



# A ‘Design for Energy Minimization’ approach to reduce energy consumption during the manufacturing phase



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## ABSTRACT

The combustion of fossil fuels for energy generation has contributed considerably to the effects of climate change. In order to reduce fossil fuel consumption, designers are increasingly seeking to reduce the energy consumption of products over their life cycle. To achieve a significant reduction in energy consumption, it is essential that energy considerations are incorporated within the design phase of a product, since the majority a product's environmental impact is determined during this phase. This work proposes a new ‘Design for Energy Minimization’ (DfEM) approach, which is intended to provide increased transparency with respect to the energy consumed during manufacture in order to help inform design decisions. An energy simulation model based on this approach is then presented to aid designers during the design phase. The application of this novel design tool is demonstrated in two cases: That of a simple product (designed by a single Original Equipment Manufacturer (OEM) through a centralized approach); and a complex product (designed by a number of designers within a supply chain using a distributed approach). The subsequent benefits to energy minimization are then discussed and conclusions drawn.

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## 1. Introduction

Increasingly, environmental concerns have focused on energy consumption as energy demand continues to grow, with the use of fossil fuels creating problems such as air pollution, acid rain and climate change [1]. Unfortunately, fossil fuels remain the main source for power generation in the foreseeable future [2] despite the inherent uncertainties in supply estimates [3]; thus the most effective method of CO<sub>2</sub> reduction is through the rationalization of energy consumption. This has led governments to introduce a number of energy auditing and accreditation standards, such as “Energy End-Use Efficiency and Energy Services” [4] and “European directives on the ‘Eco-Design of Energy-related Products’” [5].

It is commonly reported that over 90% of the life cycle costs of a

product are determined in the design stage [6]. Decisions taken in an early conceptual design phase can influence the outcome of a design exercise more significantly than any optimization step later on in the design process [7]. According to Otto and Wood [8], 80% of the environmental damage of a product is established after 20% of the design activity is completed.

Thiede et al. [9] have argued that environmental aspects are not sufficiently considered in simulations of manufacturing processes and a number of design methodologies concerned with the reducing environmental impact of a product have been investigated. The most commonly adopted is Design for Environment (DfE) which is concerned with the impact of design throughout the life cycle all the way from material preparation and manufacture to use and end-of-life management of a product. DfE considers a range of environmental impacts associated with various resources consumed within a product lifecycle, including material, water and energy.

Energy is consumed across all of the phases of a product life cycle with the level of energy consumed in each phase varying significantly depending on the product. For example, in the case of electrical products the greatest contributor to environmental impact is often due to the consumption of electricity during the

Abbreviations: DfEM, Design for Energy Minimization; ESM, Energy Simulation Model; DfE, Design for Environment; AEMS, Advanced Energy Metering Systems; LCA, Life Cycle Assessment; HOQ, House of Quality; S-LCA, Streamlined Life Cycle Assessment; TE, Theoretical Energy; AE, Auxiliary Energy; IE, Indirect Energy; CES, Cambridge Engineering Selector.

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'Use' phase, and this has been the focus of most design tools and guides. However in the majority of manufacturing applications, the production phase still represents a significant proportion of energy consumption during a product lifecycle [7].

In order to minimize the energy consumption during the manufacturing phase of a product, this work proposes a new design methodology which considers energy through a number of design stages; called Design for Energy Minimization (DfEM). This methodology breaks down the energy flows attributed to the production of a product. The design process can be optimized for energy minimization, in all design phases according to the simplified flowchart given in Fig. 1.

In this work, an overview of various 'Design for X' approaches is initially provided, together with an overview of the established design methodologies used in most applications. The latter part of this paper introduces and describes the DfEM methodology in detail as well as outlining its application within centralized and distributed design applications.

## 2. Overview of the existing design process

The design process involves a sequence of activities to enable a concept or an idea to develop into a detailed solution. The related activities are grouped together where certain decisions are made at the end of that stage, with the level of detail and finality of the design increasing with each subsequent stage. There are many different design models that can be applied depending on the nature of the product and the scope of the product development. A common design model, and the one adopted by this research, is by Pugh [10] which consists of three generic design stages: 1) Conceptual Design, 2) Detail Design and 3) Manufacture.

Once the product's design requirements have been established, the aim of the conceptual design stage is to generate ideas by searching for essential problems, combining working principles and selecting a suitable concept. The second stage is detail design which develops the concept chosen at the previous stage into a more concrete proposal with specifications of geometry, materials and tolerances of all parts of the product. Production costs and robust performance are the main concern at this stage. Finally the focus of the third stage, manufacture, is to minimize the component and assembly cost.

Computer modeling provides an increasingly important support tool, which can be used in these design stages to aid in decision making for a wide variety of design requirements in both products and processes. Examples include the combined use of heat flow simulations with experimentation to aid in the design of a laser beam deposition process [11] at the conceptual stage, a mathematical model for the design optimization of heat recovery steam generators [12] at the detail design stage and process modeling for continuous manufacturing [13].

## 3. Evolution of design methods

Traditionally, design methods were focused on form and function. With the industrial revolution and the start of mass production in the early-mid 20th Century, products began to be designed for producibility. The focus of design methods expanded to include quality [14], safety [15] and assembly [16]. The development of the Design for Assembly (DfA) methodology sparked a proliferation of various analytical techniques that guide designers towards integrating various issues into product design, marking the start of design methodologies that have ultimately been collected and codified under 'Design for X' [17]. One such method, namely 'Design for Manufacturing' (DfM) led to enormous benefits such as the simplification of products, reduction of assembly and manufacturing costs, improvement of quality, and reduction of time to market [18]. More recently, with the increasing concern about climate change and the environmental impact of products, a new design strategy, referred to as 'Design for the Environment' (DfE) has been developed to minimize environmental impacts [19], for example combined with life cycle analysis in the design of vehicle chassis components [20].

As design decisions greatly influence the overall environmental impact of a product environmental considerations should be integrated as early as possible in the design phase [7]. As part of the DfE approach, a range of environmental issues (e.g. resource consumption, end-of-life disposal, waste management, recyclability, reusability, use of toxic and hazardous material) associated with a product are to be considered at the design stage. As DfE covers a wide scope, specific tools such as Design for Disassembly, Design for Recycling, Design for Remanufacture and Design for End-of-Life that focus on a particular life cycle phase or environmental aspect have also been developed. However as far as this research could establish, there has yet to be an agreed approach for the systematic consideration of energy minimization across a product life cycle. Therefore this research proposes a novel DfEM approach that can be integrated through the different design stages, across the life cycle phases and that complements the other tools within the DfE family. The DfEM approach presented in this paper is detailed in the following sections.

