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A Methodology for Process and Energy Mapping In Production Operations

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Abstract: *The Manufacturing industry is increasingly accountable for the environmental impact that its activity has. Manufacturing operations design has shifted from a traditional strictly cost and quality approach to now including energy efficiency, zero waste and reduced carbon emissions. Although manufacturing companies have focused on reducing energy at a facilities level, research indicates that manufacturing processes generate a significant environmental impact through energy consumption, resource depletion and greenhouse gas (GHG) emissions. To understand the consumption of energy in a production environment, it is necessary to outline the energy flow within the facility along with the classification of energy usage and its relationship to processes and production outputs. It is also important to identify auxiliary (non-value added) energy within production as the area with the greatest potential for savings through changes in operational behaviour.*
A review of methodologies that categorise energy usage in industry highlighted that companies still lack appropriate methods to effectively address energy efficiency in a comprehensive manner. This paper introduces a practical process mapping methodology that combines energy management with value stream mapping. The methodology is based on Lean manufacturing principles and upon application to a couple of industry use cases has been shown to successfully illustrate the relationship between the energy usage and production activities for a particular value stream. Furthermore the significant energy users (SEUs) in relation to the actual production process chains have been identified and the quantification of the auxiliary (non-value added) energy usage within the value stream is being developed.

1. Introduction

Worldwide, industry consumes almost one-half of all commercial energy used and is responsible for roughly similar shares of greenhouse gases [1]. With a growing energy demand and a requirement for diverse energy sources, there has been an increase in the regulatory and legislative activity intended to minimize the environmental impact from energy-use and energy-pricing increases. With that, for an increasing number of companies it is imperative to have a supply chain capable of quantifying carbon footprint and setting goals for future reductions. To stay competitive in the 21st Century, manufacturing companies need to include sustainability into their manufacturing optimisation schemes.

Sustainable Manufacturing (SM) is the new paradigm [3] necessary for manufacturing companies and involves the integration of all relevant dimensions that affect or have effects on third parties while conducting manufacturing operations, including energy, environmental impact and life-cycle analysis. Hence, when designing or improving a manufacturing system, which may have a tooling strategy, material-handling methods and production methodologies, an alignment with economic, ecological, and social goals has become an essential strategic objective of manufacturing companies [2-5]. Hence, an isolated consideration of traditional economic variables without evaluation of ecological and social impact is no longer acceptable and a balance between traditional material, equipment and personnel resources is required.

To allow for sustainability and to meet environmental legislative requirements, manufacturing industry must be capable of understanding its energy requirements, its energy consumption and the manner in which this is managed, particularly in the production environment. Although, there are various sustainability assessment tools available, these tools are complex, require vast level of data and technical expertise to utilise [5]. Hence, this paper proposes a practical and less-complex methodology for the assessment of energy usage in a production environment.

The methodology utilises the combination of the lean manufacturing principle of Value Stream Mapping (VSM) with energy management and upon application to a standard manufacturing site, outlines the process flow, energy metering requirements, the technical utilities servicing the process and an identification of the relevant SEUs. This methodology allows a manufacturing company to visualise their production process from an energy perspective and determine the next steps for improvement in energy management and consumption.

2. Energy Flows & Classification in Production Operations.

Production processes consume raw materials and transform them into products and wanted or unwanted by-products and use a significant amount of energy to do so. Some of this energy is used for value-added activities embodied into the form and composition of products, while the rest of the energy is wasted in terms of heat losses and emissions. Indeed, manufacturing processes generate a significant environmental impact through energy consumption with related resource depletion and GHG emissions [19]. To understand the consumption of energy in a production environment, it is necessary to outline the energy flow within the facility along with the classification of energy usage and its relationship to processes and production outputs.

