CIRP Journal of Manufacturing Science and Technology 4 (2011) 258–264

Contents lists available at ScienceDirect

CIRP Journal of Manufacturing Science and Technology

journal homepage: www.elsevier.com/locate/cirpj

A framework for modelling energy consumption within manufacturing systems

Y. Seow *, S. Rahimifard

Centre for Sustainable Manufacturing and Reuse/Recycling Technologies, Loughborough University, UK

ARTICLE INFO

Article history:
Available online 12 June 2011

Keywords:
Sustainable development
Modelling
Energy efficient manufacturing

ABSTRACT

Energy is an inextricable part of life in the 21st century, thus its availability and utilisation will become increasingly important with the concerns over climate change and the escalation in worldwide population. This highlights the need for manufacturing businesses to adopt the concept of 'lean energy' based on the use of the most energy efficient processes and activities within their production facilities. The energy consumption in manufacturing facilities can be reduced by either using more efficient technologies and equipment, and/or through improved monitoring and control of energy used in infrastructure and technical services. The research reported in this paper adopts a novel approach to modelling energy flows within a manufacturing system based on a 'product' viewpoint, and utilises the energy consumption data at 'plant' and 'process' levels to provide a breakdown of energy used during production.

1. Introduction

Energy is the most fundamental resource for future economic growth and prosperity and its consumption is expected to continue to grow over the coming decades, with world energy demand estimated to be 45% higher in 2030 than today's levels [1]. The worldwide 'industrial' energy consumption is predicted to increase by 40% in 2030 from 2006 levels [2]. A study has suggested that this could be exacerbated by a potential shortfall in energy supply due to declining fossil based energy sources as shown in Fig. 1 [3]. Furthermore, it is commonly reported that for the foreseeable future, the main source of power generation will be from fossil fuels [1,2] and therefore the rationalisation of energy consumption still provides the most effective method of CO_2 reduction. Governments have consequently responded by introducing a number of energy related legislation, audits and accreditation. More recently European regulations have specifically addressed energy usage with the introduction of directives such as Eco-Design of Energy using Products (EU Directive 2005/32/EC) and Energy End-Use Efficiency and Energy Services (EU Directive 2006/32/EC).

Environmental practices and strategies in manufacturing businesses have changed over the past two decades, from simply meeting the regulations and legislative requirements to increasingly adopting a proactive approach in being environmentally responsible with respect to their products and processes.

Nowadays, environmental challenges are seen as competitive business opportunities rather than insurmountable cost burdens. It is therefore claimed that the increasing number of legislation and directives along with rising cost of fuel will provide significant impetus for manufacturers to reduce energy consumption.

The major research assertion made is that the efficiency and productivity of energy consumption in manufacturing applications has to be carefully examined, highlighting a need for methodologies and tools that can provide a detailed breakdown of energy usage within a manufacturing system. The authors believe that this work can support minimisation of energy consumption during manufacture and influence design decisions for even greater energy savings. This paper outlines a novel modelling framework to represent the total energy required to manufacture a unit product. The initial part of the paper provides a brief overview of existing research work in this area, with the main sections outlining the framework for modelling embodied product energy (EPE) during manufacture and concludes with a case study that used discrete event simulation to establish the EPE.

2. A brief review of most relevant research

In recent years, there has been a significant growth in research activities directed at environmentally conscious/benign manufacturing [4,5] with a common aim of creating goods and services using processes and systems that are non-polluting, at the same time conserving energy and natural resources. The energy consumption is one of the main considerations within a life cycle assessment (LCA) study [6], however, due to the information intensive nature of LCA and the lack of accurate data related to energy demand across a product life cycle (in particular during the manufacturing phase),

* Corresponding author.
E-mail address: mmys@lboro.ac.uk (Y. Seow).

1755-5817/$ – see front matter © 2011 CIRP.
doi:10.1016/j.cirpj.2011.03.007

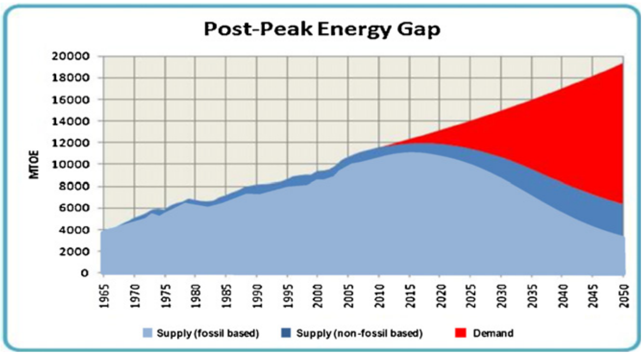

Fig. 1. Growing gap between energy supply and demand.
Adapted from Chefurka [3]

significant assumptions and simplifications are often made. This has motivated numerous research programmes to investigate energy consumption within a manufacturing facility so as to gain a better understanding of the energy use and breakdown.

