CIRP Annals - Manufacturing Technology 59 (2010) 25–28

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Minimising Embodied Product Energy to support energy efficient manufacturing

S. Rahimifard *, Y. Seow, T. Childs (1)

The Centre for Sustainable Manufacturing And Reuse/Recycling Technologies (SMART), Loughborough University, Ashby Road, Loughborough, LE11 3TU, United Kingdom

ARTICLE INFO

Keywords:
Sustainable development
CO_2 emission
Energy efficient manufacturing

ABSTRACT

Green sources of power generation and efficient management of energy demand are among the greatest challenges facing manufacturing businesses. A significant proportion of energy used in manufacturing is currently generated through fossil fuels. Therefore in the foreseeable future, the rationalisation of energy consumption still provides the greatest opportunity for the reduction of greenhouse gases. A novel approach to energy efficient manufacturing is proposed through modelling the detailed breakdown of energy required to produce a single product. This approach provides greater transparency on energy inefficiencies throughout a manufacturing system and enables a 20–50% reduction of energy consumption through combined improvements in production and product design.

1. Introduction

Energy is a key component in the development of modern society; it promotes economic growth and improves the quality of life. The escalation in worldwide population has contributed to the rising energy consumption, and demand levels are estimated to be 45% higher in 2030 than current levels [1]. As a consequence of our strong dependence on energy, there is a growing concern about energy availability and its environmental impacts. Much of our electricity is still generated from carbon based sources such as coal, oil and gas (see Fig. 1) which accounts for more than half of the world's greenhouse gas emissions [2]. This has led to governments introducing an array of environmental legislation, energy auditing and accreditation standards. Therefore, energy demand and its rationalisation are now gaining greater visibility within modern manufacturing businesses. Improving energy efficiency is not only one of the most significant ways to reduce the overall environmental impacts, but could also represent substantial cost savings and competitive advantages [3].

The research reported in this paper highlights the need for appropriate methods and tools within manufacturing businesses that can provide a breakdown of energy usage within their production facilities, and enabling them to assess the efficiency and productivity of their energy consumption. The paper outlines a novel modelling framework to represent the total energy required to manufacture a unit product. A case study has been used to demonstrate how product and production efficiencies can be assessed using this Embodied Product Energy (EPE) model.

2. A framework for modelling Embodied Product Energy during manufacture

A number of modelling approaches have been used to investigate the energy consumption within a manufacturing facility.

These can be viewed under two generic perspectives of 'plant' and 'process' levels. At the 'plant' level, most of the research work has focused on modelling and reducing the energy consumed by infrastructure and other high level services (e.g. ventilation, lighting, heating and cooling) which are responsible for maintaining the required production conditions/environment [5,6]. On the other hand, research on the 'process' level has focused on modelling the energy consumption of equipment, machinery and workstations in production facilities [7,8]. Whilst these areas of research have identified various methods for improving energy used by buildings, technical services and production processes [9], it is argued that the independent considerations of energy consumption at 'plant' and 'process' levels are unable to provide an overview of "how much energy is required to manufacture a unit product?".

At present, the energy considerations from the 'product' viewpoint are included as part of the Life-Cycle Assessment (LCA) studies. However, the data intensive nature of a LCA coupled with the lack of accurate data related to the energy consumption across a product life-cycle often results in significant assumptions and simplifications [10], thus highlighting the need for a more holistic approach on modelling EPE during the manufacturing phase. The proposed framework aims to represent the amount of energy attributed to the manufacture of a unit product through the integration of energy used both at the 'plant' and at the 'process' levels. This modelling approach could further support detailed LCA studies, providing a greater insight into the energy consumption during the manufacturing phase of a product life-cycle.