Imported energy in the form of electricity, gas or solid fuels, for example, coal or peat, along with onsite renewable energy systems provide the primary energy source for a facility. Solid fuels, oil or natural gas are mainly utilised by energy transformation/generation systems such as boilers to generate heat for process and space heating. Electricity (both imported and renewable) is used by energy transformation/generation systems mainly to run electric drives to generate mechanical energy. Typical applications include pumps, air conditioning (chill generation, ventilation) and compressors. The energy carriers are the means by which energy moves through the facility that include compressed air, hot/chilled water, electricity and steam. Energy utilisation systems are the end users of both the electrical and thermal energy. For example, equipment drives and motors use electricity and clean-lines utilise hot water. The energy drivers are the variables such as production volume and weather changes expressed in degree days, which affect energy consumption. In terms of technical services, energy flows can be represented by electricity (imported and/or wind turbine) used by a compressor (energy generation system) to generate compressed air (an energy carrier). The compressed air is used for a product cleaning operation and the main energy driver is production volume, as the use of compressed air will increase as the volume of production increases [7, 19].

Previous research on manufacturing energy consumption has focused on developing more energy efficient machines/processes [20]. However, the energy requirement for the active removal/joining of materials can be quite small compared to the background functions needed for the overall operation of the manufacturing system [21]. Drake et al. [22] showed that there are significant amounts of energy associated with machine start-up and machine idling. As a result, in a mass production environment, more than 85% of the energy is used for functions that are not directly related to the production of parts [21]. This suggests that energy saving efforts which focus solely on updating individual machines or processes may be missing a significant and perhaps bigger opportunity. Other studies carried out in multiple industries such as dairy, meat processing and textile have focused on industrial energy use and energy efficiency [7]. Most of the efforts have gone into technical services plant upgrades and less attention has focused on the energy usage at process and equipment level. Hence a more holistic mapping of the relationship between production and energy consumption should be applied as research also suggests that lack of understanding between production operations and energy usage prevents energy efficient decision making in real-time [23, 24]

A review of methodologies that categorise energy usage and energy efficiency in industry highlighted that industrial companies still lack appropriate methods to effectively address energy efficiency in a comprehensive and practical manner [6,7]. This is primarily due to:

- The complexity of production sites that due to business needs, operate more than one production process.
- Production sites may produce various types of products, each with different energy intensity factors.
- Specific energy consumption depends on the production rate and Significant Energy Users (SEUs) are typically viewed in isolation from production operations rather than in conjunction with it (i.e. cycle time and energy usage analysed together to determine process SEUs).
- Comparing different installations (i.e. process equipment, technical services upgrades) using energy efficiency indicators can lead to misleading conclusions, when attempting to take all variables associated with energy efficiency into account.

- The analysis of thermal energy is considerable more complicated in practice than the analysis of electrical usage.

Hermann et al. [3] and Thiede et al. [5] proposed work that focused on the optimization of the process chain with the objective of securing the best electric energy efficiency. The study proposed a five-step approach using a simulation model. These steps include; (1) Analysis of production process chain; (2) Energy analysis of production and its equipment; (3) Energy analysis of technical building services; (4) Load profile and energy cost/energy supply contract analysis; (5) Integrated simulation and evaluation of the production system. However, the work was not extended to an industrial facility or practical application.

Seow and Rahimifard [23, 25] provide a product perspective of energy monitoring and attribute the energy consumed by the product to both the process and the plant. Energy consumption in manufacturing can be categorized into Direct Energy (DE) and Indirect Energy (IE), which constitute the embodied energy of a product. DE is the energy required to manufacture a product in a specific process and can be subdivided further into theoretical energy (TE), the energy necessary for actual value creation and auxiliary energy (AE), the energy required by supporting activities for the individual machine/process. Indirect Energy (IE) is defined as the energy necessary to maintain the production environment (lighting, heating, or ventilation). For the development of the proposed methodology for mapping energy usage in production, the authors developed a more defined energy breakdown based on the energy classification by Rahimifard et al. [24].

