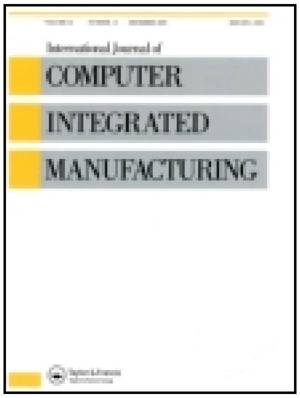

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Simulation of energy consumption in the manufacture of a product

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Energy rationalisation, the elimination of unnecessary energy consumption, is becoming increasingly important in a resource constrained world. The use of energy is a significant contributor to greenhouse gas emissions and much research has been done to reduce energy use in manufacturing. So as to enable the rationalisation of energy consumption, it is essential that it is understood where energy is being used. This paper describes the design and implementation of a simulation model that has been generated to support the modelling of energy consumption within manufacturing systems. The simulation model allows various 'what-if' scenarios to be investigated thereby enabling engineers to understand the impact of various manufacturing parameters on energy consumption and thus reduce reliance on energy and the production of greenhouse gas emissions.

Keywords: energy modelling; low carbon manufacturing; simulation; energy efficiency; discrete event simulation

1. Introduction

Energy minimisation is becoming a critical consideration in the manufacturing industry due to rising oil prices and uncertainties in energy supplies driven in part by soaring demand. In light of this, coupled with projections of shortages, improving energy efficiency has become increasingly vital. This rationalisation of energy consumption is not only a cost-effective way of cutting carbon emissions but can also improve productivity and energy security. It is reported that energy efficiency improvements as high as 30% can be achieved with current technology (European Commission 2008). Future manufacturing businesses adopting new energy efficient technologies and practices for their processes and systems can stand to significantly reduce and minimise their energy consumption.

In order to reduce energy consumption and other environmentally related impacts, there is a need for detailed real-time information regarding both products and processes (Taisch *et al*. 2011). However, current research in energy and existing commercial energy management products have focused mostly on auditing and monitoring of energy consumption so as to provide historical records to aid energy saving efforts (Herrmann *et al*. 2010, Müller and Löffler 2010, Vijayaraghavan and Dornfeld 2010, Wang *et al*. 2012). However, these improvements are often incremental and often do not provide sufficient support for decision making. In contrast, decisions taken at the design phase of a product can influence the energy savings more significantly than optimisation steps later on in the product development process (Duflou and Dewulf 2004).

Modelling can be useful for analysing complex systems as various aspects can be mapped into models and analysed in place of real systems (Wanyama *et al*. 2003, Wohlgemuth *et al*. 2006). For example, some decisions may involve heavy investments in equipment or refurbishments, thus a discrete event simulation (DES) that is able to provide 'what-if' scenario planning is beneficial for optimising and evaluating these decisions.

This paper introduces an energy framework that can be integrated within a simulation engine to provide greater energy transparency within manufacturing systems. The vision is that such decision support tools can enable manufacturers to go beyond incremental improvements by enabling better design of their products and systems. The research presented in this paper is the result of the work completed as part of a PhD (Seow 2011). This paper comprises three parts: (1) current commercially available software for energy management and analysis, (2) overview of the Embodied Product Energy (EPE) framework to support the Energy Simulation Model (ESM) and (3) description of the ESM and its application for evaluation of a product during the manufacturing phase. The paper concludes with proposals for further development of the model and conclusions.

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2. Review of commercially available software for energy evaluation and analysis

The need for improved management and monitoring of energy consumption within a manufacturing facility has led to a proliferation of energy management software tools. These tools can be categorised into two main approaches: (1) product life cycle based or (2) energy management based. The analysis of energy embodied within a product is typically established through the use of Life Cycle Analysis (LCA) based software which uses generic process data from a pre-existing life cycle inventory database. Currently, most LCA software is unable to model and attribute to a product energy consumption from overhead processes such as heating and lighting within a production facility. To monitor and analyse energy consumption within a building or a facility, the second group of software systems (energy management) is used. This allows the energy consumption within a specific manufacturing facility to be tracked and monitored enabling detailed analysis and control.

2.1. *Product lifecycle based*

Ten commonly used software packages have been evaluated to determine their suitability for modelling the EPE during production (a summary of the review is shown in Table 1). In general, the LCA tools reviewed were able to establish the embodied energy of a product using data from inbuilt databases or external databases such as Eco Invent. As long as the processes required are known and the parameters can be defined, the software packages are able to calculate the energy required to produce a product. Comprehensive LCA packages such as SimaPro 6.0 (Pré Consultants 2011), Gabi 4.0 (PE International GmbH 2007) and TEAM 4.0 (Ecoliban Group 2011) are able to model energy embodied within a product across different life cycle phases but the final embodied energy is attributed within the overall environmental impact of the product, and hence a singular embodied energy value cannot be established.

Most of the LCA software is unable to model the specific energy flows within a production system. Of the software reviewed, only Umberto® (developed by the Institute for Environmental Informatics, Hamburg GmbH) is able to conduct energy and material flow analysis through graphical modelling and visualisation within the program (Ifu 2011). The energy flows modelled were static and thus unable to model changing production rates and variations in processing parameters. Of the software reviewed, only one is able to model energy flows within a production system, two consider the energy consumption within facilities, three provide decision support for energy improvements and one provided energy efficiency considerations.

There is a distinct lack of LCA tools that are able to model the energy consumption within a production system and can account for both process energy and the energy required by the building services. All the reviewed LCA software use generic data when calculating the energy required by manufacturing processes which is based on a *per unit mass* basis with limited flexibility for the addition of customised energy data from a specific production plant. Most of the LCA software provides a detailed breakdown of the environmental impact of the product over the life cycle which only highlights the life cycle phase that is most energy intensive but provides little or no detailed breakdown on the energy embodied by the product.

2.2. *Energy management systems*

Energy management systems (EMS) are typically used to help companies control their energy use by systematically tracking and planning energy use in equipment, processes, building, industrial facilities and entire corporations. The European standard for EMS is EN16001 (British Standards Institution 2009) which requires organisations to measure and assess actual energy use and record significant changes through tracking past, present and unexpected energy consumption.

The most basic energy management tools are in the form of a spreadsheet where utility bills are entered and an analysis is carried out with the collected data. An example of a Microsoft Excel based tool is Energy Lens by BizEE (2011). The Quick Energy Profiler, Quick PEP, by the US Department of Energy Industrial Technologies Program, DOE-ITP (US DOE 2011a) is another simple tool that helps users to establish a baseline for the energy consumed within a plant or facility.

For large amounts of data, a database management system is required. Using a modern computer-based monitoring and control systems, which are designed to operate on a plant wide basis, can yield further major improvements in energy efficiency. This can be integrated within a thorough energy management program which usually consists of metering and monitoring of energy consumption, identifying and implementing energy saving measures and verifying savings with real measurements. Software systems such as Optima (Optima Energy Management 2011) bring together groups of readings, calculating totals and averages and indicating trends and optimum operating conditions within a single platform. Other systems such as T&D Solution (Itron 2011), AVReporter (KONsys 2011), xChangepoint (EPS Corp 2011) and

Table 1. Summary of various LCA software and their features.

Name of software	Developer	Availability		Availability	Applicability	Calculation of embodied energy	Modelling of energy flows within production	Consideration of facility energy consumption	Decision Support for energy efficient improvements	Energy efficiency considerations
		Desktop	Web-based							
SimaPro 6.0	Pré Consultants	✓		Licensed	Products	✓				
GaBi 4.0	PE International	✓		Licensed	Products	✓				
TEAM 4.0	Ecoliban Group	✓		Licensed	Products	✓				
CES Eco Audit Tool	Granta Design	✓		Licensed	Products	✓				
EcoFly 3.0	PlesTech	✓		Licensed	Products	✓			✓	✓
CarbonScope™	CleanMetrics		✓	Licensed	Products	✓				
WattzOn	Synthesis Studios		✓	Freeware	Products	✓				
Umberto 5.0	Institute for Environmental Informatics	✓		Licensed	Products	✓	✓			
Athena® Environmental impact estimator 4.1	Athena Sustainable Materials Institute	✓		Beta version is free	Buildings	✓		✓	✓	
Building for Environmental and Economic Sustainability, BEES	National Institute of standards and Technology		✓	Freeware	Buildings	✓		✓	✓	

Table 2. Evaluation of various energy management software.