In the EPE framework, the energy consumed by various activities within a manufacturing application is categorised into two groups: Direct Energy and Indirect Energy. The Direct Energy (DE) is defined as the energy used by various processes (e.g. casting, machining, spray painting, inspection, etc.) required to manufacture a product, whereas the Indirect Energy (IE) is the energy consumed by activities (e.g. lighting, heating, ventilation, etc.) to maintain the 'environment' in which the production processes are carried out within a manufacturing plant. Furthermore in this framework, the DE has been divided into: (i) Theoretical Energy and (ii) Auxiliary Energy, as depicted in Fig. 2. The Theoretical Energy (TE) is defined as the minimum energy required to carry out the process (e.g. energy required to melt a specific amount of metal during casting or

---

* Corresponding author.
E-mail address: S.Rahimifard@lboro.ac.uk (S. Rahimifard).

0007-8506/$ – see front matter © 2010 CIRP.
doi:10.1016/j.cirp.2010.03.048

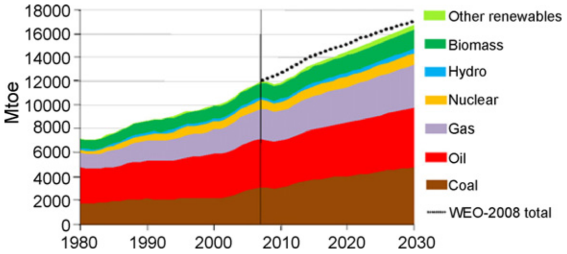

Fig. 1. World primary energy demand by fuel [4].

removing a specific amount of material during a machining operation). In most cases, the value of the TE for a process can be calculated based on existing knowledge and/or appropriate mathematical models (e.g. the total energy for Grinding (U_{total}) based on specific energies of ploughing (U_{pl}), chip formation (U_c), primary rubbing (U_{pri_r}), and secondary rubbing (U_{sec_r}), using the equation: $U_{total} = 0.5(U_{pl} + U_c) + U_{pri\_r} + U_{sec\_r}$) [11].

The Auxiliary Energy (AE) is 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). The AE for a process can often be determined or measured through empirical studies. Therefore the total Direct Energy consumed by product *A*, requiring *n* processes can be represented as:

$$\mathrm{DE}_A = \sum_{i=1}^{n} (TE(i)_A + AE(i)_A) \tag{1}$$

In the case of IE, the energy consumed by various activities such as lighting and heating maybe used by a number of processes or in some applications a process may require specific processing environment (e.g. clean room for inspection). Therefore within the EPE framework, a production 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. This is comparable to defining cells or departments within a traditional production system based on similarity of processes (e.g. a machining cell) or products (e.g. a food production line), except that in this case the grouping of activities is based on similarity of Indirect Energy requirements. In this approach, the IE attributed to product *A* in zone *m* (i.e. $IE\mathrm{zone}(m)_A$) can be calculated based on total Indirect Energy consumed within zone *m* per hour (i.e. $IE\mathrm{zone}(m)$) divided by the total number of product A processed in that zone per hour (i.e. $60/T\mathrm{zone}(m)_A$), where $T\mathrm{zone}(m)$ is the time product *A* spends in zone *m*, as expressed in Eq. (2):

$$IE\mathrm{zone}(m)_A = \frac{IE\mathrm{zone}(m)}{60/T\mathrm{zone}(m)_A} \tag{2}$$

Consequently, the total Indirect Energy required by product *A* requiring *m* manufacturing zones can be represented as:

$$IE_A = \sum_{j=1}^{m} IE\mathrm{zone}(j)_A \tag{3}$$

Finally, the total Embodied Product Energy during the manufacturing phase of product *A* life-cycle can be calculated by summing the DE for *n* processes together with the IE for *m* zones within a production system, as depicted below:

$$\mathrm{EPE}_A = \sum_{i=1}^{n} DE(i)_A + \sum_{j=1}^{m} IE\mathrm{zone}(j)_A \tag{4}$$