The existing research in this area can be broadly viewed under two different perspectives of 'plant' and 'process' level. The first area, the 'plant' level perspective, has focused on the energy consumed by infrastructure and other high level services that are responsible for maintaining the required production conditions or environments. Examples of such energy consuming activities would be ventilation, lighting, heating and cooling within a facility [7]. Energy management systems (EMS) are commonly used to monitor these activities [8]. For example, Boyd et al. [9] utilises a statistical analysis approach to determine the manufacturing Energy Performance Indicators based on 'plant level' variables. This work has been integrated into the American Energy Star performance rating system of manufacturing facilities.

On the other hand, the research targeting the energy consumption at the process level has concentrated on individual equipment, machinery and workstations within a production system. For example, as part of an international initiative on 'cooperative effort on modelling process emissions in manufacturing' (CO_2PE) [10], substantial research has been targeted to document, analyse and reduce process emissions for a wide range of available and emerging manufacturing processes [11,12]. The taxonomy used to structure the data is shown in Fig. 2.

Overcash et al. [13] along with a group of other engineers are working to produce an engineering rule-of-practice-based analysis of separate unit processes used in manufacturing and the information is collated in the form of a unit process life cycle inventory (UPLCI) which would help the evaluation of manufactured products through the quantification of various parameters including: input materials, energy requirements, material losses and machine variables. Their work also uses a similar process taxonomy adopted by the CO_2PE initiative.

In addition, the process specific energy assessment investigated by Gutowski et al. [14] has taken a step further to develop generalised 'equipment-level' energy models, using average energy intensities of different manufacturing processes to evaluate the efficiency of processing lines. However, the considerations of energy flows at plant or process level cannot provide an overview of "how much energy is required to manufacture a unit product". The remaining sections of this paper will discuss a distinctly different approach based on a 'product' view which is not only capable of providing an estimation of total energy but also a breakdown of energy usage within the facility.

3. Modelling energy consumption during manufacturing phase

3.1. Product viewpoint for energy flow modelling

The proposed approach in this research is based on a product viewpoint and investigates the combination of energy used both at the plant and process levels, with the aim of representing the amount of energy attributed to the manufacture of a unit product,