			Approach				Data Requirement				Complexity		Availability		Type of Analysis	
System level	Name of software	Developer	Accounting	Monitoring	Management	Benchmarking	Utility data	Facility and Production data	Excel Tool	Full software Suite	Desktop	Web-based	Carbon accounting	Energy pricing and demand management	Operational improvements	Efficiency improvements
Overall system	Energy Lens	BizEE	✓		✓		✓	✓	✓		✓					
	Quick Plant Energy Profiler (Quick PEP)	U.S DOE- ITP	✓			✓	✓			✓		✓		✓		
	Optima	Optima Energy Management	✓	✓	✓		✓				✓			✓		
	T + D Solution	Itron	✓	✓	✓			✓				✓		✓		
	AVReporter	KONsys	✓	✓	✓		✓	✓			✓	✓		✓		
	Changepoint	EPS Corp	✓	✓	✓			✓	✓	✓		✓	✓	✓	✓	
	eSight	Esight Energy Group	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓
	Energy Management Application Platform	EnerNOC	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓
	Hara Environmental and Energy Management	Hara	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓
	EnergyCAP	EnergyCAP Inc.	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓
Building	Energy Plus	U.S DOE- BTP	✓			✓	✓			✓		✓				✓
	Opt E-plus	National Renewable Energy Laboratory, NREL	✓				✓		✓		✓					✓
	SUNREL		✓				✓		✓		✓					✓
	DOE-2	Lawrence Berkeley National Laboratory	✓			✓	✓		✓		✓					✓
Compressed air	AIRMaster+	U.S DOE- ITP	✓	✓	✓			✓		✓		✓			✓	✓
Fan	Fan System Assessment Tool (FSAT)		✓	✓	✓			✓		✓		✓			✓	✓
Motors	Motor Master +International		✓	✓	✓			✓		✓		✓			✓	✓
Process	Process Heating and Survey Assessment Tool (PHSAT)		✓	✓	✓			✓		✓		✓			✓	✓
Pumps	Pumping System Assessment Tool (PSAT)		✓	✓	✓			✓		✓		✓			✓	✓
Steam	Steam System Tool Suite (SSST)		✓	✓	✓			✓		✓		✓			✓	✓

eSight (eSight Energy Group 2011) can be based on real-time information obtained remotely through special energy metres that transmit energy consumption data to a server.

Fully comprehensive software solutions like Energy Management Application Platform (EnerNOC 2011), Hara Environmental and Energy Management (Hara 2011) and EnergyCAP (EnergyCAP Inc. 2011) include more sophisticated features such as planning and scheduling tools to optimise energy use and supply, energy balance management tools to support real-time monitoring and control of peak energy demand, and in-depth evaluation tools that correlate external variables such as weather, production and building occupancy to energy use.

Other energy tools have also been developed for the modelling and analysis of energy consumption of a building. Energy Plus (DOE Building Technologies Program) is the primary software tool used for energy performance analysis of commercial buildings and enables multi-zone air flows and heat balances to be modelled (US DOE 2011b). The Opt E-plus and SUNREL (both by National Renewable Energy Laboratory) enable the optimization of building design by simulating various designs and technology options against energy performance (NREL 2011). The tool facilitates many simultaneous calculations and thus can manage thousands of simulations incorporating dynamic interactions between the building envelope, the external environmental and its occupants.

DOE-2 is a portable program that is compatible with most computer systems and provides designers and researchers with a quick energy analysis of various building parameters and the impact on thermal comfort of the occupants (Hirsch 2009). Various levels of detail on the building design or alternative design options can be included based on the user's requirements.

Specific process support tools have been developed by the US DOE-TIP to aid with identifying and analysing energy system saving opportunities within a plant or facility (US DOE 2011a). The suite of tools cover a range of services typically found in production plants such as compressed air, motors, pumps, process heating and steam. For example the Motor Master + and AIRMaster + use plant specific data and evaluate the energy consumption of motor and compressed air systems based on various equipment configuration system profiles. They also provide estimates of energy savings that can be made from a range of energy efficiency measures. In addition, MotorMaster + provides purchasing decision support and analysis through the evaluation of the cost effectiveness of repairing or replacing motors. The other tools that provide efficiency assessments are the Fan System Assessment Tool, the Pumping System Assessment Tool, Process Heating Assessment and Survey Tool and Stream System Tool Suite. A summary of the energy management tools discussed are shown in Table 2.

The EMS are able to model and monitor the energy flows within a production system and correlate the production variables to the plant energy consumption. However, the energy breakdown is based on a plant perspective and cannot provide a comprehensive energy analysis and evaluation for a particular product.

Both LCAs and EMS are therefore static analytical tools. However, the use of DES enables the dynamics of a system to be captured allowing for a better understanding of how a system operates. DES is a popular technique for studying industrial processes and commonly used in planning (Banks *et al.* 2000, Law and Kelton 2000). The time aspect can be used to investigate time-dependant parameters, which is useful in many energy consuming processes. However, most of the commonly used DES models do not support energy considerations (Arena, Simul8, Plant Simulation and Anylogic) as default function. Nevertheless, some researchers have attempted to create customised models within DES software to model energy flows (Heilala *et al.* 2008, Solding *et al.* 2009, Page and Wohlgemuth 2010, Herrmann *et al.* 2011). Often the analysis of energy-related information has to be integrated manually by the user through the correlation of energy with other functions such as time or cost. The current efforts to use DES to model energy are very much process based and whilst they successfully model the energy flows in the production system they do not provide an indication of how much energy consumption improvement can be made and how it can be used to improve product design. A comprehensive review of various approaches to energy modelling is detailed in Herrmann *et al.* (2011). The approach presented in this paper is novel as it uses a product perspective to evaluate the energy used to manufacture the product and further uses DES to provide a breakdown of energy use from the facility as well as the processes. This framework, which also evaluates the efficiency of the energy consumed, is further described in the next section.

3. EPE framework to support energy modelling

The approach adopted by this paper is based on an EPE framework reported in Seow and Rahimifard (2011a). In this framework, the energy consumed by various activities with a manufacturing application is categorised into two groups: Direct and Indirect Energy as illustrated in Figure 1. The Direct Energy

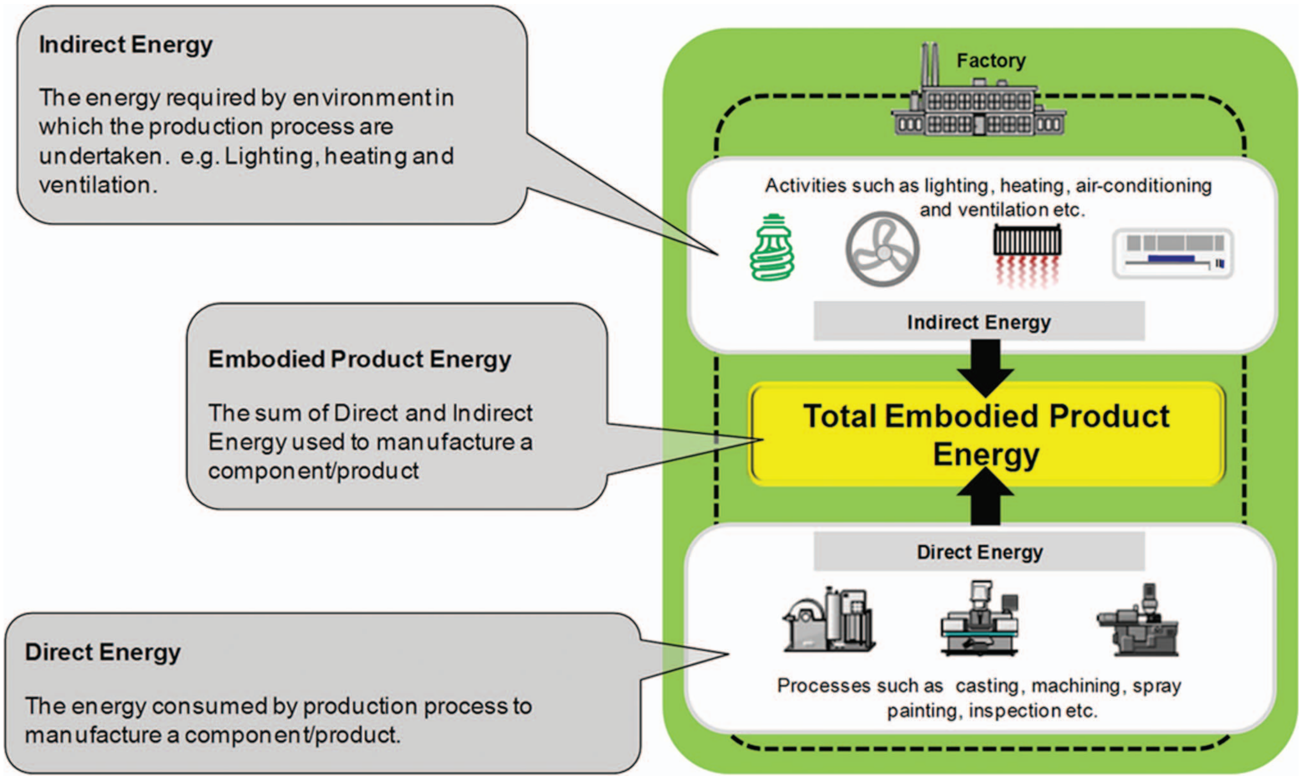

Figure 1. The EPE framework consists of the Indirect Energy and the Direct Energy.

(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 a factory or manufacturing plant (e.g. lighting, heating and ventilation).

The DE can be further divided into:

(1) Theoretical Energy (TE) which 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)
(2) Auxiliary Energy (AE) which refers to 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 also includes non-productive modes such as machine start-up, standby and cleaning.

A systematic approach has been used to calculate the DE and IE for various processes required in the production chain of a product. A combination of theory, empirical studies or reference sources can be used to determine the values of DE and IE. In most cases, the value of 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 specification (e.g. data from equipment manufacturers) and where data are 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 the number of products processed in that 'zone' per hour. The sum of the TE and the AE (i.e. DE) together with the IE for all the processes within a production system represent the total embodied energy of the product (i.e. EPE).

