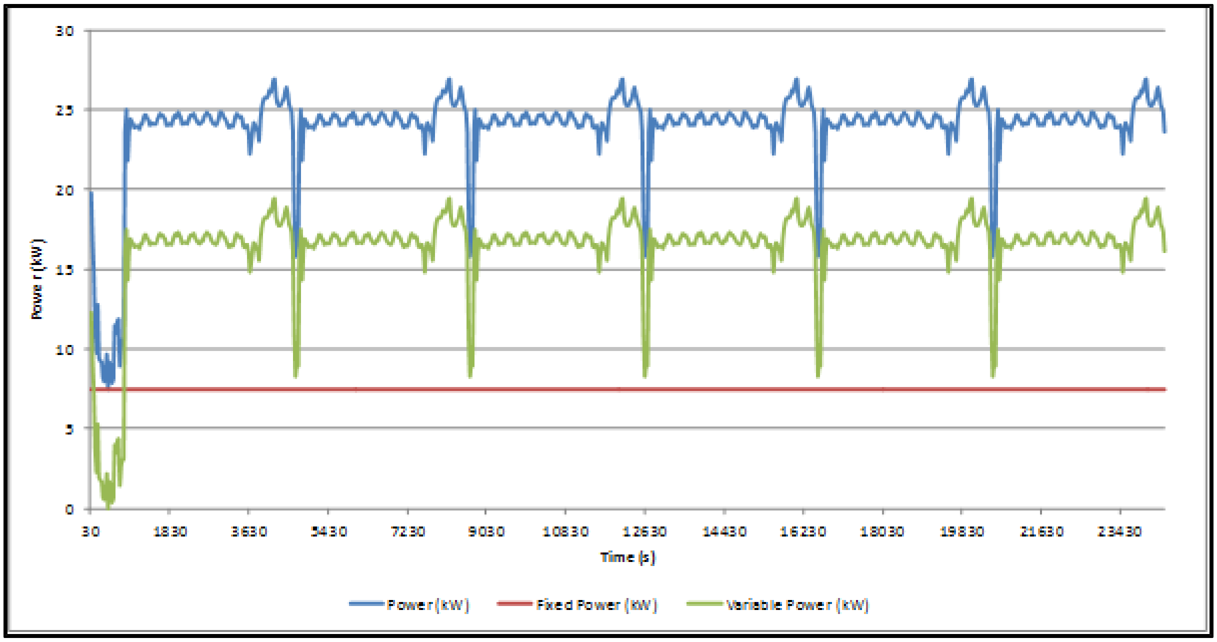

Figure 7 Final Power Profile for GRND01 with a Full Batch (12 Parts)

Apart from direct electrical energy, the Grinders utilise compressed air, dust extraction and coolant to carry out manufacturing processes.

As discussed in the previous section, the compressed air study evaluated the compressed air consumed by a HAAS grinder (GRND02) to represent all HAAS grinders. This machine is used to process Product A and therefore is assumed to have the same operation as GRND01, which has been examined in this power study. The main difference between the two is that GRND02 uses centralised coolant whereas GRND01 has a localised coolant pump. Figure 8 shows the total compressed air every 15 minutes from the previous study. It was noted that the compressed air consumption profile pattern and the machine process profile were similar. This indicated that if more granular data were available, concurrent production and compressed air consumption could be broken down into fixed and variable energy. However a lack of qualitative data to describe the compressed air consumption and understand the relationship between machine operation and service delivery meant that at this time this task was not possible. Therefore using the previous study's data, the average compressed air consumption could be estimated. The estimated average compressed air consumption of GRND01 was 0.007521m^3/s or 27.08m^3/hr. Using the energy/compressed air ratio the energy consumed per second to deliver this amount of compressed air was 0.000883964 kWh/s. Therefore it is assumed that GRND01 consumes a constant 3.182 kW of power of compressed air.