The energy breakdown is applicable to a large scale manufacturing company, typically one with traditional precision manufacturing processes, where multiple products require equipment or processes from multiple value streams or strategic business units (SBUs). The proposed energy breakdown, outlined in Figure 1, below, illustrates how the overall energy consumed by an industrial facility is divided into Indirect and Direct energy. The Indirect energy consists of all energy used to maintain the building/facility working conditions, such as lighting and ventilation, required to enable operations to take place that are not directly used by production. The direct energy relates to the production dependent energy. This is subdivided into Value-added Energy and Auxiliary Energy. The Value-added Energy consists of the energy utilised by each process to carry out an operation that increases the value of the process (i.e. the energy used by a milling machine to remove material from a product). The Auxiliary Energy is the energy consumed by each process that is not necessarily contributing to the formation of a product, e.g. idle running of the machine, supply of technical services during idle time). The proposed energy breakdown draws particular attention to the auxiliary energy usage and the potential areas in the factory where energy efficiency measures can be introduced based on operational and behavioural changes in production operations. This proposed energy breakdown allows decisions makers a more holistic view of energy usage in an industrial facility, with the focus on the potential for reduction through behavioural and operational change.

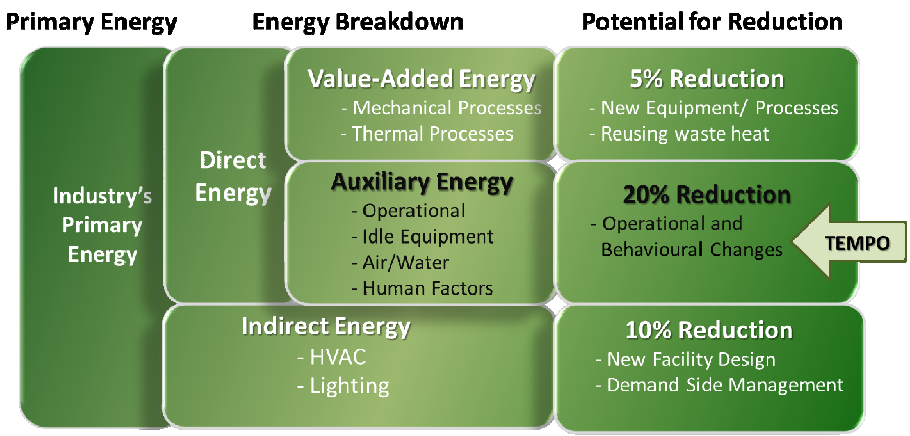

Figure 1. Proposed Energy Breakdown Methodology

Information from an industry study [35] in Ireland established that the relative percentage of direct versus indirect energy usage on a large manufacturing site was 57% (DE) to 43% (AE) respectively. In other words 57% of the energy consumption went towards making the products and 43% of the total energy consumption went towards supporting the production environment. The direct energy usage was then analysed into either the value added energy or the auxiliary energy. In this case study, the value added energy accounts for 31% of overall energy usage and the auxiliary energy accounts for 26% of overall energy usage. To identify this auxiliary energy within a production environment for potential cost reductions, this paper describes a practical methodology which is a combination of energy management and the lean principle of Value Stream Mapping (VSM).

3. Combining energy management and value stream mapping

Energy management focuses on the systematic use of management and technology to improve energy performance in a selected site. It requires that energy procurement, energy efficiency and renewable energy be integrated, proactive and incorporated in order for it to be fully effective [26]. Value Stream Mapping (VSM), a widely used tool of Lean Manufacturing, is a type of symbolic model that graphically enables the end user to observe the material and information flow as a product or service travels through a value chain [13]. The model represents the flow of resource such as materials, information and personnel along with their interactions, beginning with a sales order right through to delivery of the product or service to the customer. It specifies activities and cycle times and also identifies value-added and non-value added activities in the process. It allows the visualisation of all the manufacturing system, rather than just the equipment [5, 13]. Wormak and Jones [14] suggests that five principles of the