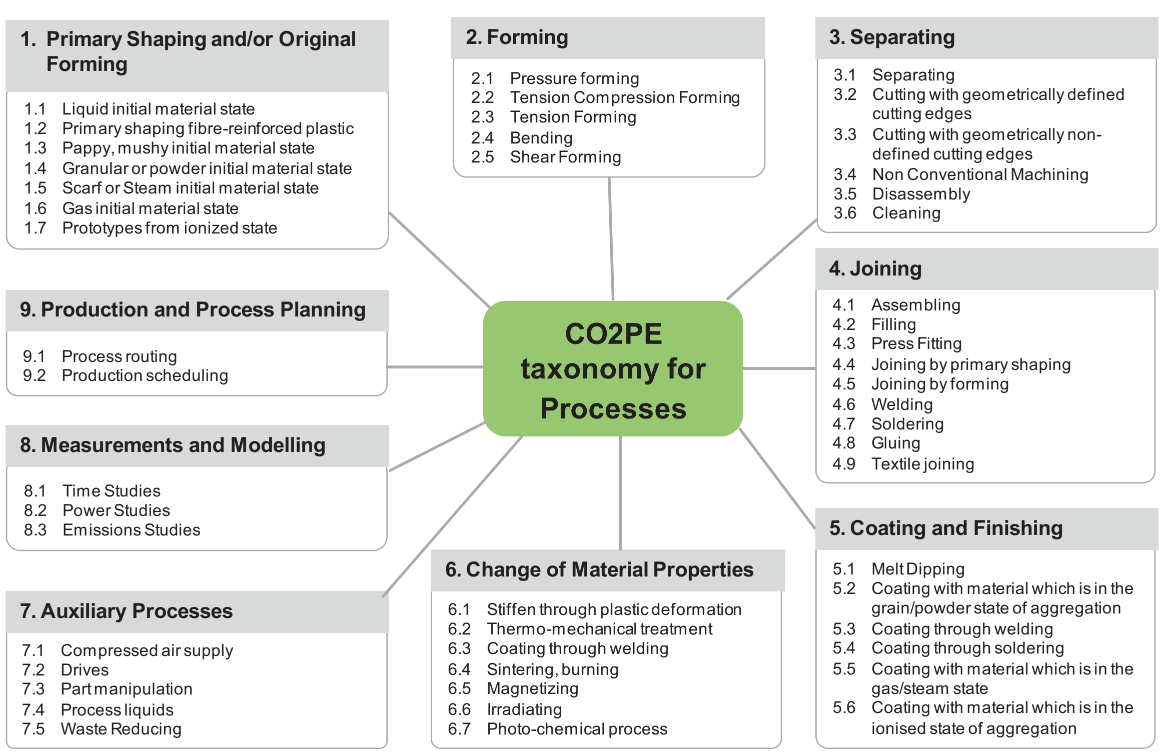

Fig. 2. Taxomony of processes used by CO_2PE [10].

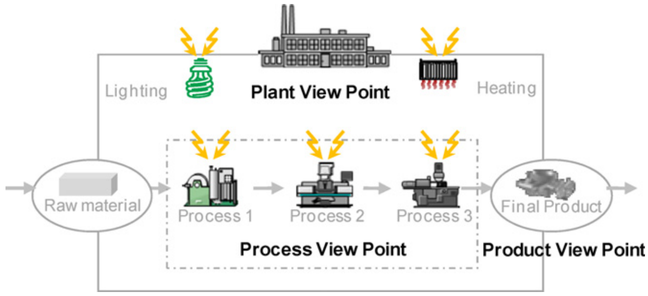

Fig. 3. Plant, process and product viewpoints to energy flow modelling during manufacture.

as depicted in Fig. 3. The complexities, assumptions and simplifications typically included in a LCA study, highlights the need for such an approach when modelling EPE during the manufacturing phase.

3.2. Indirect and direct energy

In this approach, the energy consumed by various activities within a manufacturing application is categorised into two groups: direct and indirect energy. The direct energy (DE) is defined as the energy used by various processes required to manufacture a product (e.g. casting, machining, spray painting, inspection, etc.), whereas the indirect energy (IE) is the energy consumed by activities to maintain the 'environment' in which the production processes are carried out within the factory or manufacturing plant (e.g. lighting, heating and ventilation).

Further in the EPE framework, the DE is divided into: (i) theoretical energy (TE) refers to the minimum energy required to carry out the process (e.g. energy required to melt a specific amount of metal during casting, or removing a specific amount of material during machining operation); and (ii) auxiliary energy (AE) as the energy required by the supporting activities and auxiliary equipment for the process (e.g. generation of vacuum for sand casting, or pumping of coolant for machining). It should be noted that the value of AE also includes non-productive modes such as machine tool start-up, standby and cleaning.

In the case of IE, the energy consumed by various activities such as lighting and heating may be required by a number of processes, and/or a process may require specific environment (e.g. clean room for inspection). Therefore, in this approach, a manufacturing facility is considered as a number of 'zones' where a 'zone' is defined as an area within the manufacturing plant with similar indirect energy requirements.

The EPE model utilises data related to the DE and IE at both the 'plant' and 'process' levels to represent the total energy required to manufacture a product. The total embodied product energy is the sum of all the energy used by the processes required to manufacture the product and the energy consumed by the environment in which the processes are in, as illustrated in Fig. 4. A combination of theory or empirical studies is required to determine the values of the DE and IE, as detailed in the next section.

3.3. Modelling embodied product energy

A systematic approach has been used to calculate the DE and IE for various processes required in the production chain of a product. In most cases the value of the TE for a process can be calculated based on existing knowledge and/or appropriate mathematical models. Most of the traditional production processes depend on material removal, melting, vaporisation or deformation, and therefore the energy required can be determined through a number of specific process parameters. For example in the machining process, the TE can be calculated based on values for the specific cutting energy for the material, U, and volume of the material to be removed, V, i.e. ($U \times V$). Likewise, the AE can be calculated based on system specifications (e.g. data from equipment manufacturers), and where data is unavailable, empirical studies can be conducted to measure energy required for the auxiliary processes. In the case of IE, the energy attributed to a product is calculated based on total energy consumed within a zone (per hour) divided by number of products processed in that 'zone' per hour. The sum of the TE and AE (i.e. the DE) together with the IE for all the processes within a production system represent the total embodied energy of the product, as illustrated in Fig. 4. An example based on the machining of a simple part with the details of the calculations using the EPE framework is detailed in Seow and Rahimifard [15].