Furthermore, a number of ratios of TE, DE, and IE have been identified in order to assess and analyse the efficiency of processes, products and production systems. For example, the ratio of TE over DE (see Eq. (5)) is referred to as the ‘Efficiency Ratio for a process ($ER_{process}$)’ and can be used to analyse the productivity of a process, as shown in Fig. 3. Ideally where possible, the Auxiliary Energy for a process should be minimised as the AE can often be considered as non-value-added energy consumption. Therefore, a higher value of $ER_{process}$ (i.e. values closer to 1) is indicative of a very efficient process. Similarly, the ratio of TE over EPE is defined as the ‘Efficiency Ratio for a product ($ER_{product}$)’ and the ratio of DE over EPE is referred to as ‘Efficiency Ratio for a production system ($ER_{production}$)’, as depicted in Eqs. (6) and (7). The higher value of $ER_{product}$ (i.e. values closer to 1) indicates a higher efficiency of energy consumption during the manufacture of a product, due to minimal energy being used through AE and IE in producing the product. Finally, the $ER_{production}$ can be used to analyse the productivity of a manufacturing system where a higher value (i.e. values closer to 1) is indicative of effective use of energy during production, as the IE can also be considered as non-value-added energy consumption.

$$0 < ER_{process} = \frac{TE}{DE} < 1 \tag{5}$$

$$0 < ER_{product} = \frac{TE}{EPE} < 1 \tag{6}$$

$$0 < ER_{production} = \frac{DE}{EPE} < 1 \tag{7}$$

3. 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 modelling and calculation of the AE, TE, DE and IE for various processes in a typical production system. An energy simulation model (see Fig. 4) has been developed to allow a number of ‘what-if’ scenarios for the analysis and evaluation of energy consumption during the manufacturing phase of a product life-cycle.

The simulation model shown in Fig. 4 has been based on a single production system and includes the various processes and manufacturing zones required to produce a simple product. A subset of data related to Theoretical Energy is 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

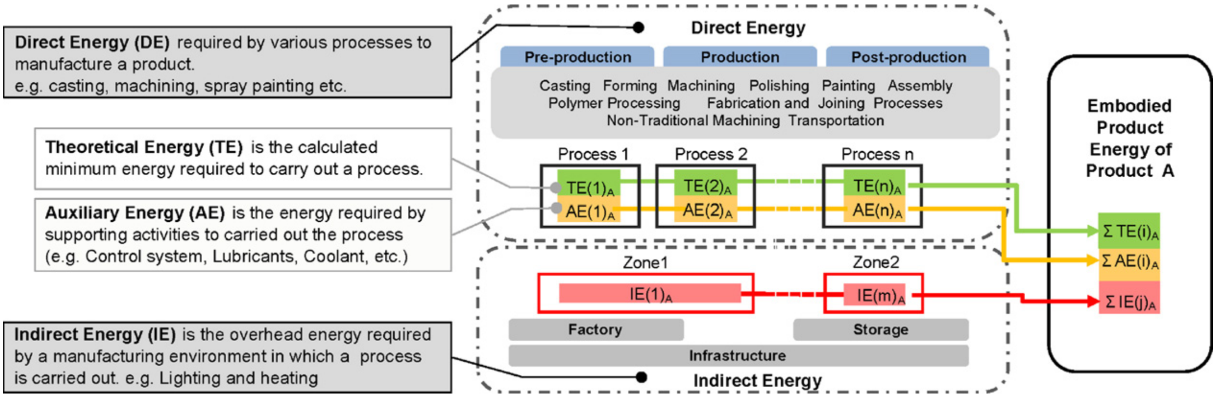

Fig. 2. The Embodied Product Energy framework for modelling energy flows during manufacture.

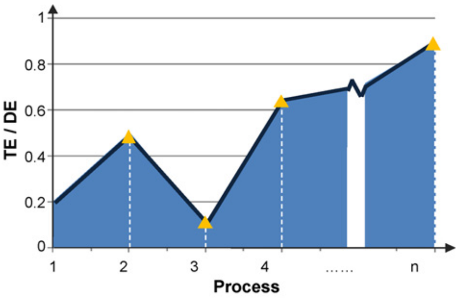

Fig. 3. The efficiency ratio for a process.