Lean thinking philosophy are required for value stream mapping. Firstly, value must be defined; providing the customer with the right product or service, at the right time and price, as determined in each case by the customer. Secondly, the value stream must be determined; specifying particular activities needed to design order and distribute a specific product from concept to launch. Thirdly, tasks must be designed so that through progressive achievement stoppages, scrap and backflow are eliminated. Fourthly, the "pull system"; a system designed so that nothing is produced by the upstream supplier until the downstream customer requires it, must be implemented. Finally, the target of complete elimination of waste should be constantly reviewed with the aim that all activities across a value stream create value.
The use of VSM and energy management is present in the literature and has been trialled in certain industries in the US [13]. An example of this is the work carried out by the US Environment Protection Agency in the development of the "Lean, Energy and Climate Toolkit". It provides strategies and techniques to improve energy and environmental performance in tandem with achieving leans goals such as quality, reduced waste and improved customer responsiveness [27]. Despite the fact that it provides significant information in relation to lean principles, energy monitoring and targeting and green-house emissions management, the output tool is still quite complicated and prior knowledge of VSM is required to understand and use it.
Based on the principle that VSMs serve as a magnifying glass to view the whole manufacturing system, Fraizer et al. [28] has proposed the use of the "concept of value" and the VSM tool as a means of determining energy consumption in a current state. In particular, the work focuses on determining energy characteristics of the process. Kayakutlu et al [29] propose the use of Bayesian Networks (BN) as means of analysing the relationship. Bayesian networks are a kind of causal map that represent probabilistic graphical models that use probability theory, computer science and statistical tools. Causal maps are the representation of thoughts in relation to a particular subject expressed in nodes and arrows. These are mainly constructed through interviews and analysis, and represent the beliefs, values and expertise of decision makers of the particular subject discussed [30]. Despite the fact that BN has several advantages for making inferences, particularly for data with missing values [13], it is a complicated technique that requires training and knowledge in the subject.
Paju et al. [5] suggest the concept of Sustainable Manufacturing Mapping (SMM). This is based on the combination of VSM, Life Cycle Assessment (LCA) and Discrete Event Simulation (DES) to provide a simple, highly visual model that allows for the assessment of sustainability indicators in manufacturing. The main outcomes are goal definition, identification for sustainability indicators and modelling of current and future state process maps. Despite the robustness of SMM work, the main challenges observed are the idea that a goal-oriented approach can be quite complicated, as the assessment does not use the same indicators every time to carry out an evaluation. In larger multinational companies, where each VS or SBU operate as "small factories" it could be difficult to compare

performance against one another, or even set targets for the company as a whole if the indicators are not shared across the board.
Due to the complexity and prior knowledge of particular techniques for the application and implementation of the above methodologies, the process mapping methodology proposed in this paper follows the basic principles of Value Stream Mapping and encompasses the concept that production is multidimensional and that system dynamics are critical to the evaluation of a production area. It also includes both direct and indirect factors that affect energy efficiency in production operations.

4. Generic Process Mapping Methodology

The primary aim of the proposed process mapping methodology is to effectively acquire production and energy data from a production environment that could be modelled to provide both steady-state and dynamic energy consumption and potentially provide a multi-dimensional hierarchical view of this energy consumption and cost directly related to production equipment.
The proposed methodology was designed around the following principles:

- The methodology is not related or restricted to a specific case but generic in nature and applicable to diverse manufacturing types (i.e. continuous and discrete manufacturing).
- The methodology pursues a holistic perspective of the relationship between manufacturing processes and energy consumption, including all relevant process and energy flows as well as their interdependencies.
- The methodology is flexible so that it can be applicable to small and medium sized enterprises typically facing obstacles towards energy efficiency measures and usage of simulation.
- The methodology provides multi-dimensional evaluation of improvement measures in all relevant fields of actions.
- The methodology can adapt to an ever-changing production environment such as equipment relocation or process improvement.

The methodology consists of five main steps; (1) Process Step Identification, (2) Equipment Identification, (3) Determination of SEUs, (4) Technical Services Identification and (5) Data Collection Availability. These steps are generally applied to one value stream or strategic business unit to create a process map but can be scaled up and/or aggregated to factory level, providing the overall production process and energy usage of a factory.