A more detailed energy analysis can also be made by considering the ratio of TE to AE (with a higher value for TE and a 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). Three ratios have been defined:

(1) $ER_{process\ (A)}$ for the efficiency of the process when manufacturing product A = TE/DE,
(2) $ER_{product(A)}$ for the efficiency of the manufacture of product A = TE/EPE, and

(3) $ER_{plant(A)}$ for the efficiency of a production system during the manufacture of product A = DE/EPE.

$ER_{process}$ can be used to assess the inefficiencies introduced through non-productive auxiliary activities, ER_{plant} can be indicative of the inefficiencies introduced through the IE and finally $ER_{product}$ highlights both the inefficiencies caused by the AE and IE component. Values closer to 1 are indicative of effective use of energy. A detailed explanation and the use of the ratios can be found in Rahimifard *et al.* (2010).

The EPE model can also be used to examine the impact of other production parameters such as number of setups, batch sizes, production schedules, etc. The energy breakdown and efficiency ratios generated through the framework can allow designers or engineers to target the most energy intensive processes for energy minimisation. A case study of three different products is presented in Seow and Rahimifard (2011a) which shows how the breakdown of energy into IE, TE and AE enables the identification of optimisation parameters which play a major influence on the energy consumption within a production system.

The EPE framework along with the simulation model detailed in the next section can 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. This provides a focused area for energy optimisation which is essential when the parameters that contribute to overall energy consumption are numerous.

4. Energy simulation model

4.1. *Overview of the ESM*

A simulation model has been designed and used to support the application of the EPE framework within manufacturing systems. The ESM can be used to consider a number of 'what-if' scenarios for optimisation and improvement in energy efficiency in manufacturing applications. The flexibility offered by simulation techniques enables a wide range of variables representing process routes, batch sizes, production lead times, queue times, etc. to be incorporated within the model. Because of this flexibility, the simulation model is suited to analysing both new and existing product developments. The use of simulation can provide information about the effects of trying different methods before actually testing them (Rittershaus *et al.* 1995). In this respect, to implement this simulation model, it is useful to know the processes that will be involved in product manufacture (i.e. after process planning has taken place), but it can also be used to help decide on the processes that could be used and their associated energy requirements.

For the generation of a simulation model, it is necessary to clearly define different data types that may or may not be interrelated, but that influence the outcome of scenarios. In the case of the this ESM, which uses the EPE framework, the relevant data types have been defined as follows: various processes are defined as events; products as entities; buffers as queues; product and processing data as attributes; and the energy consumed by activities used to manufacture the products are defined through variables (as illustrated in Figure 2). Statistical distributions can also be allocated within the simulation model to represent batch sizes, processing and queuing times, etc. The ESM model receives input data related to product and processing parameters and generates outputs in the form of energy data such as energy consumption per process and product as well as related efficiency ratios.

In practice, different batches of products may be manufactured on the same production line. The use of

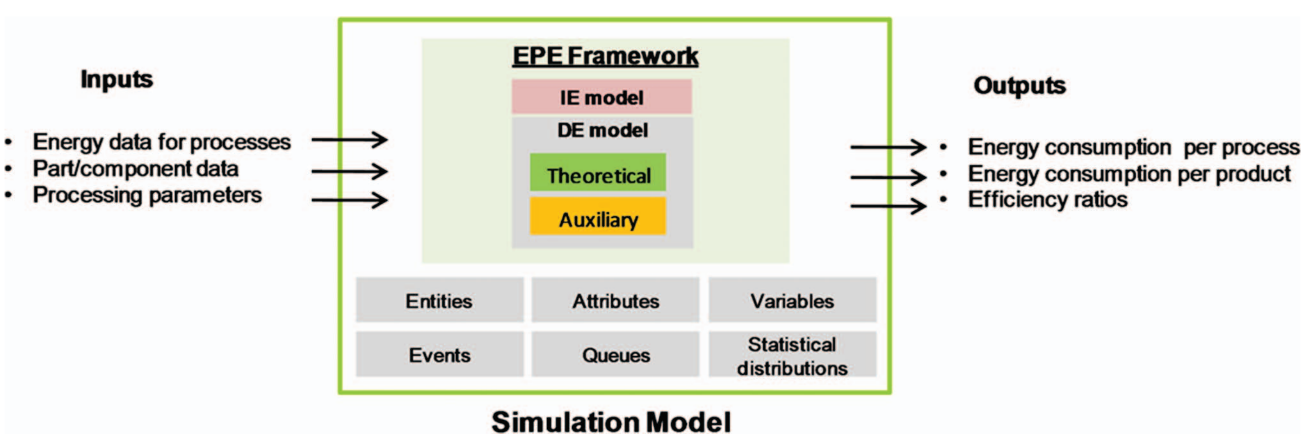

Figure 2. Inputs and outputs from the simulation model.

a simulation model provides the additional functionality to address different batch sizes and the impact it would have on overall energy consumption and thus the embodied energy per product can be established. In addition, different product types that have a similar process chain (i.e. require same resources) can also be analysed and the impact of different product features on energy consumption can also be examined.

For example, a larger batch size could result in the reduced frequency of machine reconfiguration and therefore lead to energy savings from the elimination of multiple machine start-ups. The benefit of scale not only reduces material and labour costs but also energy costs as the IE of the process could be attributed to a larger product quantity. The simulation model can be used to assess the impact of varying batch sizes on embodied energy per product through the function of throughput time. This can allow the user to compare energy efficiency between achieving economies of scale and economies of scope. Additionally, because the ESM considers individual events, entities and manufacturing zones separately, a generic model can be produced for a particular facility which can then be modified as required for new processes or products. Each 'investigation' does not require the creation of a new ESM.

4.2. *Software implementation for ESM*

A simulation software package called Arena^{TM} developed by Rockwell Automation (2011), which was readily accessible by the authors, has been utilised to design and implement the ESM. Arena^{TM} is widely used both in industry and academia and is therefore an appropriate choice to develop and energy management simulation model. It is a general purpose DES software and utilises a graphical interface to simplify the model development. There are many alternative commercially available DES packages, for example, SIMUL8, Witness and Plant Simulation, which are suitable for

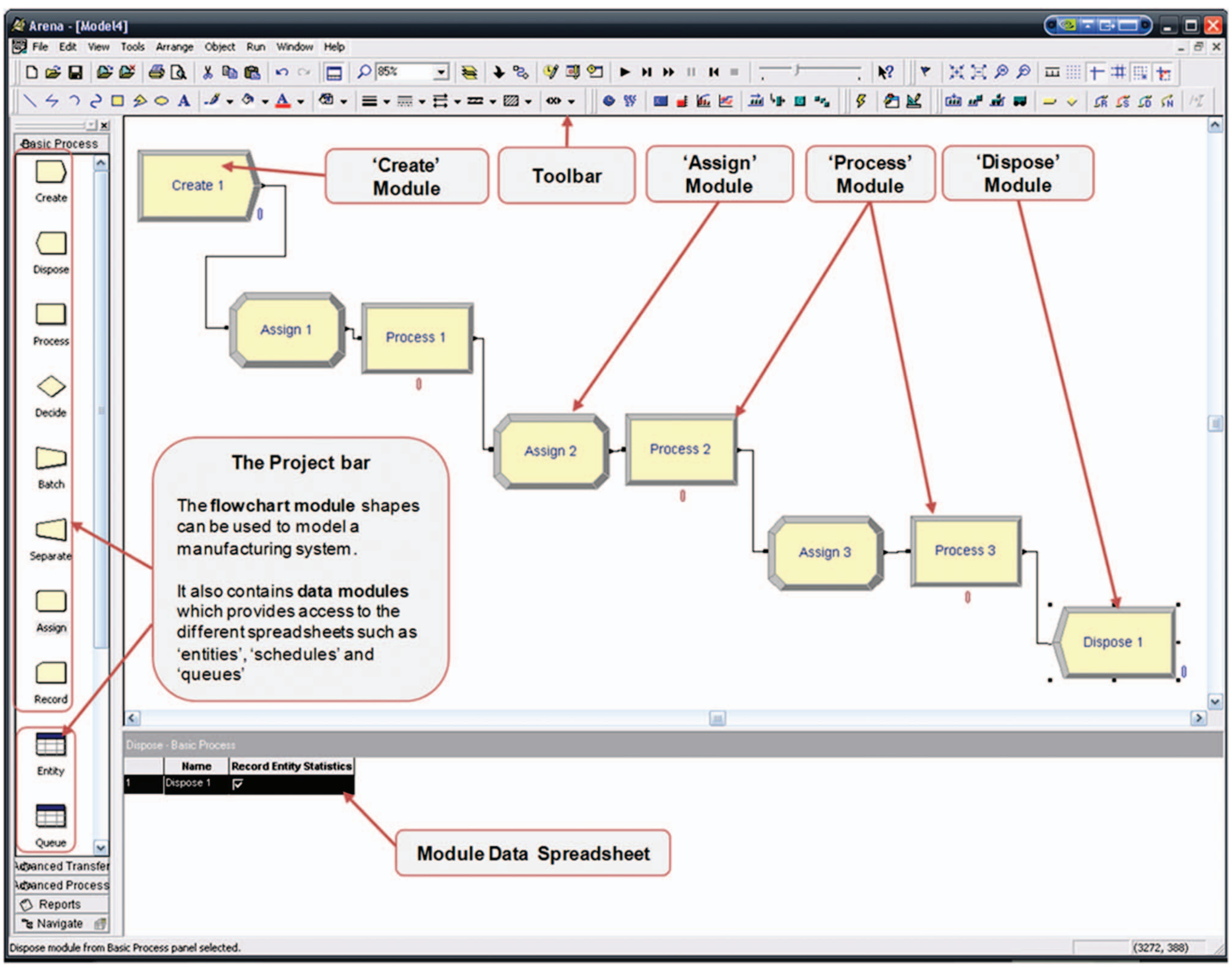

Figure 3. Overview of simulation window in Arena showing the different modelling modules and features.

the implementation of the described ESM and for which the approach presented in this paper would require only minor modification. Figure 3 provides an overview of the main working window in Arena and highlights the various modules and shows how they can be placed to represent a production system.