In this approach, the EPE model is not only able to detail the energy consumption for the various processes, but also highlights the energy hotspots within a manufacturing facility. Such energy intensive processes can then be examined to improve their efficiency or where possible be replaced with a less energy intensive process. In addition, more detailed assessments of the process efficiencies can be made by considering the ratio of TE to AE (with a higher value for TE and lower value for AE representing an energy efficient process) and similarly the ratio of DE to IE (with a higher value for DE and lower value for IE representing an energy efficient production system). Further details on the efficiency ratios can be found in Rahimifard et al. [16]. The EPE model can also be used to examine the impact of other production parameters such as number of required setups, batch sizes, production schedules, etc. This could provide an insight into identifying optimum setup patterns and batch sizes, as well as opportunities to explore other causal factors that may affect the energy consumption of the processes.

3.4. Energy simulation model

The implementation of EPE framework within a practical application necessitates the development of a decision support tool, capable of representing the complexity involved in measur-

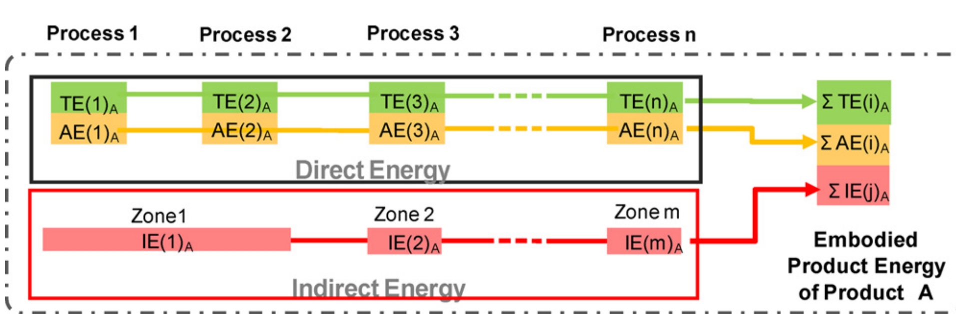

Fig. 4. Framework for modelling embodied product energy.