Process Step Identification: Each process step in the production chain is identified and labelled according to production specifications or internal factory documents. Both the throughput (i.e. batch size) and the cycle time for each process step for each unit of manufacturing (i.e. cycle time/batch) is identified. Differentiation between automated and manual steps is highlighted, as manual steps are not considered unless determined to have a significant impact.

Process Equipment Identification: The equipment used for each process is then identified along with the quantity of equipment per step. This is critical as there may be a one-to-many relationship between the process step and process equipment although generally each product will only take one path through the process. Process equipment energy consumption data is then collected. The electrical consumption provided by the manufacturer (typically referenced on the equipment plate or manuals) should be collected, as well as any thermal energy usage (i.e. gas to generate process heat).

Determination of Significant Energy Users: Based on the cycle time and the energy consumption data of each item of equipment, a list of process SEUs can be determined. It is critical to take into account the accurate cycle times, as the machine rating alone may not be suitable to assess the scale of the energy consumption involved from a product perspective.

Technical Services Identification: It is necessary to identify the technical services (compressed air, water, steam, nitrogen, dust extraction, etc.) used by each process step. These services require both electrical and thermal energy and should be accounted for as part as the energy usage of the process. As specific metering at the process step is not usually available, a method of allocating consumption of the technical services across the value stream must be developed.

Data Collection Availability: It is necessary to identify if there is sub-metering available at process level for both electrical and thermal energy. If energy meters are installed at this step then information can be gathered from the energy monitoring system. If meters are not in place, then it may be possible to use control information from variable speed drives (VSDs) or programmable logic controllers (PLCs) on the machines or to deploy sensors that can gather data on the behaviour of the process (cycle time, temperature, etc).

The required data is collected by reviewing existing manufacturing specifications complimented with interviews from manufacturing personnel (i.e. Operators, Values Stream, Supervisors, etc.) along with other on-site investigations conducted to corroborate the information. The information is then entered into the model developed, shown in figure 2 below, and the output is an Energy and Process Map containing the 5 elements.