## 4. Life cycle approach to DfEM and integration with the design process

To consider the energy minimization over a product's life cycle a wide range of sources of energy use including material, manufacturing, use and end-of-life, need to be investigated. For energy consuming products (e.g. electronic products, cars, lights) the 'use' phase might be the most important to consider, however for many other non-energy consuming products (such as furniture or packaging), the production phase may represent a significant

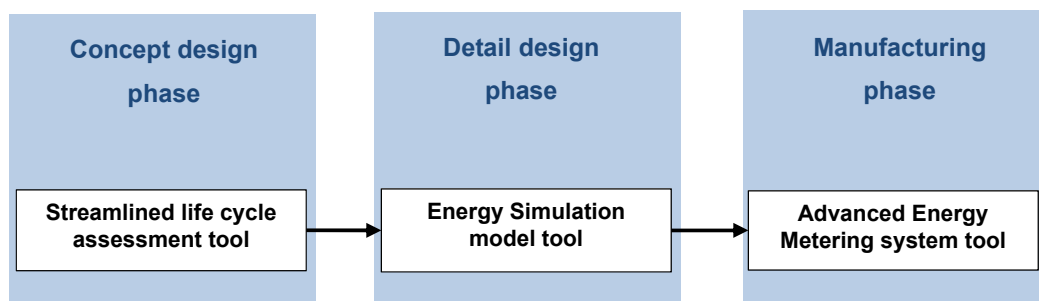


Fig. 1. Simplified DfEM flowchart giving the phases of design along with the relevant tool.

proportion of energy consumption over its life cycle [21]. In addition, the scope of the issues to be considered is also wide ranging. For example the type of material used, the processes used, the functionality of the product and how the product is transported all have energy implications. Thus unlike the other “Design for X” tools such as Design for Disassembly or Design for Recycling, DfEM needs to be considered at every phase of a product’s life cycle [22].

The importance of energy consideration during the design process has been recognized within the DfE approach, however as far as this research has been able to establish, there has been a limited number of systematic and comprehensive approaches that can be integrated within the whole design process for reducing energy consumption over the product life cycle. The few DfE tools that consider energy consumption are often qualitative and highly subjective, with the effectiveness of the tool often dependent on the experience of the designer [23]. In addition these tools have also gained little acceptance as they are not well integrated within the design process. Those that are quantitative are highly complex models and require information that is usually unavailable at the initial design stages as the product details and specifications have yet to be established and are therefore unknown. Devanathan et al. [24] and Zhang and Li [25] have tried to address these issues by correlating design parameters to energy factors at the early stages of design, however these methods have limited applicability for completely new product concepts and the mapping between functions and features of the product is still relatively complex.

A large body of work in the area of energy minimization exists in the fields of building and architectural design, where the need for energy decision making early in the design process is well understood, Karimpour et al. [26] highlighted the need for a whole life-cycle approach to building design, focusing not just on embodied energy but also such things as heating and cooling systems, appliances, hot water systems and renewable energy generation; all of which affect the total energy and therefore the greenhouse gas emissions. The multidisciplinary nature of this approach is highlighted by Lin and Gerber [27], who present a decision-making methodology along similar lines to DfEM but specialized for building design. A further design methodology for building energy optimization is presented by Evins [28]. This methodology relates initial capital costs to carbon emissions and presents a multi-level approach, covering the design of the building itself, plus the design variables that affect the energy supply system and those that affect operations, covering the whole lifecycle of the building under consideration. The design of buildings is not directly relevant to product design, since the variables for buildings are well known and can be predicted in advance, whereas those for product design are much more difficult to quantify. However, the existence of lifecycle energy minimization design methodologies for architectural design shows the utility of this approach if the variables for product design can be adequately accounted for, which is what the DfEM methodology is intended to achieve.

## 5. The DfEM methodology

It is necessary for the DfEM methodology to encompass the entire product life cycle so that energy minimization is considered at every phase of the life cycle; supporting a cradle-to-grave approach. This work uses the previously described three-stage design approach to incorporate energy considerations at each stage of the design phase of a product. This novel approach allows a deeper and more comprehensive consideration of energy implications in design, beyond that available in existing Design for X methodologies. In practice, the combination of this three stage design process and a life cycle design approach necessitates the ability to provide support for design decisions at various levels of

complexity. For example, in the conceptual design there may be a requirement for only a quick and simple assessment to highlight the impact of selecting alternative materials and processes. Whereas in detail design, there will be a need for much more comprehensive support in the form of predicting the energy requirements for various process chains/groups. Similarly, in the manufacturing stage there is a need for a greater level of information based on energy data collection, monitoring, auditing and assessment. A set of appropriate tools to support these varying requirements is described in this section.

### 5.1. Tools to support DfEM in manufacturing

Although the ultimate scope of DfEM covers the entire product lifecycle, this study has been limited to the production phase of a product life cycle. Therefore only the tools that provide the assessment of energy consumption within this phase are considered.

In this context, to support the different requirements within the design process, there are three main categories of tools that have been proposed within this research, these are 1) Streamlined Life Cycle Assessments (S-LCA) in the Concept Design phase, 2) Energy Simulation Models (ESM) during the detail design phase and 3) Advance Energy Metering Systems (AEMS) in the manufacturing phase.

### 5.2. Streamlined Life Cycle Assessment

Typically a LCA is used to evaluate the environmental impact of a product which includes the energy consumption during production. However for a product that does not yet exist, it is unrealistic for a designer to have access to all the specific information about the materials and processes required for a comprehensive LCA at the early stages of product design. The analysis of different categories of environmental impact in relation to life cycle phases can help designers formulate the best opportunities for implementing these aspects into product planning [29].

In order to minimize the complexity and time taken to conduct a full LCA, streamlined models and additional assumptions have been used to reduce the evaluation effort in traditional LCA. These condensed LCA are known as streamlined LCA (S-LCA) which encompasses a group of approaches designed to simplify and reduce the time, cost and effort involved in conducting a full LCA while still facilitating accurate and effective decisions. Duflou et al. [30] have developed an Eco-PaS tool which can be applied in the early stage of the design process by estimating the environmental impact of a product based on functional requirements rather than technical parameters (which are often unavailable at the early design stage) needed by typical LCA applications.