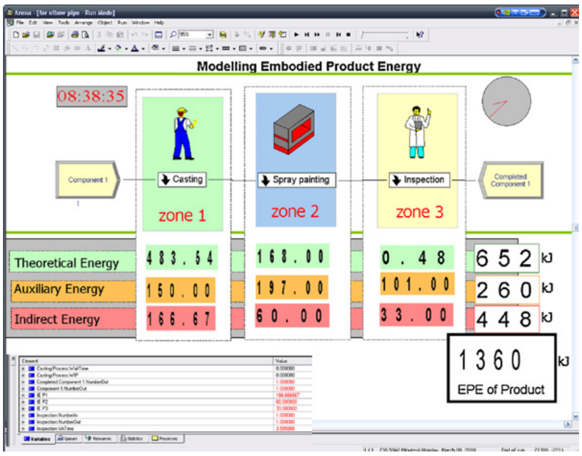

Fig. 4. Simulation of energy flow modelling during manufacture.

the Auxiliary Energy and Indirect Energy, recorded by advance metering devices and commercial energy management systems used within empirical studies.

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 are calculated and added together to represent the total EPE for the product assembly. Furthermore if required, the assembly and transportation activities can also be included in the EPE calculation. In 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 Theoretical and Direct Energies 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.

One of the main objectives proposed for the practical use of such energy simulation models is to increase their accuracy and resolution using a number of case study products (i.e. to train the models), so that they could be used as a design support tool capable of ‘predicting’ energy requirements for new product designs in various applications, as will be discussed later in the paper.

4. An example case study

A simple part (i.e. an elbow pipe) requiring 3 main processes, namely Casting, Spray Painting and Ultrasonic Inspection, is used to demonstrate the application of EPE modelling. The part is made from an aluminium alloy.

The TE for casting process has been calculated based on values for the latent heat of melting of the material (L), specific heat capacity of the material (C), temperature of the material (T), melting temperature of the material (Tm) and finally mass of the material (m), using the equation [$mC(Tm - T) + mL$]. Similarly for Ultrasonic Inspection, the values for number of transmitters (N_{trans}), power of transmitter (P) and duration of transmission (T) were used to calculated the TE requirement, using the equation [$N_{trans} \times (PT)$]. Finally the TE for the Spray Painting together with AE for all three processes were measured 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 each zone was calculated based on the total IE consumption per hour divided by the throughput for each zone, which in this case were 12 parts per hour for the casting process, 20 parts per hour for spray painting and 30 parts per hour for the ultrasonic inspection process. It should be noted that in this case study, the times spent in each zone were inclusive of queuing (waiting) time, set-up time, part loading and unloading times, etc., and therefore these times were greater than the actual processing

Table 1
Equations for calculating EPE for a simple elbow pipe fitting.

Calculation of EPE for Product A

Process 1: Casting	Process 2: Spray Painting	Process 3: Inspection	Total
$TE(1)_A$: mC(Tm-T) + mL = 0.5*0.46(1809.2-298.15)+0.5*272 = 484 kJ *m : Mass (kg)* *C : Specific heat capacity (kJ/kg)* *Tm : Melting temperature (K)* *T : Temperature of metal before melting (K)* *L : Latent heat of melting (kJ/kg)*	$TE(2)_A$: determined empirically = 168 kJ	$TE(3)_A$: N_{trans} * P *T = 8 x 0.5 x 2 = 4 W * 2 = 0.24 kJ/min * 2 = 0.48 kJ *N_{trans} : Number of transmitters* *P : Power of transmitter (W)* *T : duration of use (mins)*	**$\sum TE_A$** **652 kJ**
$AE(1)_A$: Vacuum + Process Inefficiencies = 100 + 50 = 150 kJ	$AE(2)_A$: Pump + Process Inefficiencies = 125 + 60 = 197 kJ	$AE(3)_A$: Conveyor System = 101 kJ	**$\sum AE_A$** **448 kJ**
$IE(1)_A$: IEzone1/(60/Tzone$(1)_A$) = 2000/(60/5) = 167 kJ *IEzone1 : Average IE consumed in the zone per hour (kJ/hr)* *Tzone1 : Time part spends in zone 1 (mins)*	$IE(2)_A$: IEzone2/(60/Tzone$(2)_A$) = 1800/(60/3) = 60 kJ *IEzone2 : Average IE consumed in the zone per hour (kJ/hr)* *Tzone2 : Time part spends in zone 2 (mins)*	$IE(3)_A$: IEzone3/(60/Tzone$(3)_A$) = 1000/(60/2) = 33 kJ *IEzone3 : Average IE consumed in the zone per hour (kJ/hr)* *Tzone3 : Time part spends in zone 3 (mins)*	**$\sum IE_A$** **260 kJ**
$EPE(1)_A$ = 800 kJ	$EPE(2)_A$ = 425 kJ	$EPE(3)_A$ = 135 kJ	**$\sum EPE_A$ =** **1360 kJ**