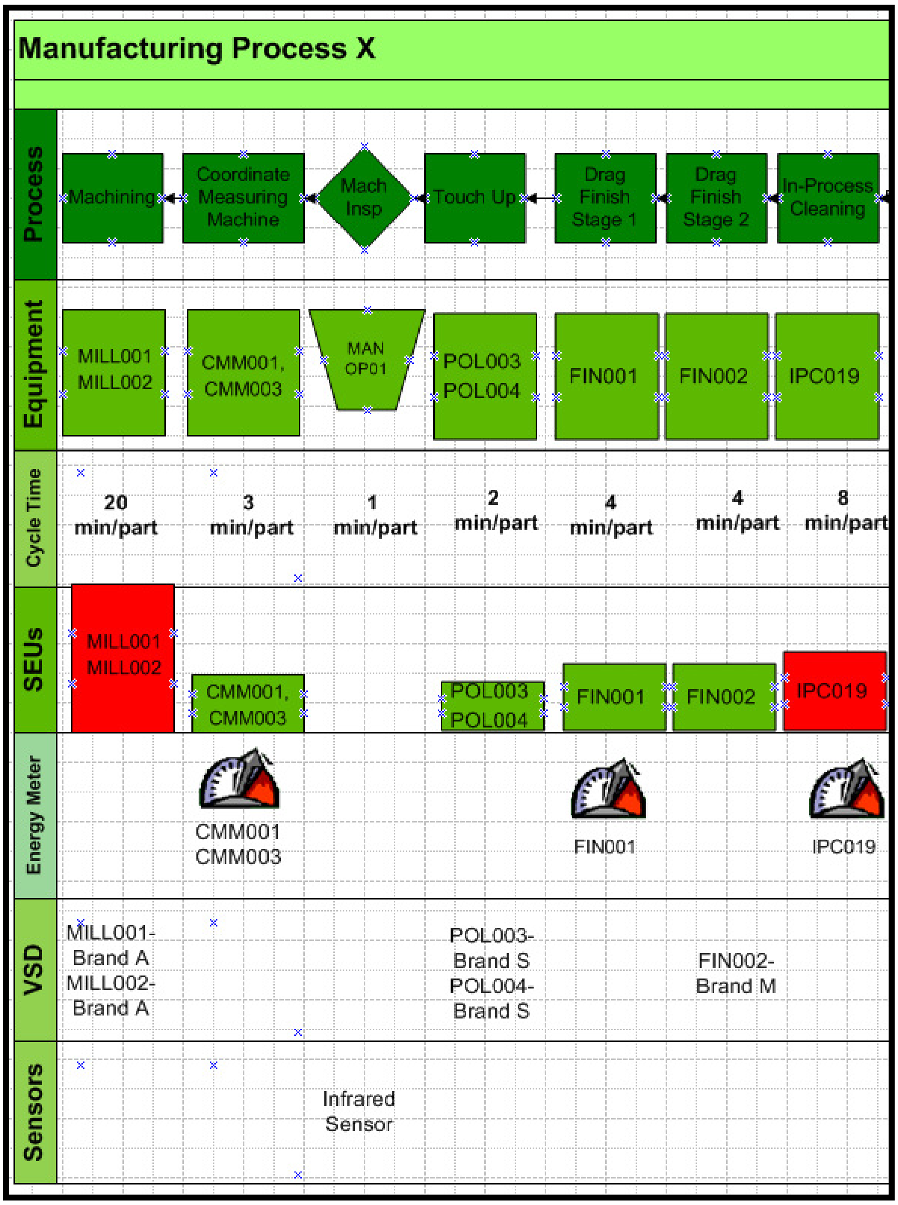

Figure 2 Detailed Model Information and Energy and Process Map

By applying the steps to a production environment, the relationship between process, equipment and energy usage is highlighted and can be used to understand how manufacturing activities function within an industrial facility and how energy and manufacturing are interrelated. It also determines the SEUs, hence creating a plan of work for the machines that require further investigation. This can be done by means of an industrial power study. By gathering data for machines that represent the various machine types used in the factory and the associated utilities, the analysis of the data collected can be used to generate machine power profiles and energy “signatures”. This serves as a basis for a more in depth understanding of the 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 total cost of energy consumed by the VS [32].

5. Implementing the methodology: Case Studies

The methodology was implemented in two sites; Site A a discrete manufacturing facility and Site B a continuous manufacturing facility. The site description and outcomes of the implementation is discussed below.

Case Study 1: Site A is a medical device manufacturing facility that comprises manufacturing areas, utilities, administration and personnel services. The facility consumes approximately 20 GWh of electricity and 15 GWh of gas annually. With the aim of reducing energy usage and costs, energy efficiency projects and renewable energy systems have been installed. These include a 450KW biomass (wood chip) boiler, a gas CHP (900kW) plant, and a 3MW Wind Turbine. Whilst significant progress has been made at the facilities level, over 57% of the site energy is consumed by production processes. Hence, opportunities to target energy usage and carbon dioxide emissions in their production operations exist.
The facility has a wireless energy monitoring system (EMS) installed across production and utilities. Electrical meters connected to the EMS have been placed on the main incomer, transformers, on fifteen distribution boards that service different areas of the plant, as well as on air handling units, dust extraction system and main compressors. As part of a pilot project, twenty-five production equipment meters were installed on one of the value streams. Gas is monitored at incoming and significant energy user levels and a number of compressed air and other meters are also installed and are used whilst monitoring and reporting energy usage.
Data was gathered for the 5 steps of the methodology described above by means of process instructions, manufacturing floor visits and interviews with key personnel. The resultant was a visual representation of the process and energy relationship for the manufacturing area. In tandem, an Industrial power study was conducted to attain power profiles for the machines in order to; understand the machines’ electrical consumption during productive and idle states, and (b) ascertain the utility services such as compressed air, coolant, process water (de-ionised water) and dust extraction consumed at each machine station during

productive and idle states. This confirmed the initial SEU calculations as well as highlighted the equipment that required further monitoring.
The results of the work proved to be significantly useful to the organisation particularly for the acquisition of new equipment and the expansion of the manufacturing floor. It was particularly valuable when determining the sizing of a HVAC system for a new extension to the building.