Additionally, Granta Design [31] has developed a streamlined LCA tool called the Eco Audit tool (part of the Cambridge Engineering Selector (CES) suite of software) which uses information about product composition, processing, usage, transportation, and disposal. The tool then combines this with eco-property data on the materials and processes used in the design to calculate the energy usage and CO<sub>2</sub> output resulting from each stage in the product life cycle as shown in Fig. 2. This high level overview is particularly useful during the first stage of product design (i.e. concept design) which can guide the design strategy by identifying materials and processes that fulfill the functional requirements at a minimal energy cost for the product. Birch et al. [32] found the CES materials and processes database to be an excellent base for greater automation to aid the designer by suggesting alternative materials and processes at the design stage. According to Giudice et al. [33], the integration of environmental aspects upstream of the design

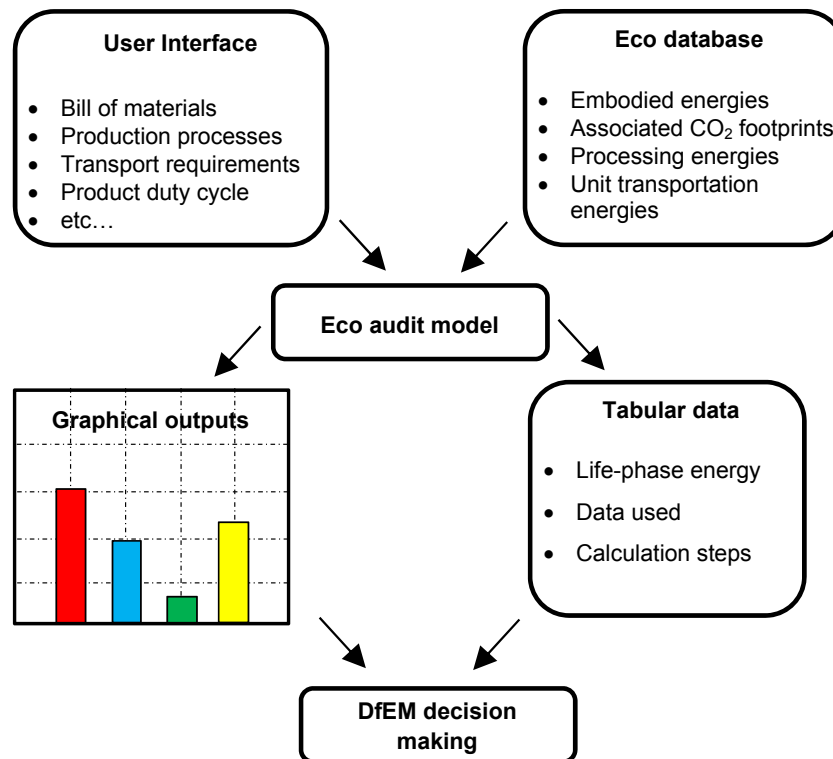


Fig. 2. Streamlined Life Cycle Assessment can be conducted through the use of software such as CES EcoAudit. Figure adapted from Granta Design (2010).

process will provide the versatility necessary for intervention and improvement of products during their development.

### 5.3. Energy simulation model

For the detail design phase of the design process, a greater level of detail is available in terms of the design specifications such as part features, dimensions and finishing. This information provides an indication of the manufacturing parameters that are required to achieve the design specifications. At this stage, the energy consumed during the production phase can be estimated with greater accuracy. It is therefore proposed that an Energy Simulation Model (ESM) can be used to evaluate the embodied energy of the products by modeling energy flows within the production phase of a product life cycle. The objective of this work is not to advance the capabilities of existing energy simulation techniques, but to provide an appropriate algorithm to explore design optimizations based on energy implications. In this respect, the ESM can be used to consider a number of ‘what if’ scenarios for the embodied energy within a product. The ESM aids the decision making in process parameter selection, machine selection as well as facility services selection. The ESM would also bridge the gap between high level streamlined LCA tools used at conceptual design and those used to monitor energy consumption as part of the manufacturing stage. There are three main aspects to the ESM - the energy database, the simulation engine and a House of Quality (HOQ) based design support tool as shown in Fig. 3.

The energy database contains the characterization of a range of processes. Detailed energy data for the processes can be obtained from empirical measurements within an existing production system, existing databases for particular processes or from theoretical calculations.

The simulation approach reduces modeling efforts through pre-existing process modules that can be applied to reflect the process

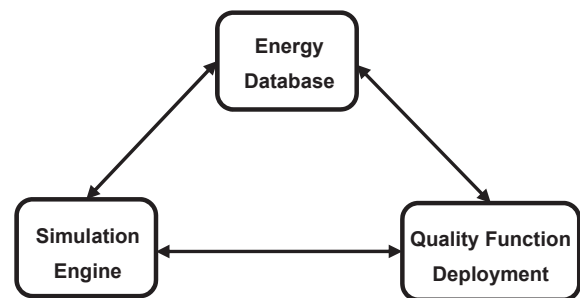


Fig. 3. The three interlinking aspects of the Energy Simulation Model.

chains required to manufacture the product for energy evaluations. The simulation engine is also highly flexible in the level of detail as well as the range of energy considerations to be modeled. Energy parameters can be adjusted depending on needs and the systematic variation of these parameters can also support optimization analysis and ‘what-if’ scenario planning.

The outputs of the simulation highlight energy hotspots that could provide the focus for energy improvements which can then be evaluated against design parameters using a HOQ based design support tool for improved product design.

### 5.4. Advanced energy metering system

The last stage of the design process is supported by Advanced Energy Metering Systems (AEMS) as shown in Fig. 4. At this stage, the energy consumption within the manufacturing plant is the primary focus of the DfEM strategy. AEMS are networks of relevant metering, sensing and information devices used to collate the relevant data and information to support decision making [34]. In the manufacturing context, AEMS can be highly complex and are



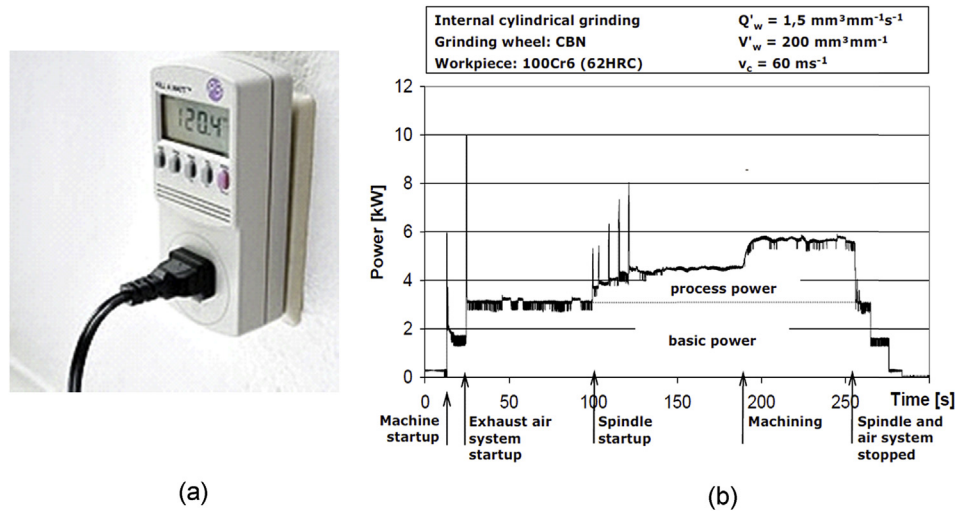


Fig. 4. Advanced Energy Metering systems to track energy use of processes and equipment in a manufacturing facility (adapted from Herrmann et al., 2008) (a) photograph of metering system (b) example plot of system output.