4.3. *Application of the ESM*

A simple example of a product, an elbow pipe, has been used to demonstrate how the simulation model can be used to generate a range of data through the variation of manufacturing parameters. There are three processes required to manufacture the elbow pipe: casting, grinding and inspection. The DE and IE associated with the processes contribute to the EPE of the elbow pipe, as shown in Figure 4.

This paper shows the application of the simulation model to establish the DE and IE of the part. There are primarily two major tasks involved in the calculation of DE and IE within the ESM (1) definition of the energy data required by the model and (2) representation of DE and IE calculations with the model, as outlined below and explained in the following sections.

4.3.1. *Definition of energy data within the model*

Typically, a wide range of data may be required for developing a simulation model. The range and amount of data is entirely dependent on the complexity of the manufacturing system and the processes being modelled. The data can be entered manually by the user or automatically imported through spreadsheets. To allocate the data to products passing through the system, the ‘Assign’ module is used in Arena to tag data to an entity representing the product. Furthermore, the energy data is tagged to the products as ‘Attributes’ which is a specific value that can differ from one entity to another. ‘Attributes’ can be defined and values can be assigned by the user. If the TE and the AE are already known (which may come from empirical measurements, calculations or reference values) for the particular product, the values can be entered directly.

In cases where there is a huge volume of data, it is possible to use Microsoft Excel or similar spreadsheet tool to tabulate the TE and the AE data for the processes and the products so that the data can be easily imported from databases or managed in a centralised file. The use of the ‘Read’ module reduces the need to input the energy data into individual ‘Assign’ modules but allows the user to store the data in a single file which can be linked to the other ‘Process’ modules in the simulation model. In addition, since the majority of data loggers use Excel files to store data, the use of Excel provides compatibility between Arena and these data loggers and simplifies the data transfer process, especially in cases where large volumes of data are involved.

A similar module called the ‘Write’ module can export the data to an Excel file. This can be useful as the graphic generation capabilities in Arena are

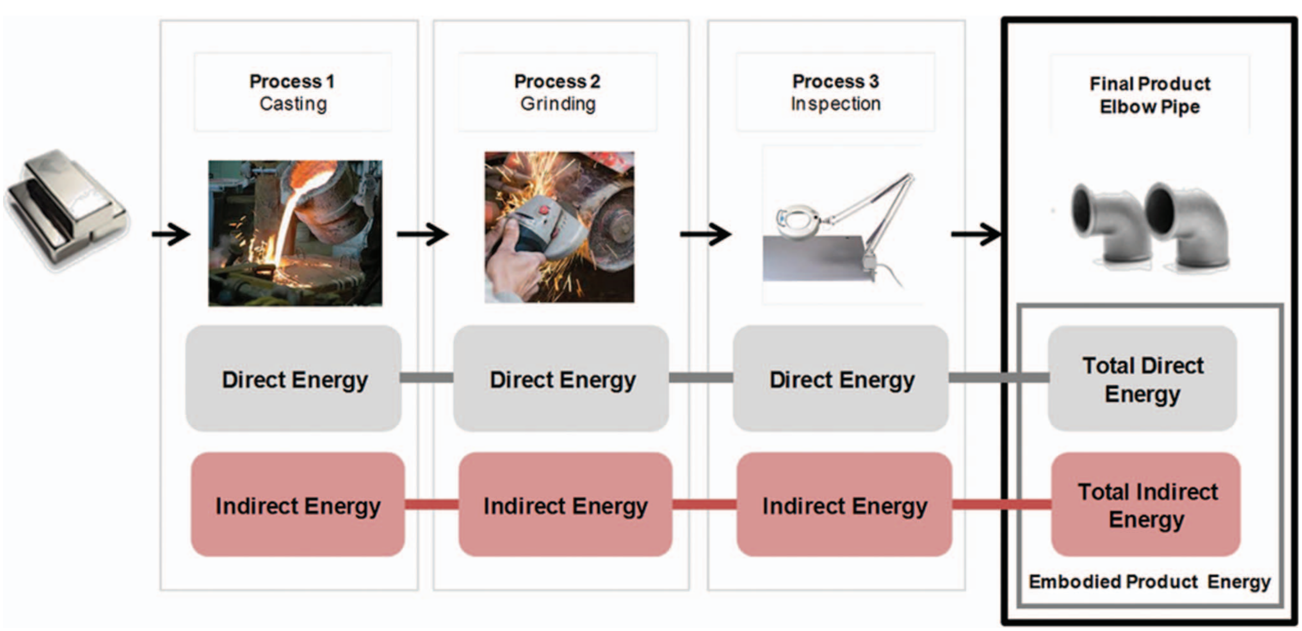

Figure 4. The processes used in the manufacture of an elbow pipe and energy.

limited. In Excel, complex charts and data formatting can be used to present the results in a clear and concise manner. The export of data to Excel provides greater flexibility for further data analysis due to Excel's versatility in data processing.

4.3.2. *Representation of DE and IE calculations within the model*

In applications where empirical data are unavailable, DE can be established through mathematical models which can also be represented within the ESM. The equations used to calculate the energy consumption of the product at each process are defined through the 'Variable' module in Arena. A 'Variable' is an element of information that reflects the characteristic of the system. In contrast to 'Attributes', 'Variables' are accessible by entities and can be changed by any entity. The data input for the 'Variable' can be specified using 'Attributes' and the equation is then built in a separate 'Assign' module in the form of an expression.

For example, to establish the TE of casting, the following data are required: mass of the product (m), the latent heat of fusion (L), the specific heat capacity (C), melting temperature (T_m) and the room temperature (T). The equation is summarised in Table 3 along with the equivalent used in the model. All these can be specified within the 'Assign' module as 'Attributes' with a specific value as shown in Figure 5.

The equations relating to the AE of the process are defined in a similar manner as those for TE. For example, in the a casting process, the AE is derived from the losses through heat generation, sand preparation, as well as the operation of the hydraulic system to lift and pour the molten metal. The values for each of these are first defined as 'Attributes' and then linked through an equation that is defined through a 'Variable' as shown in Equation (3) in Table 4. Typically, however, AE values are easier and preferable to establish through empirical measurements or through machine specifications.

The IE of a manufacturing zone can be defined as a function of the throughput. As such, the duration in which a product spends in a process can be used to determine the throughput and consequently the IE can be attributed to the part. Further details on how to calculate IE can be found in Seow (2011).

The cycle time of the process for the product can be defined as a constant singular value or as a mathematical/statistical expression as expressed in Equation (4). The cycle time, CT, is expressed as a normal distribution here.

$$CT = NORM(Mean, StdDev) \tag{4}$$

where 'NORM' indicates a Normal distribution, 'Mean' is the mean value of the cycle time for the process, and 'StdDev' is the standard deviation for the cycle time for the process.

Similar to the TE and the AE, the IE can be defined within the Arena model as show in Table 5.

4.4. *Output from the simulation model*

Once the relevant parameters have been assigned to the processes, they can be brought together to generate data. There are three main outputs incorporated in the ESM model as outlined below and described in the remaining sections of this paper:

(1) The real-time data related to process flow
(2) The EPE data
(3) The energy graphs

Table 3. Expression of the equation used to establish TE within Arena.