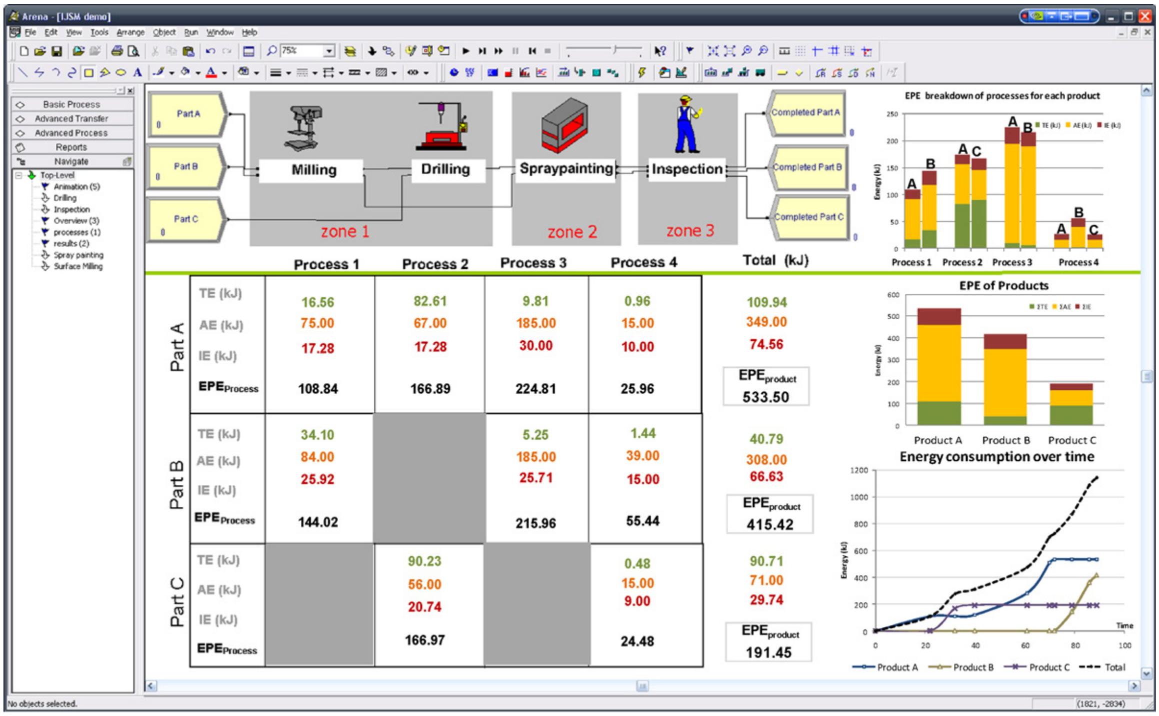

Fig. 5. Screen print of the simulation model in Arena^{TM} showing details of the energy values and charts.

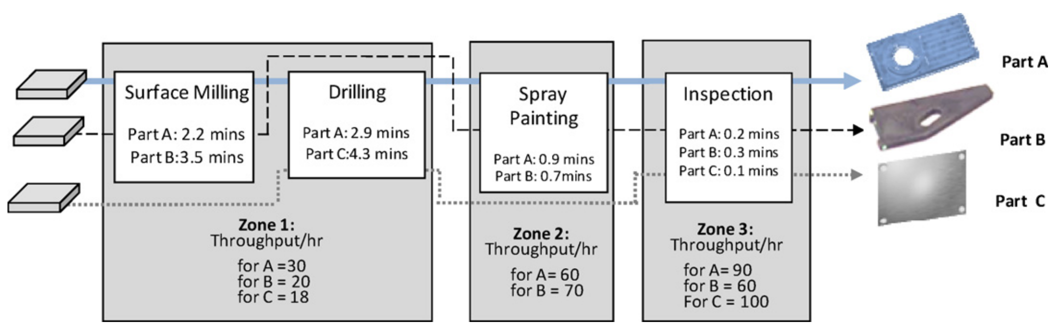

Fig. 6. Simulation of energy flow during manufacture.

ing, modelling and calculation of the DE (TE, AE) and IE for various processes in a typical production system. An energy simulation model is also required to establish 'what-if' scenarios for the analysis and evaluation of energy consumption during the manufacturing phase of a product life cycle. Through the use of a simulation model, the manufacturing process flows can then be easily altered for different products and the model can be expanded to include product or process variations. Additional production variations such as batch sizing, lead times and queue times can also be included in the model.

The simulation model shown in Fig. 5 has been based on a single production system and includes the various processes and manufacturing zones required to produce 3 different parts A, B and C. Subsets of data relating to theoretical energy are calculated by the simulation tool using appropriate mathematical models representing various processes (see the example case study). This calculated data is complemented with actual (real) data related to the auxiliary energy and indirect energy, recorded by advance metering devices and commercial energy management systems used within empirical studies. The manufacturing system has been modelled using software developed by Rockwell Automation called Arena^{TM}, which is a general purpose, widely used software in both industry and academia [17]. It is a discrete event simulation and automation software and uses SIMAN processor and simulation language.

In the model, the manufacturing system comprises of 1 milling machine, 1 drilling machine, 1 spray painting booth and an ultrasonic inspection centre. The product is a metal component that comes in three variations. Part A is a milled part with several holes drilled in it; Part B is an asymmetrical profile that is milled and Part C is a square plate with one hole drilled in each corner. The production steps as well as the processing times are given in Fig. 6. The parts each require different sets of processes and have different processing times. The parts are processed in batches of 10 and are assigned to the workstation once they become available.

The TE for the cutting processes – milling and drilling have been calculated based values for the specific cutting energy, U, and volume of material removed, V, using the equation ($U \times V$). Similarly for ultrasonic inspection, the values for the number of transmitters, N_{trans}, power of transmitter (P) and duration of transmission, T, were used to calculate the TE requirement, using the equation ($N_{trans} \times P \times T$). The TE for spray painting together with AE for all the other processes was determined empirically. In this example, the IE requirements were different due to the specific nature of each process; therefore 3 manufacturing zones have been defined for this application. The attribution of IE for a single part in

Table 1
Calculation of TE and AE for the casting process for the part.