developed based on specific requirements. The use of AEMS for the purpose of product design can prove a powerful tool for understanding where energy input originates in the manufacturing stages. AEMS therefore need to be heavily reliant on energy management systems. In order to gain an accurate picture of the energy consumption in manufacturing, energy management systems are used to track and measure the energy used in a production facility, providing a breakdown of energy consumption by various elements in a production system including both the buildings and production operations. An example of energy management software is Optima developed by Optima Energy Management [35]. It can track and monitor real time energy consumption, buys energy at best available prices and allows budgets and targets to be set for cost savings. Energy management systems depend on AEMS to provide energy data from various aspects of the manufacturing plant as well as data from external sources affecting energy use such as weather and building occupancy. AEMS provides support at the manufacturing stage through the monitoring and tracking of energy consumption at set time intervals, including real-time [36]. Atypical consumption rates could indicate an incident or anomaly on the manufacturing line and could serve as an early warning system for production issues. The energy savings made through process and operational improvements as a result of changes to product design could be quantified through AEMS.

##### 5.5. Integration of tools within the DfEM methodology

Each phase of the design process has its own requirements and focus thereby requiring a different set of tools [37]. For example, creative based tools such as brainstorming and the morphological box are commonly used during the concept design phase whilst more analytical tools such as Failure Mode and Effects Analysis (FMEA) and Value Analysis are often applied to evaluate and establish the feasibility and robustness of the ideas as well as to determine the most appropriate method of realizing the product concept. Although these tools can be used independently within each phase of the design process, clearly greater benefits could be achieved through integration of these tools, as the data/knowledge generated by each can support the decisions made in other phases. This is especially true for the DfEM methodology. According to Giudice et al. [33] the environmental objective to be achieved in product design can be summed up in two principal categories:

- Conservation of resources, recycling, energy recovery
- Prevention of pollution, waste and other impacts

These objectives can be achieved through an appropriate combination of design strategies some of which include: improvement of materials and energy efficiency; optimization of functionality, avoidance of hazardous materials and energy efficiency, and, design for cleaner production and use. The accuracy of the ESM is enabled by the precise values for energy consumption of the production facility, generated by the AEMS. This in turn can improve material and process selection within CES by providing energy data sets relating to materials and processing that are customized according to the manufacturing plant, thereby increasing its accuracy. The proposed methodology not only supports the long term improvement of new designs using accurate and relevant energy information but also enables critical analysis of existing designs. In addition, the ESM is also able to provide production improvements to increase the energy efficiencies and optimization within production. These improvements can be factored in during the concept design phase so that design decisions are a result of optimized functionality as well as minimized energy embodiment. Through the integration of the suite of tools for DfEM, other design strategies can be established in combination so as to meet the environmental objectives. An overview of the DfEM tools is shown in Fig. 5.

## 6. Using the energy simulation model (ESM) as part of DfEM

As shown in Section 5.3 the Energy Simulation Model consists of an energy database, a simulation engine and a decision support tool. The ESM is primarily based on the energy modeling framework described in Rahimifard et al. [38]. The simulation engine is supported by an energy database that provides a back end system comprising of material, process and production energy related data. Together with the product and engineering specifications, the simulation engine is able to establish the energy consumed during the production phase of the product. The outputs of the simulation will indicate the energy 'hotspots' which can then be used to provide focus for energy improvements within manufacturing. To ensure that these improvements do not impede the design and quality of the product, they can be assessed through the decision support matrix which evaluates the energy optimization solutions against the design specification of the product. Details of the

	Concept Design (CD)	Detail Design (DD)	Manufacture (M)
Available tools	<ul style="list-style-type: none"> <li>Brainstorming</li> <li>Morphological box</li> <li>TRIZ</li> <li>Axiomatic Design</li> <li>Systematic Design</li> <li>Simplified LCA</li> </ul>	<ul style="list-style-type: none"> <li>QFD</li> <li>FMEA</li> <li>Value Analysis</li> <li>DfA/DfM</li> <li>DfX</li> <li>DfEM</li> </ul>	<ul style="list-style-type: none"> <li>Computer Aided Manufacture</li> <li>Computer Aided Process Planning</li> <li>Just in Time Manufacturing</li> <li>Lean Manufacturing</li> <li>Energy Management Systems</li> </ul>
DfEM	<b>Simplified Lifecycle Assessment</b> <ul style="list-style-type: none"> <li>Material selection</li> <li>Process Selection</li> </ul>	<b>Energy Simulation Model</b> <ul style="list-style-type: none"> <li>Process Parameter Selection</li> <li>Machine Selection</li> <li>Facility services selection</li> </ul>	<b>Advanced Energy Metering system</b> <ul style="list-style-type: none"> <li>Energy monitoring of Processes</li> <li>Energy demand management</li> </ul>

Fig. 5. Application of various tools in a product design process to aid energy minimization.

database, the simulation engine and the decision matrix are further described in the following sections.

### 6.1. Energy database

The energy database is the knowledge base element of ESM. Initial data can be determined either theoretically or empirically and statistical relationships can be established to train the simulation engine to predict the amount of energy consumed by the processes and activities for different production parameters such as batching, queue times, process routing and process set ups.

As the energy model becomes more robust, the data output from the predictive models can in turn be added into the energy database to build up a comprehensive understanding of the energy requirements of processes and manufacturing systems. It should be noted that the data related to energy consumption within logistics and reverse logistics activities can also be included. The energy database also provides the simulation engine with the primary energy information such as energy values associated with the manufacturing processes and auxiliary activities. Internationally, there are a number of efforts to develop a comprehensive database for various manufacturing processes some of which are the Unit Process Life Cycle Inventory, UPLCI [39] by Wichita State University and the Cooperative Effort on Process Emissions in Manufacturing, CO<sub>2</sub>PE [40] by the University of Leuven.