Process 1: casting	Variable definition: theoretical energy for process 1
Actual equation	$mL + mC(T_m - T)$ [Equation 1] Key: m = mass (kg) T = room temperature (K) C = specific heat capacity (kJ/(Kg.K)) L = latent heat of fusion (kJ/kg) T_m = melting temperature (K)
Equation defined in the model	casting_mass * latent heat of fusion + casting_mass * specific heat capacity * (melting temperature − casting room temperature) [Equation 2] Key: casting_mass = mass (kg) casting_room_temperature = room temperature (K) specific heat capacity = specific heat capacity (kJ/(Kg.K)) latent heat of fusion = latent heat of fusion (kJ/kg) melting temperature = Melting temperature (K)

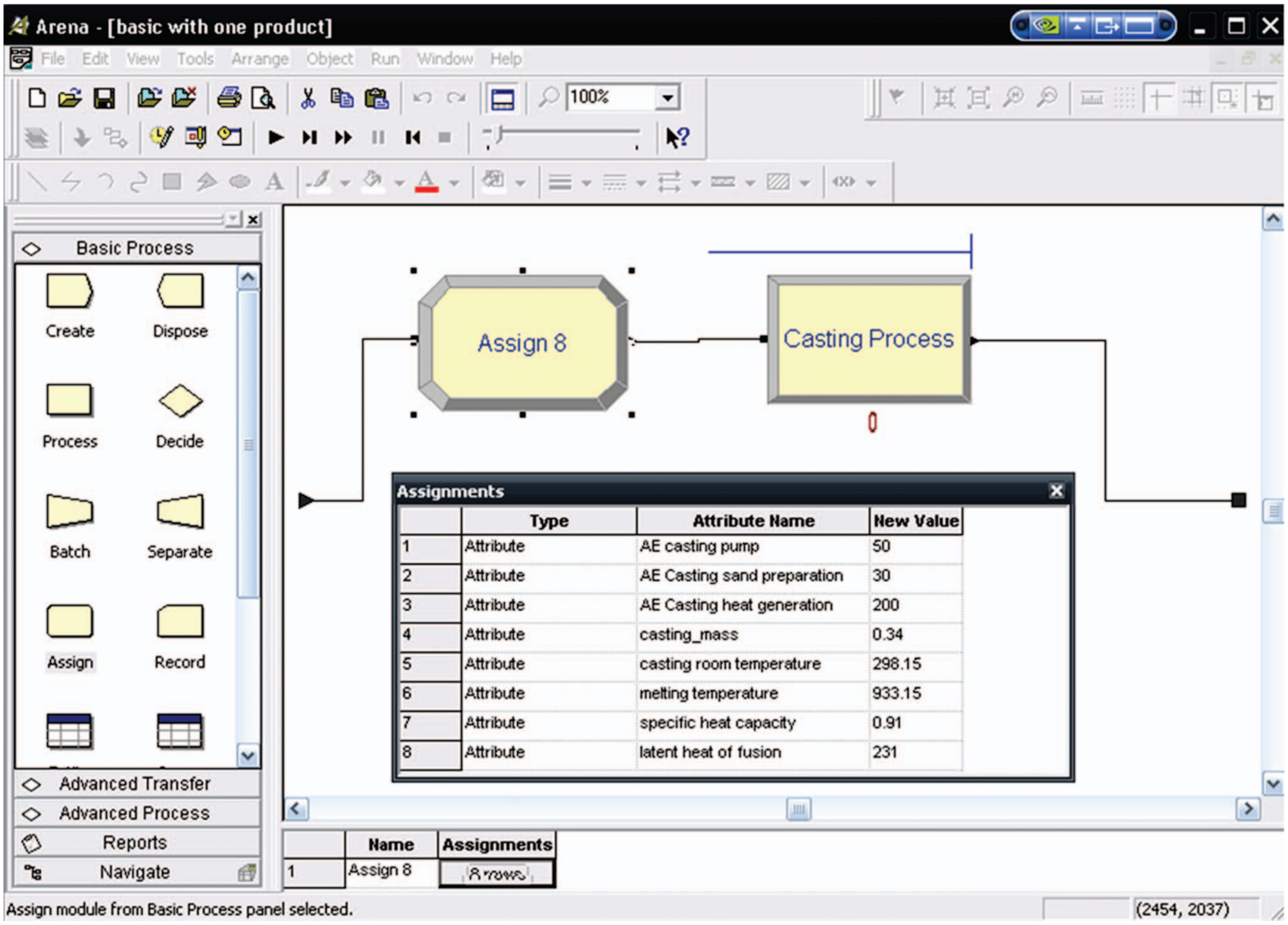

Figure 5. Data for the casting process are entered through the 'Assign' modules as attributes.

Table 4. Expression of the equation used to establish AE within Arena.

Process 1: casting	Variable definition: Auxiliary energy for process 1
Equation defined in the model	AE Casting heat generation + AE Casting pump + AE Casting sand preparation [Equation 3] Key: AE Casting heat generation = energy losses through heat generation (kJ) AE Casting pump = energy required for the pumping of hydraulic fluid (kJ) AE Casting sand preparation = energy required to prepare the sand for the mould for casting (kJ)

Table 5. The equation used in the framework and the equivalent expression used to represent the IE in the simulation model.

Process 1: casting	Indirect energy
Actual equation	$IE_{zone(m)A} = \frac{IE_{zone(m)}}{TP_{zone(m)A}}$ [Equation 5] Key: $IE_{zone(m)A}$ is the indirect energy attributed to Product *A* in zone *m* $IE_{zone(m)}$ is the indirect energy consumed by zone *m* per hour $TP_{zone(m)A}$ is the throughput of Product *A* per hour in zone *m*
Model equivalent	$IE_{zone(m)A} = IEzonem/(60/(CTzonemA))$ [Equation 6] Key: $IE_{zone(m)A}$ = indirect energy attributed to Product *A* in zone *m* IEzone*m* = Indirect energy consumed by zone *m* per hour CTzonemA = cycle time of product A through zone *m*

4.4.1. The real-time data related to process flow

In the simulation model, the process flow is represented through the flow diagrams which can be animated during the simulation run. The process flow for the elbow pipe with three processes, namely casting, grinding and inspection is shown in Figure 6. In order to maintain simplicity and clarity, a hierarchal modelling approach has been adopted. The three processes of casting, grinding and inspection have been modelled individually and each process has been further defined using a 'Sub-model'. The sub-model allows the main model to display high level information and allows for greater detail to be included in a separate modelling window. Figure 6 shows the three sub-models for casting, grinding and inspection processes. The use of the sub-models enables complex processes that require multiple activities to be decomposed into smaller blocks and also ensures that the correct information for that process is used. This also eliminates any confusion between the data requirement for different processes. The sub-models allow each process to be handled and managed individually and thus if there are changes to the operational parameters, it would be easier to locate and edit the data within the appropriate model or sub-model.

4.4.2. The EPE data

The second output is the energy data that can be calculated through the modelling engine. The energy values for TE, AE and IE which were previously defined as 'Variables' are stored and displayed within the modelling window. In addition to providing an overall EPE output, the data for each energy component have been broken down so that the TE, AE and IE values for each process can be represented. The respective energy ratios – $ER_{process(A)}$, $ER_{plant(A)}$ – are also shown as illustrated in Figure 7. The last elbow pipe to be manufactured used 1963.4 kJ of energy and the breakdown of the TE, AE and IE is clearly shown in the figure. Although the Arena screen only shows the values for the last entity that passed through the system, data for all the entities can be exported for an overview of the energy consumed by all entities. In addition, Excel allows for more in-depth analysis of the output data to be made.

4.4.3. The Energy Graphs

The data exported to Excel are presented in Figure 8 which shows the energy consumed by each elbow pipe manufactured. The breakdown of the energy consumed by the part or product can be plotted to show the TE, AE and IE showing any trends in energy consumption during the manufacture of the batch of products. The energy consumed by each of the processes for a batch of 31 elbow pipes is shown in Figure 9. A line plot indicates the EPE, TE, AE and IE for each pipe. The average energy consumed per product for a particular process, $ER_{process}$, is also indicated. In this case, process 1 (casting) required an average of 986.63 kJ, process 2 (grinding) required 639.09 kJ and process 3 (inspection) required 120.05 kJ. The breakdown of TE, AE and IE for each process is shown in a column chart on the right hand side of each plot.

Process 1 consumed the most energy but has the highest $ER_{process(1A)}$ ratio of 0.75, followed by process 2 at 0.41 and least energy consuming process with the lowest $ER_{process(3A)}$ ratio is process 3 at 0.23 as shown in Figure 9.

Overall, the TE accounted for majority of the total energy consumed (39%), followed by the IE (35%) and then the AE (27%). The total average EPE of the product is 1744.53 kJ as shown in Figure 10. The efficiency ratios of $ER_{product(A)}$ are 0.39, $ER_{process(A)}$ is 0.58 and $ER_{plant(A)}$ is 0.66.

4.5. Analysis of results

In the manufacture of the elbow pipe (product A), the casting process consumed the greatest amount of energy (986.63 kJ) followed by grinding (639.09 kJ) and the inspection process (120.05 kJ). The energy breakdown shows that a significant amount of IE has also been consumed in the casting process. Therefore, the building services associated with casting could be highlighted as the main priority for improvement and optimisation so as to reduce facility energy consumption. Despite the casting being the most energy intensive, only a small proportion of the total energy process energy is wasted through non-productive activities related to IE and AE. This is apparent by the high value for the $ER_{process1(A)}$ for casting (0.75).

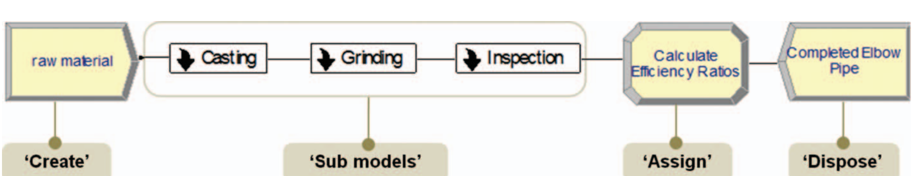

Figure 6. Process flow created for the Elbow pipe using the four main Arena modules.