	1: Surface miling	2: Drilling	3: Spray painting	4: Inspection
TE	$U \times V$ where, U: specific cutting energy (kJ/mm^3) V: volume of material removed (mm^3)		Determined empirically	$N_{trans} \times P \times T$ where, N_{trans}: number of transmitters P: power of transmitter (W) T: duration of use (s)
AE	Process liquids Drives	Process liquids Drives	Compressed air supply Drives	Part manipulation
IE	IEzone1/(Tzone1) where, IEzone1: average IE consumed in the zone per hour (kJ/h) Tzone1: throughput of zone 1 (units/h)		IEzone2/(Tzone2) where, IEzone2: average IE consumed in the zone per hour (kJ/h) Tzone2: throughput of zone 2 (units/h)	IEzone3/(Tzone3) where, IEzone3: average IE consumed in the zone per hour (kJ/h) Tzone3: throughput of zone 3 (units/h)

each zone was calculated based on the total IE consumption per hour divided by the throughput for each zone. A summary of the equations and energy considerations is given in Table 1.

In this example, the IE requirements were different due to the specific nature of each process. Both the milling and drilling processes had similar requirements and so were grouped within the same zone. Individual zones were assigned for spray painting and inspection. The attribution of IE for a single part in each zone was calculated based on the total IE consumption per hour divided by the throughput per hour for each zone, which took into account waiting and queuing times, set-up times, part loading and unloading times, etc. It is argued that the inclusion of such miscellaneous (non-productive) times provides a greater degree of accuracy in the attribution of indirect energy to a product and enables further analysis of productive versus non-productive energy consumption. Where two processes share a zone as in the case of Product A, the IE consumed by each individual process in that zone is the average of the IE for zone 1 established for Product A. In this case, the IE of product A for zone 1 was found to be 34.56 kJ and therefore the IE for process 1 and 2 is 34.56/2 = 17.56 kJ.

In this case study, Product A required the most amount of energy during manufacture followed by Product B and Product C, see Fig. 7. Process 3 required the most energy and process 4 required the least energy. Both Products A and B can reduce its embodied product energy by eliminating Process 3. From a design perspective, this could provide an opportunity for designers to eliminate the need for a spray coating on the finished product, perhaps embracing the metallic look of the original material, thus reducing the embodied product energy. Alternatively, as much of the energy consumed in Process 3 is attributed to the auxiliary process, further studies can be conducted to identify inefficiencies in these auxiliary processes such as the compressed air system, thereby improving the efficiencies or if possible, eliminating them. In this case perhaps a variable motor could be installed for the compressed air system if only a small load is required.

Clearly, the EPE framework not only provides an overview on how much energy is required to manufacture a unit product, but also enables further investigation of various factors that play a major influence on the energy consumption within a production system. Therefore it is argued that such energy simulation models can be used as effective decision tools to minimise the energy used during the operations and to support the implementation of 'energy efficient manufacturing'.

It should be noted that with the flexibility offered by modern simulation tools, it is feasible to develop more complex models representing a larger production system for products that consist of a number of components. In such cases, the embodied energy for individual components is calculated and added together to represent the total EPE for the product assembly. Furthermore, the assembly and transportation activities can also be included in the EPE calculation if required. In a production system with automated assembly and/or transportation activities, the energy flows for these processes can be modelled like any other manufacturing workstation. However, the modelling of manual assembly and transportation activities present a particularly interesting challenge for the calculation of TE and DE due to a judgemental approach required for representing the energy consumption by a human operator. This is a commonly reported challenge for other life cycle studies and one that needs further investigation.

The results from the modelling can also be used to support other tools such as the one recently developed by Duque Ciceri et al. [18] which estimates the material's embodied energy and

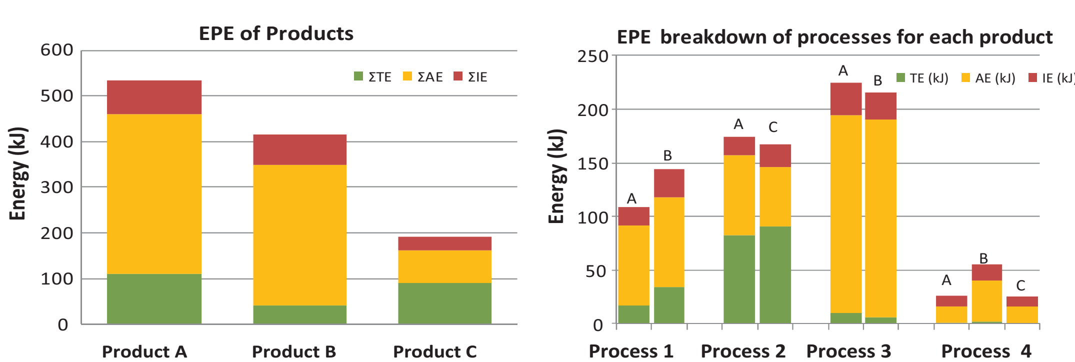

Fig. 7. Results of energy modelling showing EPE during the manufacturing phase for each product and for each process.