### 6.2. Simulation engine

A general purpose, discrete event simulation engine called Arena developed by Rockwell software was used to calculate and synthesize the energy use and energy efficiency scores for the product by using the data from the energy database described earlier, together with product and engineering specifications that would be available at the detail design phase. The energy breakdown and efficiency ratios generated by the simulation engine allow designers or engineers to target the most energy intensive processes for energy minimization. This can provide a focused area for energy optimization which is essential when the parameters that contribute to overall energy consumption are numerous. The outputs from the simulation engine can be used to populate a list of manufacturing parameters which will be considered for energy optimization by the decision support tool which forms the next stage of the DfEM process. Fig. 6 shows a screen print of the ESM simulation used in this research. It should be noted that the ESM is transferable to other commercially available simulation engines and not reliant on the use of Arena.

### 6.3. House of quality based design support tool

The decision support tool is the final aspect of the ESM. Using the energy breakdown and efficiency assessments obtained from the simulation engine, a range of energy improvement measures can be established. There are several key factors to consider when designing for energy minimization. For example, as the reduction of material usage in the design through thinner walls may mean less energy is required during the processing of the material, or, having design features that can be manufactured in the same production set up to eliminate the additional energy consumption for a new set up and energy consumed between set ups.

These factors need to be taken into account with other design specifications and hence should be evaluated together. The House of Quality (HOQ) matrix thus provides a tool for correlating the design specification against the manufacturing requirements to help the designer or the engineer arrive at an ideal solution. HOQ has also been successfully used by a number of researchers to evaluate environmental performance [41,42].

It is essential that improvements to the production processes can optimize energy use without compromising the original design specification. As such there is a need for a decision support tool that can evaluate the changes to the processes and production against the required design parameters for product functionality etc. The HOQ based design support tool that has been developed as part of the ESM and is illustrated in Fig. 7. The HOQ has been divided into 5 main areas as annotated in the diagram.

A typical HOQ matrix correlates between different needs (e.g. engineering, manufacturing, design). In this tool, a range of design attributes and production related energy improvements are assessed against each other (as shown in Fig. 7, Area 1). The design attributes can be derived from a product design specification and would include considerations such as aesthetics, ergonomics, costs, functionality and safety.

The production related improvements follow the embodied product energy framework and is divided into 3 different categories of Theoretical Energy (TE), Auxiliary Energy (AE) and Indirect Energy (IE). The energy improvements for the TE are typically related to the type of manufacturing process used, for the AE, to the production equipment used and for the IE, to the processes used to maintain the facility environment. Details of the embodied product energy framework can be found in Rahimifard et al. [38]. An example of energy improvement under IE would be the use of efficient lighting systems. The improvements can vary depending on the production facility.

Depending on the output of the simulation model priority may be given to one category over the other (as shown in Area 2) and

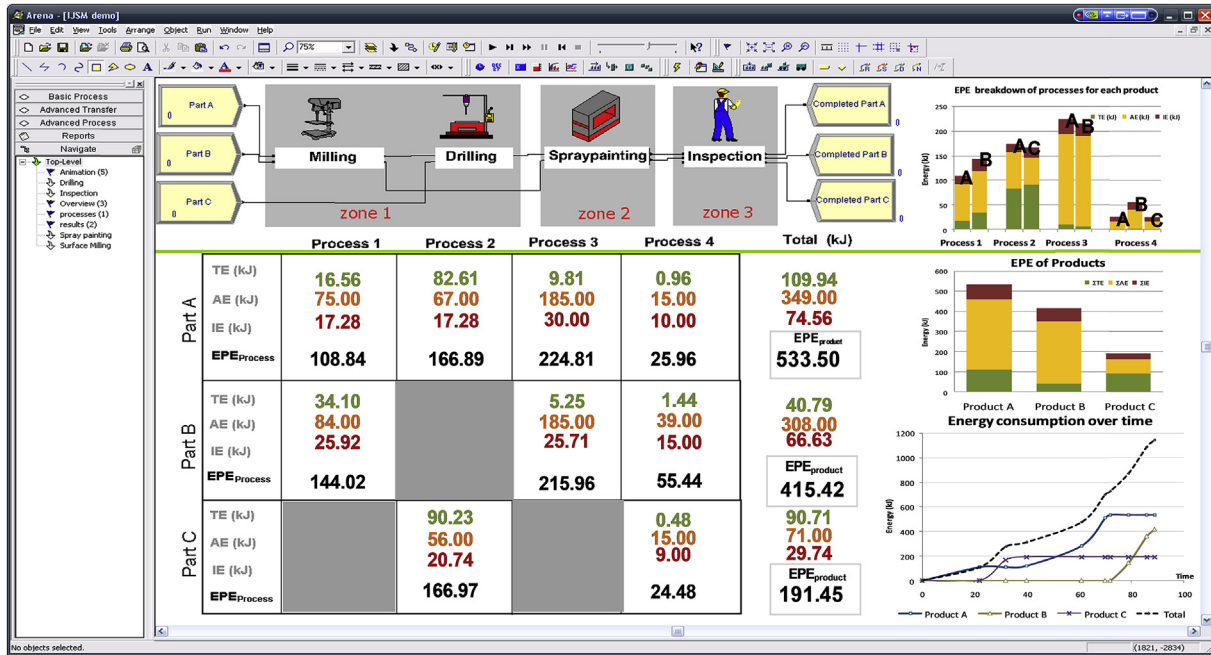


Fig. 6. Screenshot of the model in Arena showing the average EPE for a batch of products.

through a correlation matrix (as shown in Area 3), changes to the manufacturing parameters can be evaluated against the functional requirements of the product to derive the design that has minimal energy consumption during production phases of a product life cycle but also meets the design specifications. For example if the output of the simulation indicates that the TE has the greatest contribution to the energy used, and energy can be optimized through the reduction of cutting speeds. The impact of lower cutting speeds is then considered alongside design attributes such as aesthetics. In this case it might be unfavorable as lower cutting speeds might result in a surface finish that is unacceptable for the customer.

The manufacturing parameters can also be correlated to establish if they are mutually supporting or contradictory (shown as Area 4). For example, reducing feature dimensions might reduce cycle time and thus would be a beneficial energy improvement to both on the TE and the IE.

The key design factors have been listed in Area 5 which shows the impact of certain design considerations on energy consumption during manufacture.

## 7. Practical applications of DfEM

The adoption of the proposed DfEM methodology and simulation tool within a design process will depend on the product complexity and the number of designers that are involved within the product development. In this section, two main types of design strategies are demonstrated to show how DfEM can be applied within various industrial applications. The first is based on the design of a simple product, where the majority of the design decisions are controlled and made centrally within a company. The second is based on a complex product with a large number of components and subassemblies where the design decisions are often distributed across several tiers of suppliers.

