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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.

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_2 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

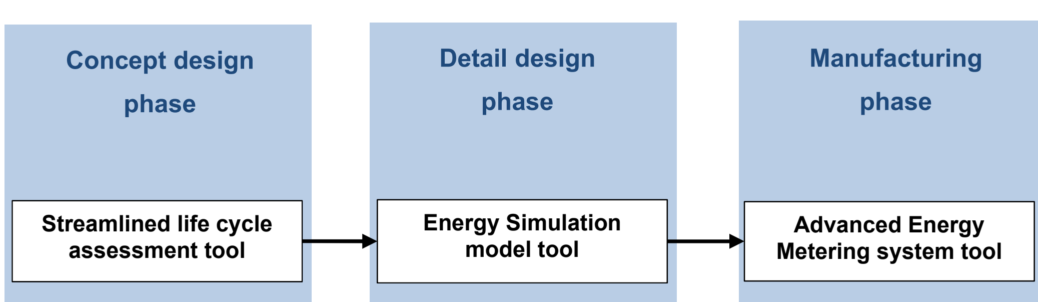

Fig. 1. Simplified DfEM flowchart giving the phases of design along with the relevant tool.