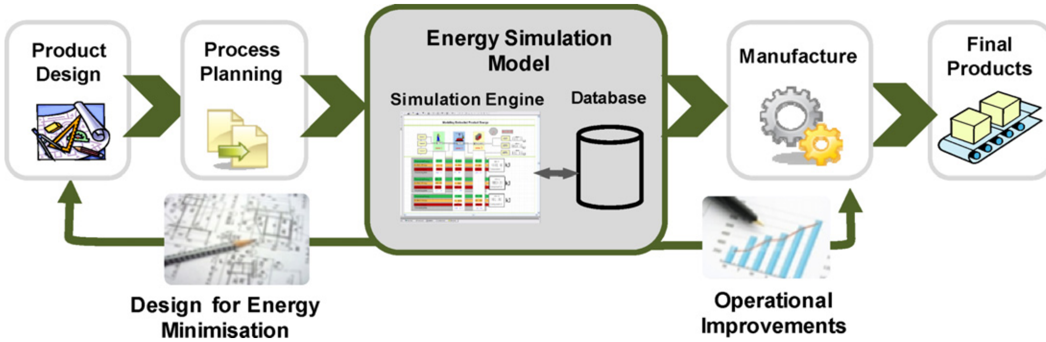

Fig. 8. A 'design for energy minimisation' approach.

manufacturing energy for a product for a quick life cycle energy analysis. The tool detailed in [18] uses data from a compilation of empirical studies, as such the EPE framework proposed in this paper could provide a structured approach for more energy studies to be conducted, thereby improving the accuracy of processing energy data available for use. Other possibilities of using simulation include process planning. For example, Chiotellis et al. [19] has used simulation to evaluate the energy consumption of various production plans. The energy model can also support operational improvements within the manufacturing facility by identifying energy intensive and/or energy inefficient direct processes and auxiliary processes.

However, the authors believe the greatest energy savings through a product's life cycle will come from product design as 90% of the life cycle costs are determined in the design stage [20,21]. Therefore this provides a great opportunity to further investigate the implementation of the EPE modelling framework within a design for energy minimisation methodology as illustrated in Fig. 8.

4. Concluding remarks

The renewable energy technologies provides great potential for power generation in the long term, however, the rationalisation of energy consumption will still provide the greatest opportunity for CO_2 reduction in the short to medium term. In the longer term energy rationalisation may also benefit through reduced dependency and demand especially if renewable technologies continue to remain costly and unreliable. In addition, the expected rapid rise in the cost of energy together with increasing number of legislative and social requirements highlight the importance of adopting an 'energy efficient manufacturing' approach in future applications. The concept of 'lean energy' based on the use of the most energy efficient processes and activities within the production facilities are the most effective way of reducing energy costs whilst maintaining outputs.

Although a number of commercial tools have been utilised to track and monitor energy use in a factory and across various workstations, the detailed breakdown of energy consumption within various processes and, more importantly, its attribution to total energy required for the manufacture of a unit product is not well understood. This paper highlights the need for greater transparency of energy consumption across manufacturing processes and outlines a modelling framework to represent the 'embodied product energy'. In addition to supporting operational decisions, the modelling of the EPE provides energy transparency right back to the design process, enabling designers to select the most energy efficient materials and processes whilst fulfilling the requirements of the product specification. Such a "design for energy minimisation" approach will potentially enable businesses to go beyond the incremental improvements achievable via existing energy management systems to consider energy efficiency and utilisation across both the design and manufacturing phases of a product life cycle.

Furthermore, LCA studies are data intensive and often based on assumptions inappropriate for the product being assessed. The energy model described in this paper could be integrated as part of the data provision, offering data that is of a greater degree of relevance in conjunction with predetermined databases (e.g. Ecoinvent), enabling a more accurate assessment of the product's impact during the manufacturing phase.

The next stage of the research will explore the implementation of the EPE framework within a simulation model capable of supporting complex 'what-if' scenarios during both the product development and operational planning, and also able to provide an estimation of energy required to manufacture a unit product.