In the case of a simple product design, all of these phases are typically managed by a single design team, whereas in the case of a complex product, more than one design team is involved in the

design process. In such cases a distributed design model, typically referred to as 'V' model, is adopted. The same basic model can be adopted in a number of design paradigms, such as IT architecture system design [43], software development [44] and manufacturing.

A good manufacturing example of complex designs that are loosely based on the 'V' model can be found within the Ford Motor company [45], where vehicles consist of a large number of assemblies and sub-assemblies; many of which are manufactured by their suppliers and must all properly function together. According to Otto and Wood [8], in the Ford product development approach, the specifications for the new vehicles are defined by the manufacturer, after which the product attributes are cascaded down to individual suppliers. In turn, these suppliers may use one of their component suppliers to manufacture the required subassemblies, resulting in the involvement of many designers at the system, subsystems, and eventually the component levels. Fig. 8 shows the difference in the product development between a simple product and a complex product.

### 7.1. Application of DfEM in a simple product

For a simple product like a plastic chair, various energy considerations and goals can be defined for the product at the start of the development phase while creating a Product Design Specification (PDS). In this case, CES can be used to assess the energy requirements for extraction, preparation and processing of various plastics to further narrow down the list of materials that meet the functional requirements for this product.

For example, the CES evaluation shows that Acrylonitrile-Butadiene-Styrene (ABS) and reinforced Polypropylene (PP) can both fulfill the product specification of the office chair; but PP is the least energy intensive to extract and prepare. After selection of the material, DfEM is used to evaluate the various production processes that can be used to manufacture the chair and provide an indication of the least energy intensive processes. In this case due to specific product geometry, the feasible processes that can be adopted are high impact injection molding and gas assisted injection molding.

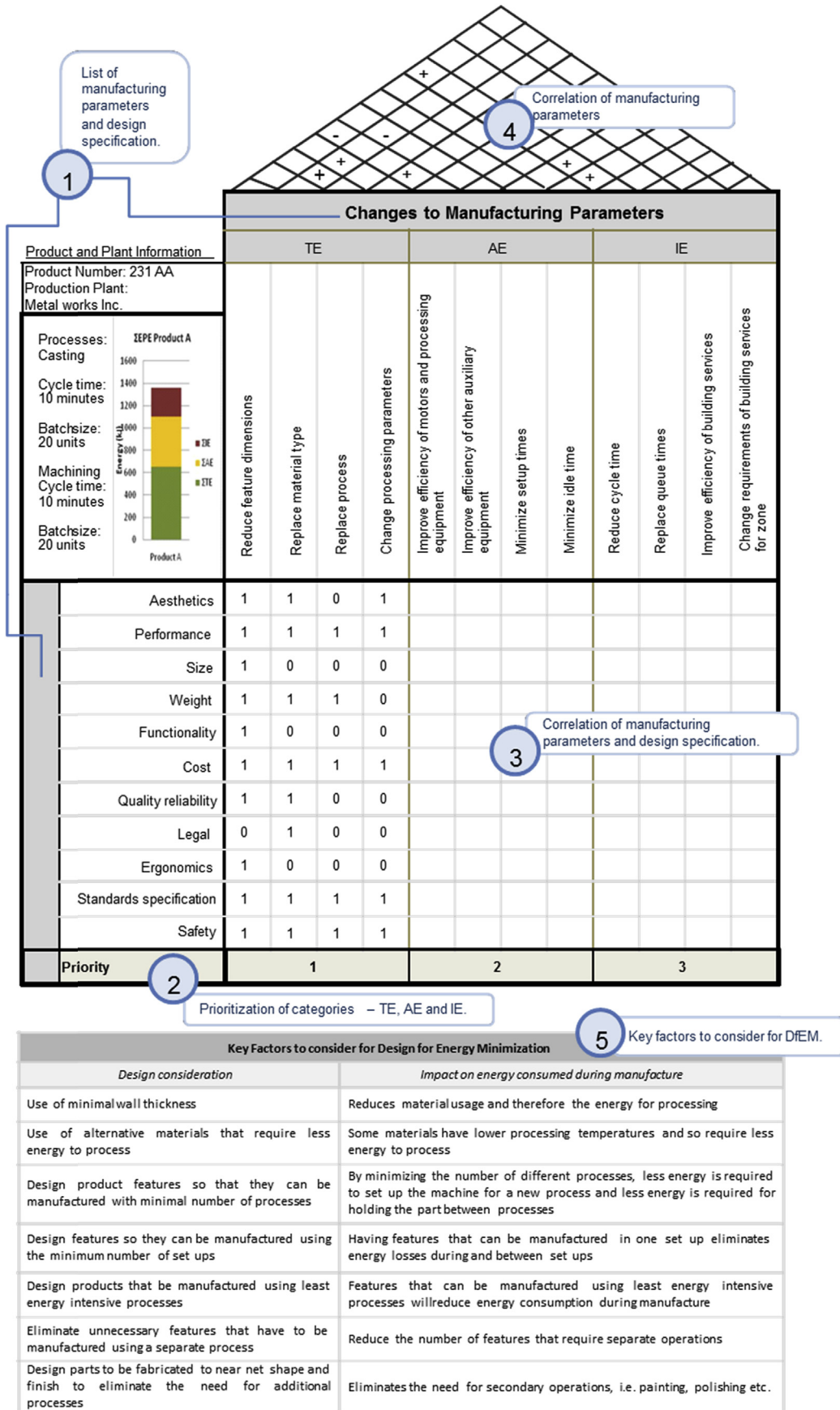


Fig. 7. HOQ based design support tool for energy minimization showing manufacturing parameters against common design specifications.