However, in the case of grinding and inspection processes, despite being less energy intensive, more than half of the total process energy is due to the non-productive activities related to the AE and IE requirements. This is reflected in the low process ratios. For process 3, the low $ER_{process(3A)}$ (0.23) is due to the large proportion of energy required to power the conveyor system in comparison to a small amount of energy required to power the transmitters for the inspection process.

A look at the AE consumption indicates that a large proportion of AE is due to the grinding process. Potential energy improvements for the grinding processes include looking at operational set-up to minimise idle time, which is achieved through high speed loading and unloading of systems or reducing set up times of work pieces and/or preloading of cutting tools. Other improvements can include optimising the auxiliary processes like the coolant and lubricant pumps by installing variable motors or by applying an inverter motor and accumulator.

In general, the processes required in the manufacture of product A consumed more energy for the supporting auxiliary activities (i.e. AE) than for 'value added' processing (i.e. TE). The TE accounts for only a third of all the energy consumed by the processes. Furthermore, the comparison of TE and the EPE through the $ER_{product(A)}$ which is 0.39 for product A indicates that the product could theoretically be manufactured more efficiently. This highlights potential for energy improvements to the auxiliary processes and the provision of facilities services. For example, the operational procedures of production equipment (e.g. grinding machine or conveyor systems) could be further examined to reduce AE consumption from idle modes of operation or unnecessary supporting processes.

Overall, on a facility level, the production system is fairly efficient as reflected in the $ER_{plant(A)}$ ratio of 0.66. This is indicative that from the total energy consumed, about a third of the energy can be attributed to IR consumption by the facility. The

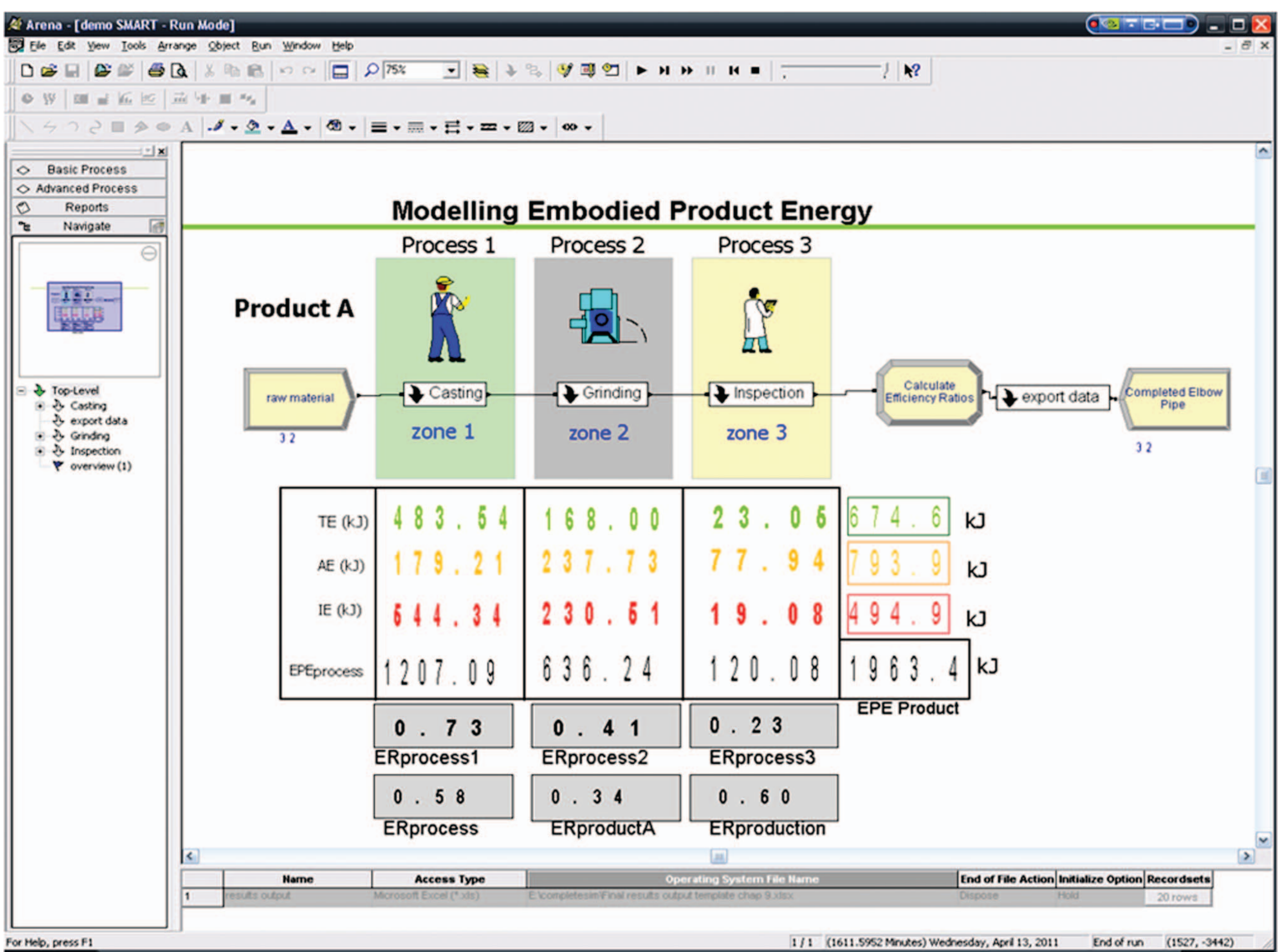

Figure 7. The output of the simulation model, the values for TE, AE and IE are displayed alongside the efficiency ratios.

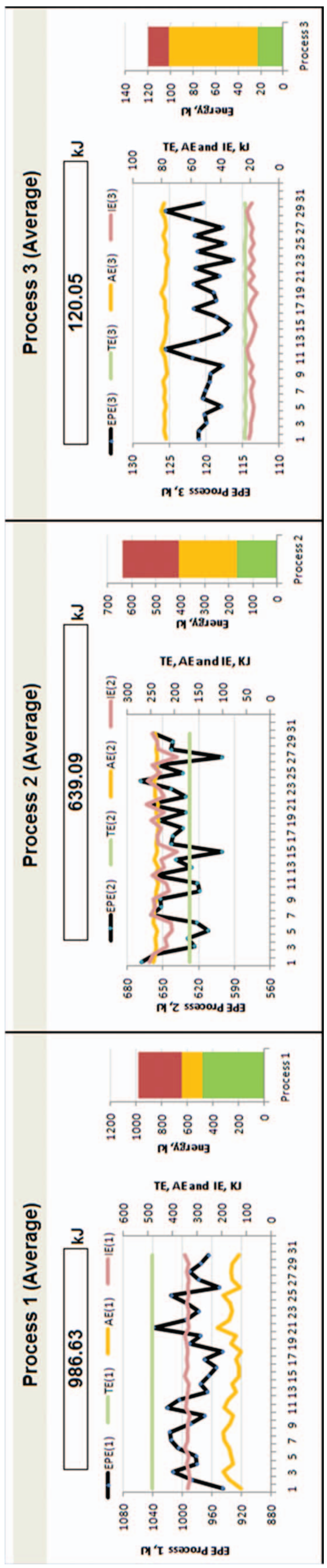

Figure 8. The process energy chart (left) showing plot of TE, AE and IE for each entity in process 1, 2 and 3. The line plot on the main axis indicates the EPE (black line). The line plots on the sub-axis indicated the TE (green line), the AE (yellow line) and IE (red line). Numerical value at the top indicates the average energy consumed. A breakdown of the average TE, AE and IE for the process is shown in the column chart on the right.

rather substantial proportion of IE indicates that further energy improvements can be made to the facility services in the casting process as it was the highest IE consumer. For example, heat recovery systems can be installed within the facility to minimise the energy load of the air conditioning systems within the casting facility.

The variation of EPE for each unit product manufactured stems from the IE and AE components and is due to varying production parameters or environmental conditions, and non-continuous manufacturing support system (e.g compressor units, chiller systems), respectively. Critically, these variations in EPE can be used to identify production planning and control issues. For example, there was in increase in EPE when the 21st unit was manufactured which could highlight long queue times, or equipment downtimes which led to a significant increase in energy used to produce that unit.

4.6. Users of the model

The model can be tailored for a range of users due to the flexibility of the system. However, it is believed that the main users of the model would primarily be designers and engineers. Designers who have an interest in understanding the energy consumption associated with the manufacture of a particular product can use the model to establish the overall energy data for a product. This provides them with an overview of the energy used to manufacture the product as a result of design decisions (e.g. the impact of designing a product to be made from injection moulded plastic instead of turned wood).

Engineers can also use the model to assess the energy consumed by a specific process route and can then compare it to alternative process routes to determine better energy efficiency. Production planners too can assess energy requirements of various production plans to minimise energy consumption through examining the energy use for each schedule. In all user cases, there may be barriers to the implementation of the ESM either from difficulties in accessing the appropriate energy consumption data or from a lack of expertise in DES. The first of these issues is tackled specifically by the description of the application of the ESM in Section 4.3, whereas the requirement, if necessary, to train internal staff or 'buy-in' expertise to implement the ESM would have to be evaluated on a case-by-case basis.