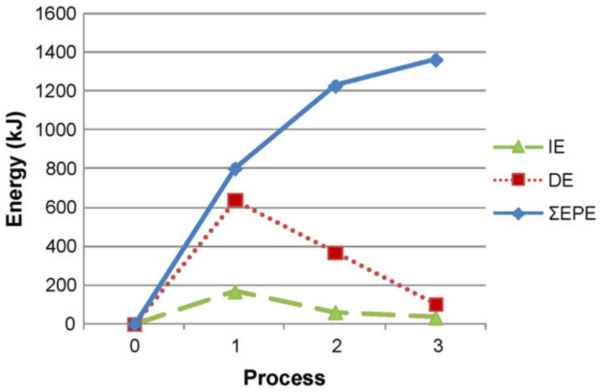

Fig. 5. Breakdown of energy consumption for the manufacture of case study product.

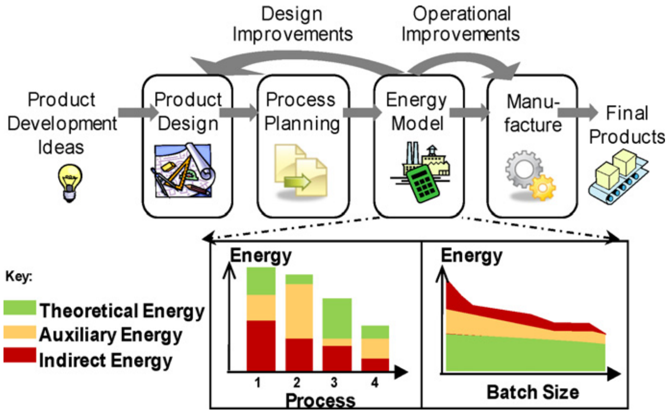

Fig. 6. Utilisation of energy simulation model to support both design and operational decisions.

time of the part. It is argued that 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.

These calculations and the associated values for the TE, AE, IE and the total Embodied Product Energy for the case study product are summarised in Table 1 and illustrated in Fig. 5.

In this case study, the TE clearly consumes the greatest proportion of total energy at 48%, followed by the AE at 33%, and in fact the IE contributes the least to the total EPE (19%). Furthermore, the values of ER_{process}, ER_{product}, and $ER_{\text{production}}$ are all relatively very high (i.e. 0.59, 0.48, and 0.80 respectively), representing efficient processes, product, and production system. Clearly, the EPE modelling 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'.

In addition to supporting operational decisions, the EPE framework could provide energy transparency right back to the design process, enabling designers to select the most energy efficient materials and processes whilst fulfilling the requirements in the product specification, as depicted in Fig. 6. Such a "Design for Energy Minimisation" approach will potentially enable businesses to go beyond the incremental improvements achievable via existing energy management systems, and to consider energy efficiency and utilisation across both the design and the manufacturing phases of a product life-cycle.