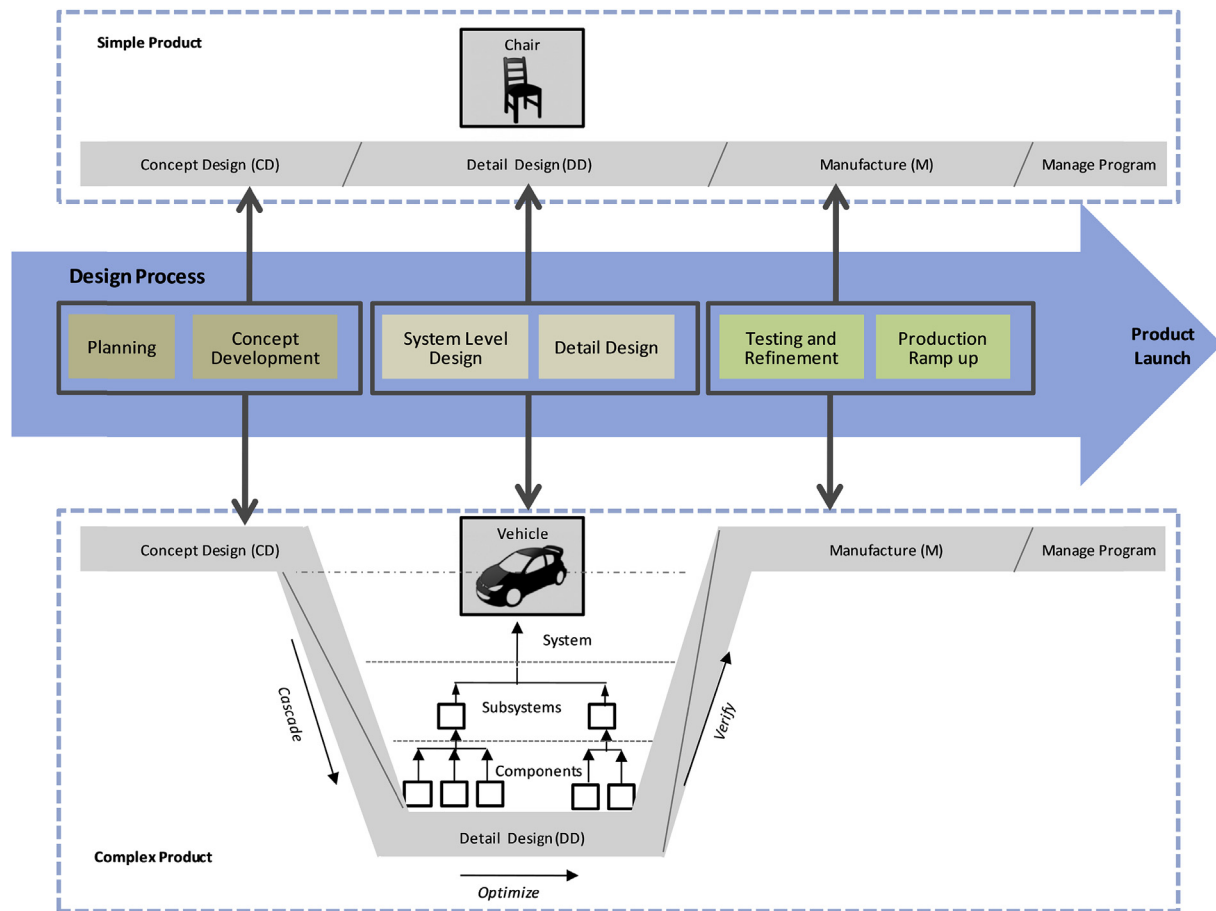


Fig. 8. Characterization of the product development process for simple and complex manufactured products (Adapted from Otto & Wood 2001).

The evaluation of these two processes indicates that the gas assisted injection molding will potentially consume more energy due to requirements for compressed air.

Finally, during the actual production of the chair advanced energy metering and management systems can be used to monitor the real time energy consumption of injection molding, process cooling, drying ovens, heating, ventilation and lighting systems. This information feeds back into the design of the next iteration of the product or the design of new products intended to use the same manufacturing space.

## 7.2. Application on DfEM in a complex product

The application of DfEM in large complex products requires more detailed consideration, as often a range of designers are involved in the design process. There are two scenarios in which DfEM can be applied in the creation of a complex product.

### 7.2.1. Scenario 1

In the first scenario, the DfEM methodology is applied independently by the design teams in each level i.e. Design Levels 2 and 3, as illustrated in Fig. 9a, to specify the design features with the goal of minimizing energy requirements over the components life cycle for the parts they were contracted to design. The components on the tertiary supply tier are then integrated with the subassembly through a secondary level design team, who then implement the DfEM methodology on that subassembly.

The energy specifications of each individual component or

module can be centrally managed through a database so that information from the respective tier can be gathered and amalgamated for the level above. The information can also be added to the Ecodesign Knowledge System [46], providing a centralized system for environmental and design knowledge and a platform for sharing knowledge that can be transferred to other design projects [7].

The overall energy information of the product can be computed through the energy specifications of each individual part and component. This system is particularly useful in light of the EuP directive and the new ISO 50001 standards [47] where manufacturers are encouraged to state the amount of the energy used in the manufacture of a product. The database can then serve as a knowledge base for OEMs, contractors and subcontractors to share knowledge which can help their DfEM process as well as benchmark against other competitors.

This bottom up approach would provide manufacturers with the opportunity to improve the energy performance of their manufacturing facilities based on their capabilities and capacity. However for small contractors with limited resources, implementing an in-house DfEM process might not be possible.

### 7.2.2. Scenario 2

In the second scenario, the team responsible for Design Level 1 applies the design for energy minimization to the whole product system and disseminates the design criteria and specifications to the other design teams as shown in Fig. 9b. DfEM is employed throughout the “design chain” activities, and the coordination of