The simulation software is able to read a range of energy information, and the outputs can be tailored to provide a range of analyses for different users. The domain requirements for each type of user, and the possible analyses and outputs are summarised

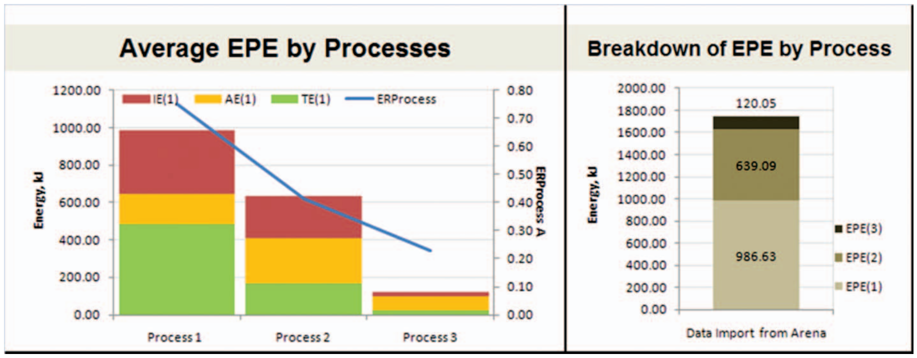

Figure 9. Plot (left) shows the average energy consumption of each process and the respective $ER_{process}$. A breakdown of the energy consumed by each process is shown in the column chart on the right.

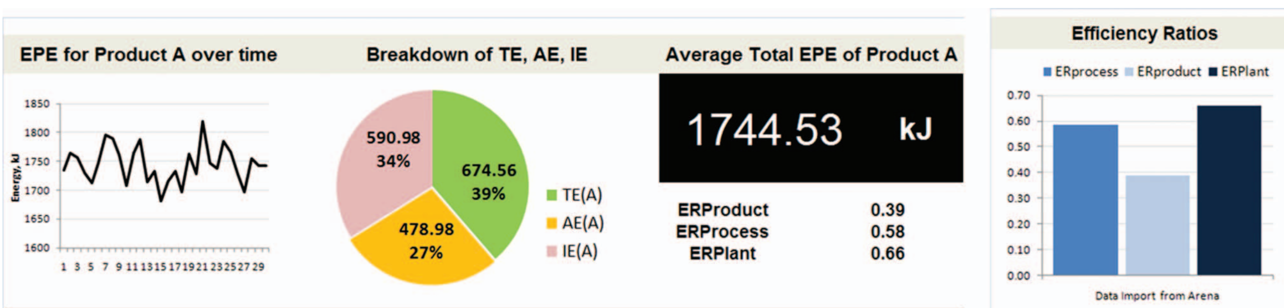

Figure 10. From left: Plot of EPE for each unit, Breakdown of TE, AE and IE for Product A, the Average EPE for Product A and the respective ER ratios, average EPE and ER ratio per process.

Table 6. Domain requirements and inputs for each user type along with the respective analysis and outputs.

User type	Data requirements and inputs	Analysis and outputs
Designer	Design features and the respective processes, material type.	Energy requirement for each design feature.
Engineer	Details of processes, material type, energy data related to the resources that carry out the processes, data from the manufacturing plant.	Energy requirement to manufacture the product using the set processes and the efficiency of the processes.
Operator	Energy consumption at different operational modes and configurations.	The impact of setup changes and processing parameter changes on the energy requirement of the resources.
Production Planner	Schedules of the jobs and the processing times for each batch of product.	Optimal schedule for maximum energy efficiency.
Energy Manager	Energy data for processing equipment and the facility.	Overall energy consumption of a facility and energy breakdown for an area or product.

in Table 6. The model developed is designed to evaluate the energy consumption required by the particular process chain based on the product features. In addition, it also tests the impact of varying production time (as a result of delays and queues) on EPE. Different batch sizes can also be varied to evaluate the impact of varying batch sizes on production time and therefore the EPE of the manufactured part.

5. Further development

The authors foresee two uses of this software: (i) the exploration of 'what-if' scenarios to see how changes in process and production operation can impact energy consumption and (ii) using the breakdown of energy flows and the modelling outputs as a supporting tool to improve product design.

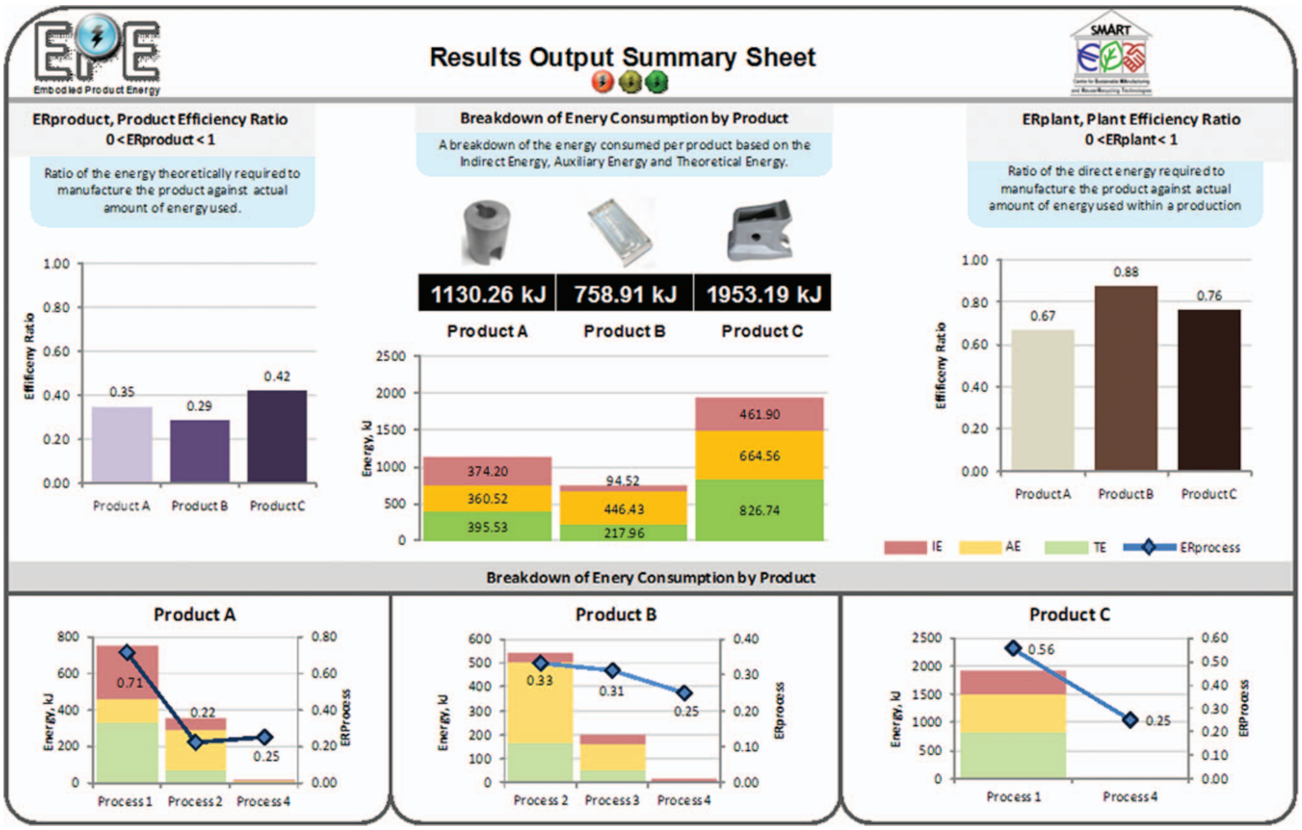

Figure 11. Use of ESM to compare different products.

As part of the exploration of 'what-if' scenarios, different products manufactured within the same facility can be evaluated. Figure 11 shows an example of the energy breakdown for three different products. Other 'what if' scenarios might include different batch sizes and/or production schedules and the impact on energy consumption. A greater understanding of the energy consumption relating to these scenarios can aid production planners and engineers in the day-to-day operation of the plant and provide insights for future production planning. In addition, the breakdown of energy consumption provided by the simulation can not only be used to support decisions for operational improvements but also upstream processes like design. A description of how the output can be used to improve design can be found in Seow and Rahimifard (2011b) although the authors intend to expand and exemplify this design for energy minimisation approach in a future publication.

Future standardisation in information entities would help to reduce cost and enable greater exchange of data (Lee *et al*. 2011). This would make simulation technology more accessible and thus enable energy modelling despite its data intensive nature. As such, the integration of the ESM with appropriate databases would potentially provide greater benefits. The ESM can also be further improved by linking detailed product and process data from the production system being analysed, thus improving the accuracy and relevance of the resulting embodied energy values. The combination of energy considerations with economic models to analyse the industrial processes from both these perspectives is still rare. Thus, it is intended to further develop the model to include economic savings from an energy reduction perspective by decoupling energy demand to peak loads, for example.