5. Concluding discussions

The existing commercial energy management tools provide a high level overview of energy consumption within a manufacturing system, hence are unable to model the detailed breakdown of energy flows among various processes, workstations and production zones. More importantly, they cannot determine the specific energy attribution for the manufacture of a unit product. The recent rise in the energy cost together with the increasing number of legislative and social requirements highlight the importance of adopting an 'Energy Efficient Manufacturing' approach in future manufacturing applications.

To support such approach, the energy consumption in manufacturing facilities can be reduced by either more efficient technologies and/or equipment to improve production processes, and also through more efficient monitoring and control of energy used in infrastructure and technical services to optimise the 'plant' level activities. The major research assertion made is that step change improvements in the productivity of energy consumption within manufacturing (and remanufacturing [12]) applications can only be effectively achieved through integration of these global factory level and local process level energy considerations through a novel framework based on a product viewpoint. The Embodied Product Energy framework and the associated energy simulation tools not only enable a reactive approach to minimise energy consumption through improved operational decisions but also support a proactive approach to improve product design by eliminating non-productive energy intensive processes. Finally, it is claimed that significant reduction in energy consumption within manufacturing applications can only be gained through such proactive "Design for Energy Minimisation" approach.

References

[1] International Energy Agency. (2008) *World Energy Outlook 2008*. . Available at: http://www.worldenergyoutlook.org/2008.asp [Accessed 15 September 2009].
[2] World Resources Institute. (2005) *World Greenhouse Gas Emissions: 2005*. . Available at: http://www.wri.org/chart/world-greenhouse-gas-emissions-2005 [Accessed 10 August 2009].
[3] Jovane F, Yoshikawa H, Alting L, Boër CR, Westkamper E, Williams D, Tseng M, Seliger G, Paci AM (2008) The Incoming Global Technological and Industrial Revolution Towards Competitive Sustainable Manufacturing. *CIRP Annals Manufacturing Technology* 57:641–659.
[4] International Energy Agency. (2009) *World Energy Outlook 2009*. . Available at: http://www.iea.org/country/graphs/weo_2009/fig1-1.jpg.
[5] Andreassi L, Ciminelli MV, Feola M, Ubertini S (2009) Innovative Method for Energy Management: Modelling and Optimal Operation of Energy Systems. *International Journal of Energy and Buildings* 41:436–444.
[6] Mills E, Shamshoian G, Blazek M, Naughton P, Seese RS, Tschudi W, Sartor D (2008) The Business Case for Energy Management in High-tech Industries. *Energy Efficiency Journal* 1:5–20.
[7] Devoldere T, Dewulf W, Deprez W, Willems B, Duflou RJ (2007) Improvement Potentials for Energy Consumption in Discrete Part Production Machines. *Proceedings of the 14th CIRP Conference on Life Cycle Engineering*, Tokyo, Japan, 311–316.
[8] Gutowski T, Dahmus J, et al, (2006) Electrical Energy Requirements for a Manufacturing Process. *Proceedings of 13th CIRP International Conference on Life Cycle Engineering*, Leuven, Belgium, 623–627.
[9] Herrmann C, Thiede S (2009) Process Chain Simulation to Foster Energy Efficiency in Manufacturing. *CIRP Journal of Manufacturing Science and Technology* 1:221–229.
[10] Hauschild M, Jeswiet J, Alting L (2005) From Life Cycle Assessment to Sustainable Production: Status and Perspectives. *CIRP Annals Manufacturing Technology* 54:1–21.
[11] Ghosh S, Chattopadhyay AB, Paul S (2008) Modelling of Specific Energy Requirement During High-efficiency Deep Grinding. *International Journal of Machine Tools and Manufacture* 48:1242–1253.
[12] Sutherland JW, Adler DP, Haapala KR, Kumar V (2008) A Comparison of Manufacturing and Remanufacturing Energy Intensities with Application to Diesel Engine Production. *CIRP Annals Manufacturing Technology* 57:5–8.