Case Study 2: Site B is a pharmaceutical and consumer goods global manufacturer that develops and manufactures the active ingredients of medical compounds for both clinical and commercial use. The facility consists of nine highly automated production buildings, as well as an R&D pilot plant and laboratories. Based on figures from 2011, the facility consumes a total of 66 GWh of energy, out of which 26 GWh are electricity and 40 GWh correspond to thermal energy. The facility has significantly improved its energy performance from a total energy consumption of 100 GWh in 2006 to current usage. It has focused on plant utilisation reduction, carrying out multiple energy efficiency projects including HVAC optimisation, nitrogen plant optimisation, and the installation of a 3MW Wind Turbine. The facility has electricity meters installed in all main areas/buildings, as well as gas meters on all significant energy users identified at a top level. There are utility meters installed at top level. Most of these meters are linked to an automation system and data historian. Whilst significant progress has been made at the facilities level, over 40% of the site energy is consumed by production processes.
The consumer health product building was selected to implement the methodology. Data was gathered for the 5 steps of the methodology described above by means of process instructions, manufacturing floor visits and interviews with key personnel. The result was a visual representation of the process and energy relationship for the building. In addition, the work also highlighted the Process and HVAC chillers were SEUs, and the need for further investigation of their performance. A study was conducted using an LIT embedded controller to monitor the unmetered service equipment utilised in the process (i.e. Process Chillers) to obtain process and energy data in order to determine the co-efficient of performance of the equipment [33]. Results were compared against best performance data from another pharmaceutical site located within the same geographical area as the site analysed [34]. These indicated that the COP of the chiller was better than the benchmark.

6. Conclusion – impact of the method on the factories

Energy flows and classification in production operations were addressed, demonstrating that to date most of the work has focused on the facilities sight, primarily due to the complexity in nature of categorizing energy in production systems. However, the concept of “Embodied Product Energy” was discussed, as well as a energy breakdown structure proposed by the authors that allows decisions makers to recognize through a visual representation the manner by which energy flows through an industrial facility. It also draws particular attention to the auxiliary energy usage, and the potential areas in the factory where energy efficiency measures can be introduced based on operational and behavioural changes in production operations. A model based on direct and indirect energy analysis from a 'product' viewpoint has been extended to identify waste or auxiliary energy in line with 'Lean' principles in manufacturing. The methodology outlines the process flow, energy metering requirements, the technical utilities servicing the process and an identification of the significant energy users. In large industrial facilities it has been shown that up to 60% of energy consumption is directly consumed in production activities, although of this, it has been shown that anywhere from 52–85% of the energy may be used for functions that are not directly related to the production of parts. In one application on an industrial site in Ireland, auxiliary energy of 26% was identified. This auxiliary energy identified represents the best opportunity to gain energy savings through operational and behavioral changes at the lowest possible cost.

The methodology was implemented in two case studies and beneficial results are apparent. The mapping has clearly identified these gaps in energy data and highlighted specific equipment (SEUs) that should now be monitored. Furthermore, the methodology illustrated where the use of VSD as energy meters could be used, thus avoiding the need for meters and reducing the overall cost of sub-metering. The development of a clear link between the temporal profile and/or efficiency of the energy consumption by the specific value stream can provide full transparency in the impacts (costs, emissions) of energy consumption and can provide positive feedback and cost reduction to reward improved performance by the value stream. The ability to link Production and Energy models is also a vital link in the future application of demand side management to industry. Further work will involve implementing the methodology in another area of the factory where no sub-metering is available. The main purpose will be to identify the SEUs as well as to propose a strategic metering plan. The analysis of the auxiliary energy will be extended to quantity, prioritise and verify the potential energy savings and the most suitable energy performance indicators developed to provide ongoing management of the production-specific energy consumption. This will allow both Energy and Production Managers to identify opportunities for energy reduction using a common approach.

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