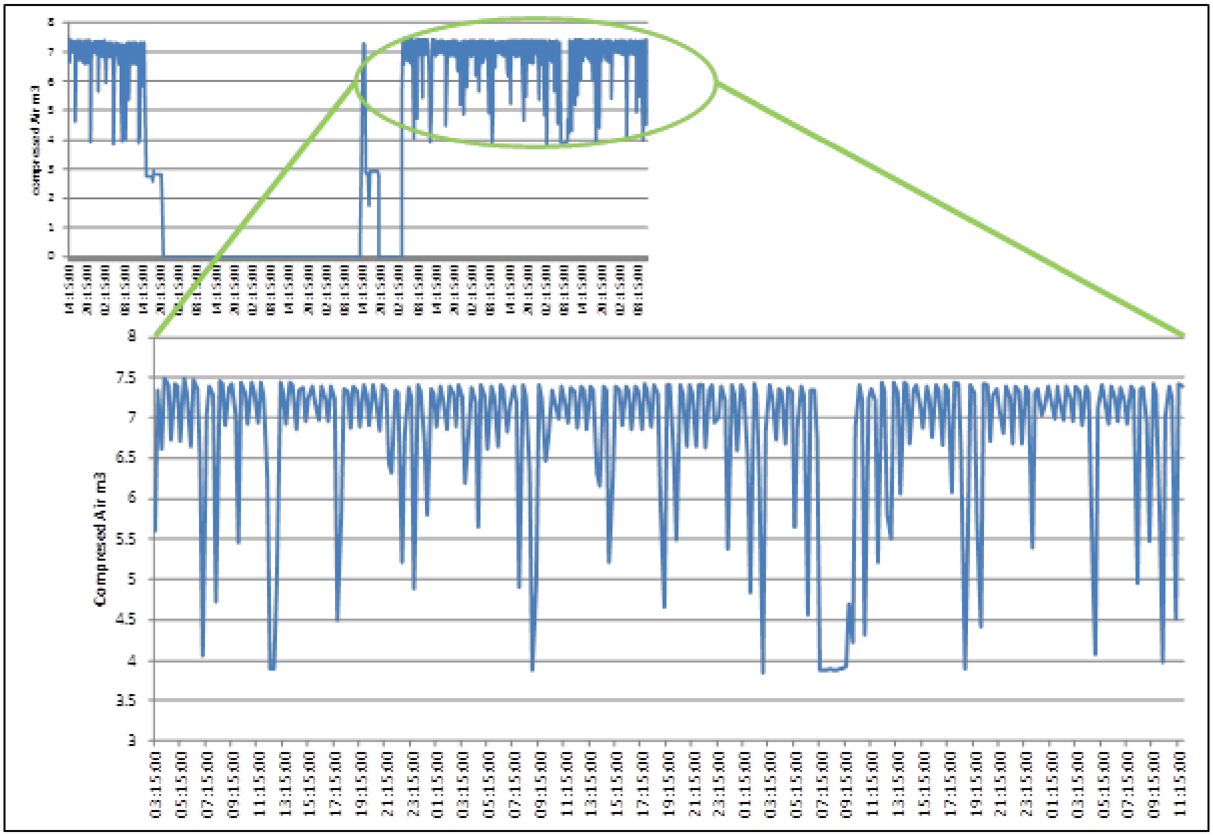

Figure 8 Compressed Air HAAS GRND02 (taken from Previous study 2012)

The localised coolant system for GRND01 was metered from 01/04/2014 11:22 until 09:44 04/04/2014. The batch times recorded as part of the study did not match the cycle times from either the company's order management data or the cycle time determined by this study. Furthermore the pattern in the power profile of the coolant pump did not match the machine process. This could have been due to background operations such as a separator, which operated out of sync with the machine process. Therefore a black box approach has been taken to assign energy consumption to the coolant service based on the equipment's energy ratings. The average power consumption for the logged period was 6.15kW.

4 Conclusions

The primary aim of this study was to determine if the machines studied had a repeating power profile pattern during production times and if so, an average machine power profile was constructed. The average machine power profile along with an analysis of power consumption during non-production times allowed for an energy signature to be determined. This enabled the determination of the fixed and variable energy consumption of the production machines and thus the value-added energy and auxiliary energy.

Electrical energy consumption data was available for the utilities at a top level (Factory or Value Stream) via the EMS and BMS however assumptions had to be made at machine level. The consumption data of compressed air systems was based on a one off measurement. The installation of CA flow meters would allow for a full understanding of their operation. It appeared the CA consumption of the grinders followed a pattern similar to the machine power profile. A more detailed study of CA at machine level would confirm this relationship and quantify benefits of a service shutdown at non-production times along with machine shutdown. The same could be said for the coolant pump for GRND01. Greater understanding of the relationships between machine states and services and thus the associated costs could provide opportunities for energy savings at machine levels.

During the metering period of GRND01 there was no significant period of idle time and therefore it was necessary to use the lowest metered power as the fixed power. It would be interesting to understand the behaviour of the grinder in an extended idle machine state, as this would more accurately quantify the energy consumption during extended non-production time and determine benefits of machine shut down during such periods.

The power study reveals energy consumption at a snapshot, highlighting the power profile of the different machines utilised. The metered data indicated that machine operations produced repetitive power profiles during productive states (i.e. when manufacturing product). It would be interesting to carry out a similar study for an extended period of time, in which productive and idle states of the machine could be observed, voltage data could be collected, producing a more consistent power profile.

Also, the use of virtual meters or embedded controllers could be a means of obtaining electrical data for machine profiles, as well as electrical and flow data from Utilities. Future work could focus on using the profiles to create rules for turning off idle machines and their associated services. In addition, the profiles should be utilised to create a model of the production lines or value stream to enable decision makers to quantify energy consumption, energy cost and the potential impact that scheduling changes might have to energy cost, CO_2 emission and production output.

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