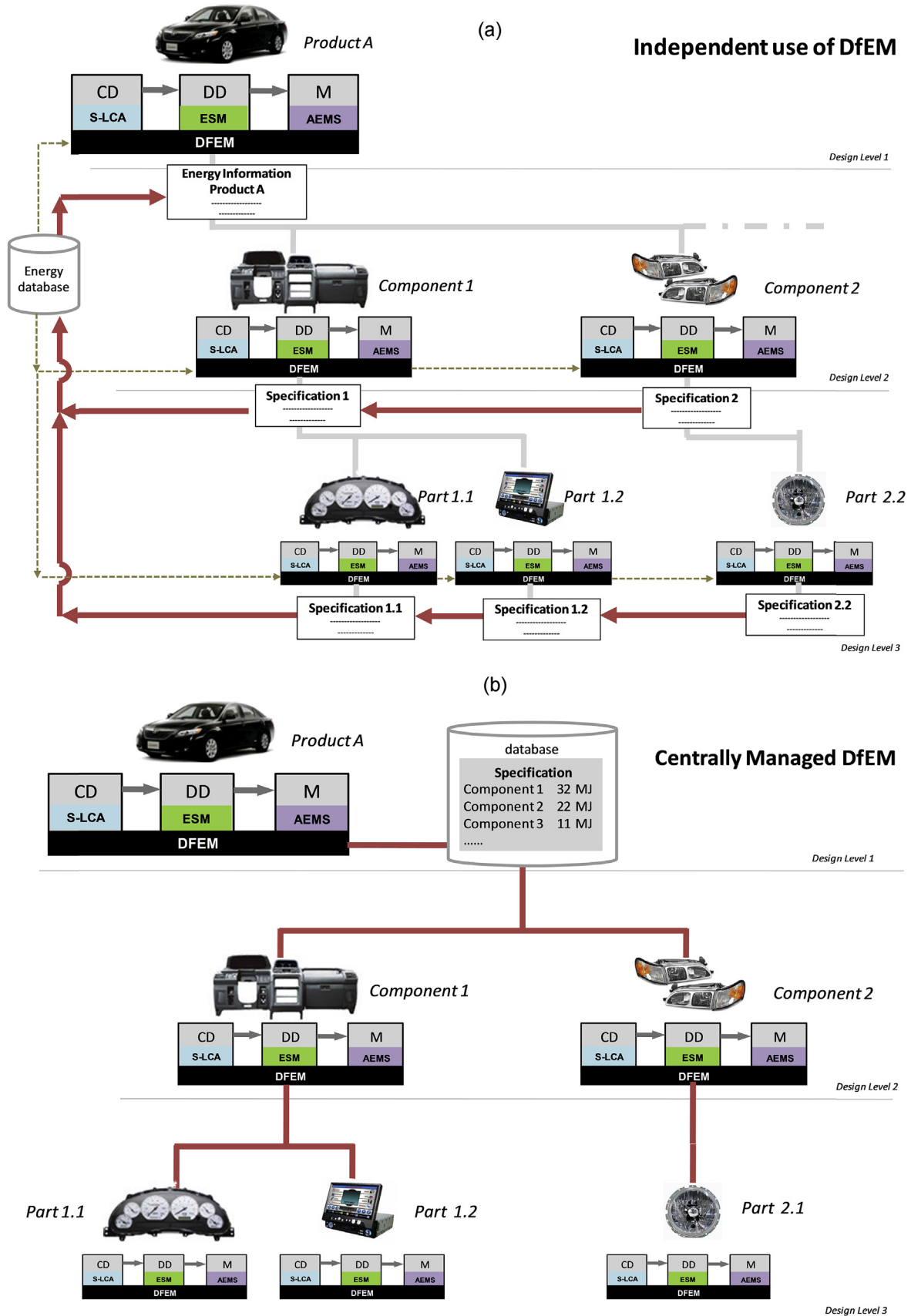


Fig. 9. (a) The independent use of DfEM across the supply chain (b) Central management of DfEM tools to distributed design for complex such as a car.

these activities is managed at the top level to ensure that the common goals are cascaded throughout the design chain.

In support of this coordination process, a centrally managed database of energy related information is made available to all the design levels. This enables the designers to retrieve information related to the products at the levels above or below the level that they are working at. For example, the team at Design Level 1 may not have all the information and knowledge to establish the initial specification, so the database can enable the contract manufacturers who have expert knowledge on the specific components to share knowledge with the design team at level 1 and enable a realistic energy specification to be created. As the database grows, generation of the DfEM database becomes easier.

Simulation models can also be used to provide information on energy usage for manufacturing, but must be closely tied to empirical knowledge to ensure accuracy. For generic processes, existing databases can provide the relevant data, whereas more specialist processes might require empirical measurement. Designers do not necessarily possess this knowledge but can acquire it from process engineers with specialist knowledge.

## 8. Discussion

Design is an integral part of any product development process and much of the decisions taken at this stage accounts for the majority of the financial and environmental cost of a product. Therefore to reduce the energy consumption of a product during the manufacturing stage, energy considerations need to be included at the design stage. By identifying where the energy is used during production and how effectively it is used, the designer gains an insight into the energy efficiency of the process in relation to a product. This knowledge can empower the designer to intelligently explore the suitability of a product feature, a material and consequently the chosen manufacturing process with energy minimization in mind.

The DfEM methodology presented in this paper together with the simulation tool enables designers to carry out 'what if' scenarios in order to identify the most practical and economically feasible design improvements to reduce the amount of energy consumed during manufacture.

The implementation of the DfEM methodology within a practical application necessitates the development of a decision support tool that is capable of representing the complexity involved in modeling and quantifying the Direct Energy (theoretical energy and auxiliary energy) and Indirect Energy for various processes in a typical production system. This is especially important for complex products like cars that may consist of thousands of components, where the model is required to record and analyze the processing parameters of each component and relate it to the energy consumption that can be attributed to each component. This would then provide the data for a quantitative analysis of the energy saved.

Such a quantitative analysis is important, because it allows energy savings to be related to costs, which are an important consideration for any industry. In general, it would be expected that a reduction in energy use would correlate with savings in production costs; however these must also be offset against other factors. The potential capital costs of new equipment as well as the cost in time and effort to implement DfEM policies, arrange new suppliers, certify new materials etc. means that not every product will benefit. If the payback period for production savings to offset implementation costs is too high, then that would rule against the use of DfEM in that specific situation.

As with most Design for X tools which improves design from just one perspective, DfEM only provides a singular view focusing

on energy consumption during production. The reduction of energy consumption in the manufacture phase may have an adverse effect on the other stages of the life cycle. Clearly the scope of this approach has to be extended to consider the energy considerations related to wider issues within a product life cycle such as the energy requirements during the use phase, logistics and reverse logistics and end-of-life.

This approach should be used in conjunction with other life cycle management tools to evaluate the overall life cycle impact of the product to ensure that the absolute environmental impact is reduced and not increased. The matter of minimizing energy consumption of a production system must be addressed as part of a multi-objective optimization process.

## 9. Conclusions

In this work, the DfEM methodology has been demonstrated to be applicable to all three stages of the design and manufacture process: Concept Design, Detail Design and Manufacture. At concept design, a streamlined lifecycle assessment is required in order to give a general prediction of manufacturing energy usage. This is supplemented at the detail design phase using an energy simulation model, which consists of an energy database, a simulation engine which assesses the manufacturing processes with data from the database and a house of quality based tool which uses the simulation results to specify specific design features. During the manufacturing phase, the processes are monitored by an energy metering system which returns empirical data on energy use in the factory, validating the results of the methodology and providing empirical data for further improvements.

The DfEM methodology can be applied to both simple and complex products, using both centralized and decentralized control. In a simple product a single team can systematically consider materials and manufacturing processes in turn in order to minimize the energy use. In a complex product, energy considerations can be controlled centrally from Design Level 1 or individually within design teams at subassembly or component level. Overall energy is then computed from the collective results of these optimizations. This demonstrates the applicability of the DfEM methodology across a broad range of types and scales of industry.

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