References

[1] International Energy Agency, 2008, World Energy Outlook 2008, available at: http://www.worldenergyoutlook.org/2008.asp [accessed 15 September 2009].
[2] Energy Information Administration, 2009, International Energy Outlook 2009, DOE/EIA-0484(2009), available at: http://www.eia.doe.gov/oiaf/ieo/industrial.html [accessed 10 August 2009].
[3] Adapted from Chefurka, P., The Looming Energy Shortfall, available at: http://paulchefurka.ca/EnergyGap.html [accessed 29 September 2010].
[4] Rusinko, C.A., 2007, Green Manufacturing: An Evaluation of Environmentally Sustainable Manufacturing Practices and Their Impact on Competitive Outcomes, Engineering Management, 54/3: 445–454.
[5] Gutowski, T., Murphy, C., Allen, D., Bauer, D., Bras, B., Piwonka, T., Sheng, P., Sutherland, J., Thurston, D., Wolff, E., 2005, Environmentally Benign Manufacturing: Observations from Japan, Europe and the United States, Journal of Cleaner Production, 13/1: 1–17.
[6] Hauschild, M., Jeswiet, J., Alting, L., 2005, From Life Cycle Assessment to Sustainable Production: Status and Perspectives, CIRP Annals—Manufacturing Technology, 54/2: 1–21.
[7] Moss, K.J., 2006, Energy Management in Buildings, 2nd edition. Taylor & Francis, London.
[8] Somervell D, (Ed.) (1991), Educated Energy Management. E&FN Spon, London, UK.
[9] Boyd, G., Dutrow, E., Tunnessen, W., 2008, The evolution of the ENERGY STAR® energy performance indicator for benchmarking industrial plant manufacturing use, Journal of Cleaner Production, 16:709–715.
[10] Katholieke Universiteit Leuven, CO_2PE, available at: http://www.mech.kuleuven.be/co2pe!/index.php [accessed: 08 March 2009].
[11] Devoldere, T., Dewulf, W., Deprez, W., Willems, B., Duflou, R.J., 2007, Improvement Potentials for Energy Consumption in Discrete Part Production Machines, in: Proceedings 14th CIRP Conference on Life Cycle Engineering (Tokyo, Japan), pp.311–316.
[12] Herrman, C., Bergmann, L., Thiede, S., Zein, A., 2007, Energy Labels for Production Machines—An Approach to Facilitate Energy Efficiency in Production Systems, in: Proceedings of 40th CIRP International Seminar on Manufacturing Systems (Liverpool, UK), .
[13] Overcash, M., Twomey, J., Kalla, D., 2009, Unit Process Life Cycle Inventory for Product Manufacturing Operations, ASME International Manufacturing Science and Engineering Conference, West Lafayette, IN, USA.
[14] Gutowski, T., Dahmus, J., et al, 2006, Electrical Energy Requirements for a Manufacturing Process, in: Proceedings of CIRP International Conference on Life Cycle Engineering 2006 (Leuven, Belgium), .
[15] Seow, Y., Rahimifard, S., 2010, A Framework for Modelling Energy Consumption within Manufacturing Systems, in: Proceedings of 43rd CIRP International Conference on Manufacturing Systems (Vienna, Austria), pp.222–227.

[16] Rahimifard, S., Seow, Y., Childs, T., 2010, Minimising Embodied Product Energy to Support Energy Efficient Manufacturing, CIRP Annals—Manufacturing Technology, 59/1: 25–28.
[17] Bapat, V., Sturrock, D.T., 2003, The Arena Product Family: Enterprise Modeling Solutions, in: Proceedings of the 2003 Winter Simulation Conference, pp.210–217.
[18] Duque Ciceri, N., Gutowski, T.G., Garetti, M., 2010, A Tool to Estimate Materials and Manufacturing Energy for a Product, 2010 IEEE International Symposium on Sustainable Systems and Technology (ISSST), pp. 1–6.
[19] Chiotellis, S., Weinert, N., Seliger, G., 2010, Simulation-Based, Energy-Aware Production Planning, in: Proceedings of 43rd CIRP International Conference on Manufacturing Systems (Vienna, Austria), pp.165–172.
[20] Roche, T., 2004, The Design for Environmental Compliance Workbench Tool, in Talaba D, Roche T, (Eds.) Product Engineering. Springer, Netherlands, pp. pp.3–16.
[21] Howard, L., Lewis, H., 2003, The Development of a Database System to Optimise Manufacturing Processes During Design, Journal of Materials Processing Technology, 134:374–382.