6. Conclusions

This paper has provided an overview of the commercial tools for assessing energy and has shown that there is a gap in the existing approaches for modelling energy flows. There is a lack of tools that can highlight the energy hotspots during a product life cycle and that can account for the complexities of production operations required to manufacture a product. Commercially available LCA software packages use generic energy data and are limited in dynamic modelling capabilities. As such, it is difficult to identify energy inefficiencies within current software packages in relation to the manufacture of a product and the improvements needed in operational parameters. DES software on the other hand does not support energy modelling as a default function. This highlights the need for an energy modelling tool such as the ESM proposed in this research to support the modelling and rationalisation of energy consumption during the manufacture of a product, enabling energy optimisation both within production activities and product design.

Through an example product, this paper has demonstrated the effectiveness of the ESM approach generated by this research to provide greater transparency of energy consumption during the production phase of a product. In addition, the flexibility offered by the ESM enables a wider range of results tailored to the specific needs of various potential users within a manufacturing facility (e.g. operators, production planners, shop floor maintenance and designers) to be generated.

This research has developed a holistic approach to the modelling of energy consumption during the manufacture of a product. This approach can help to ensure that products are designed and manufactured with minimal energy use. The decoupling of energy use and productivity, whilst maintaining the value of products and services is the key to long-term sustainability of businesses in the face of tighter legislation on energy consumption. The main domain for this research has been mainly on discrete part manufacture within sectors such as automotive, aeronautical, electrical, electronic, etc. However, within manufacturing industry, some of the most energy intensive applications are within the process industry (petrochemical, pharmaceutical, food, etc.) which highlights the need for specific research targeted at this industry. There is no doubt that maximising the energy productivity within all manufacturing sectors will play a critical role in the survival of businesses and the preservation of the environment for future generations.

References

Banks, J., *et al.*, 2000. *Discrete event system simulation*. 3rd ed. New Jersey: Prentice Hall.

BizEE, 2011. *Energy lens, energy management software* [online]. Available from: http://www.energylens.com/ [Accessed 24 March 2011].

British Standards Institution, 2009. *British standards EN 16001. Energy management systems – requirements with guidance for use*. London: BSI.

Duflou, J.R. and Dewulf, J., 2004. Eco-impact anticipation by parametric screening of machine system components. *In*: D. Talaba and T. Roche, eds. *Product engineering*. Netherlands: Springer, 17–30.

Ecoliban Group, 2011. *LCA software – team 4.0* [online]. Available from: https://www.ecobilan.com/uk_lcatool.php [Accessed 24 February 2011].

EnergyCAP Inc., 2011. *EnergyCAP enterprise account tracking* [online]. Available from: http://www.energycap.-com/products/energycap-enterprise-features/account-tracking1 [Accessed 24 March 2011].

EnerNOC, 2011. *Energy management platform* [online]. Available from: http://www.enernoc.com/solutions/ [Accessed 24 March 2011].

EPS Corp, 2011. *Energy management solution – xChange point* [online]. Available from: http://www.epsway.com/products-solutions/eps-xchange-point [Accessed 24 March 2011].

eSight Energy Group, 2011. *eSight M&T/EMS suite* [online]. Available from: http://www.esightenergy.com/default.aspx [Accessed 24 March 2011].

European Commission, 2008. *Consultation group on smart manufacturing, energy efficiency in manufacturing – the role of ICT*. Brussels: European Commission.

Hara, 2011. *Hara environmental and energy management* [online]. Available from: http://www.hara.com/solutions_overview.html/ [Accessed 24 March 2011].

Heilala, J., *et al.*, 2008. Simulation based sustainable manufacturing system design. *In*: S.J. Mason, *et al.*, eds. *Proceedings of 2008 winter simulation conference*, WSC, Miami, Florida, USA, 1922–1930.

Herrmann, C., Bogdanski, G., and Zein, A., 2010. Industrial smart metering – application of information technology systems to improve energy efficiency in manufacturing. *In*: W. Sihn, ed. *Proceedings of 43rd CIRP international conference on manufacturing systems*, 26–28 May, Vienna, Austria. Berlin: Springer, 134–142.

Herrmann, C., *et al.*, 2011. Energy oriented simulation of manufacturing systems – concept and application. *CIRP Annals – Manufacturing Technology*, 60 (1), 45–48.

Hirsch, J., 2009. *DOE2, building energy use and cost analysis software* [online]. Available from: http://www.doe2.com/ [Accessed 24 March 2011].

Ifu, 2011. *Umberto – know the flow* [online]. Hamburg Institute for Environmental Informatics GmbH. Available from: http://www.umberto.de/deen/home/ [Accessed 24 February 2011].

Itron, 2011. *T&D solution by Itron* [online]. Available from: https://www.itron.com/solutions/pages/end-to-end-solutions.aspx [Accessed 24 March 2011].

KONsys, 2011. *KONsys, energy management monitoring* [online]. Available from: http://www.konsys-international.com/default.php?cikk=247&Energy Management Software Developing&lang=en&site=konsys-international.com[Accessed 24 April 2011].

Law, A.M. and Kelton, W.D., 2000. *Simulation modelling and analysis*. New York: McGraw-Hill.

Lee, Y.-T.T., *et al.*, 2011. Core manufacturing simulation data – a manufacturing simulation integration standard: overview and case studies. *International Journal of Computer Integrated Manufacturing*, 24 (8), 689–709.

Müller, E. and Löffler, T., 2010. Energy efficiency at manufacturing plants – a planning approach. *In*: W. Sihn, ed. *Proceedings of 43rd CIRP international conference on manufacturing systems*, 26–28 May, Vienna, Austria. Berlin: Springer, 5–12.

NREL, 2011. *Energy analysis and tools* [online]. National Renewable Energy Laboratory. Available from: http://www.nrel.gov/buildings/energy_analysis.html [Accessed 24 April 2011].

Optima, 2011. *Optima energy management* [online]. Available from: http://www.optimaenergy.net/?cat=products&view=MandT.html [Accessed 24 April 2011].

Page, B. and Wohlgemuth, V., 2010. Advances in environmental informatics: integration of discrete event simulation methodology with ecological material flow analysis for modelling eco-efficient systems. *Procedia Environmental Sciences International Conference on Ecological Informatics and Ecosystem Conservation (ISEIS 2010)*, 2, 696–705.

PE International GmbH, 2007. *GaBi 4: software and data base for life cycle engineering*. Leinfelden-Echterdingen, Germany: PE International GmbH.

Pré Consultants, 2011. *SimaPro7: LCA software*. Amersfoort, The Netherlands: Pré Consultants.

Rahimifard, S., Seow, Y., and Childs, T., 2010. Minimising embodied product energy to support energy efficient manufacturing. *CIRP Annals – Manufacturing Technology*, 59 (1), 25–28.

Rittershaus, E., Weinhold, F., and Tonshoff, H.K., 1995. Process-related simulation applied to manufacturing optimization. *International Journal of Computer Integrated Manufacturing*, 8 (2), 79–91.

Rockwell Automation, 2011. *Arena simulation software* [online]. Available from: http://www.arenasimulation.com/ [Accessed March 2011].

Seow, Y., 2011. A framework for modelling embodied product energy to support energy efficient manufacturing. Thesis (PhD). Loughborough University.

Seow, Y. and Rahimifard, S., 2011a. A framework for modelling energy consumption within manufacturing systems. *CIRP Journal of Manufacturing Systems*, 4 (3), 258–264.

Seow, Y. and Rahimifard, S., 2011b. Improving product design based on energy considerations. *In*: J.R. Hesselbach and C. Herrmann, eds. *Glocalized solutions for sustainability in manufacturing*. Heidelberg, Berlin: Springer, 154–159.

Solding, P., Petku, D., and Mardan, N., 2009. Using simulation for more sustainable production systems – methodologies and case studies. *International Journal of Sustainable Engineering*, 2 (2), 111–122.

Taisch, M., Cammarino, B., and Cassina, J., 2011. Life cycle data management: first step towards a new product lifecycle management standard. *International Journal of Computer Integrated Manufacturing*, 24 (12), 1117–1135.

US DOE, 2011a. *Industrial technologies program – software tools* [online]. Available from: http://www1.eere.energy.gov/industry/bestpractices/software.html [Accessed 15 April 2011].

US DOE, 2011b. *Buildings technologies program – EnergyPlus energy simulation software* [online]. Available from: http://apps1.eere.energy.gov/buildings/energyplus/ [Accessed 15 April 2011].

Vijayaraghavan, A. and Dornfeld, D., 2010. Automated energy monitoring of machine tools. *CIRP Annals – Manufacturing Technology*, 59 (1), 21–24.

Wang, Y., *et al.*, 2012. Data analysis and evaluation system for resource and environmental attributes in the manufacturing process. *International Journal of Computer Integrated Manufacturing*, to appear. DOI:10.1080/0951192X.2012.685761

Wanyama, W., *et al.*, 2003. Life-cycle engineering: issues, tools and research. *International Journal of Computer Integrated Manufacturing*, 16 (4–5), 307–316.

Wohlgemuth, V., Page, B., and Kreutzer, W., 2006. Combining discrete event simulation and material flow analysis in a component-based approach to industrial environmental protection. *Environmental Modelling & Software Environmental Informatics*, 21 (11), 1607–1617.