Total design control within the sustainable engineering design process

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Abstract: New engineering products require designing before manufacture, the driving fundamental for which is normally that of cost. The product must be able to be produced as cheaply as possible to increase the profit margin. It is increasingly important to consider environmental issues so that new products incorporate a ‘low environmental impact’. The novel approach presented introduces the design function as the only function within the whole product creation process that can define, direct and apply the principles of sustainability. This paper reviews sustainability principles and enhances the design and manufacture model to encompass the whole life of the product from sourcing to disposal. The life cycle approach is well known but the novel sustainability approach presented considers six ‘life phases’ applying the principles of engineering design to each phase. The management concept has been developed of ‘total design control’ where it is the design function which controls and specifies all six life phases.

Keywords: sustainability; engineering design; design control; embodied energy; whole life model; life cycle analysis; Bruntland.

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Biographical notes: Anthony D. Johnson started his career as an indentured apprentice with the Royal Navy. He worked in a commercial capacity as well as a design capacity in several industries, eventually managing a busy design office for a specialist construction plant manufacturer. He has performed numerous engineering design consultancy projects during his career at the University of Huddersfield where he has taught mechanics, dynamics, strength of materials, automotive design, CAD and engineering design for 27 years. In recent years, the subject emphasis has been to blend the principles of sustainability with engineering design practice.

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1 Introduction

In 1987, Gro Harlem Brundtland published the first part of the ‘Brundtland Commission report’ entitled *Our Common Future* (1987). The report was wide ranging and summarised the three main areas of interest as:

- economic growth
- environmental protection
- social equality

These three elements are commonly known as the triple bottom line. More importantly the Bruntland commission defined sustainability as:

> “Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” [*Our Common Future*, (1987), p.37, para. 1]

True sustainability can be summarised as: development and use of products and services where ZERO resources are taken from the Earth. It is evident however that true sustainability can NEVER be achieved (Johnson et al., 2011), but may be slowed appreciably by applying sustainability techniques.

1.1 Overview and approach to total design control

The classic design approach has been expanded to encompass the six elements attributed to a product life-cycle. A measurement device of ‘embodied energy’ has been applied so that the total design control management strategy (TDCMS) can be implemented and quantified.

The strategy not only includes management control but bases its management evolution on the classic design process sequence and combining implementation and application methods with sustainability audit elements.

Also included is a brief explanation of the embodied energy metric and how sustainability and the total design control (TDC0 management model is combined. The whole process is brought together in a classic case study of a disc type flywheel energy storage system, its TDC management and the methodology behind the various sustainability audits.

There emerges a means of quantifying sustainability in terms of embodied energy so that products leaving the factory can be certified with a sustainability value that can act as a direct competition factor between rival companies, thus driving down the energy required for product creation.

2 Sustainability: whole-life assessment

This section aims to explain how convenient sustainable assessment can be achieved by splitting the life cycle into six discrete elements. Each element is then examined and best practice suggested.
2.1 Classic design and manufacture model extended to encompass sustainability

It has been previously shown by Johnson et al. (2011, 2012) and Johnson and Gibson (2014) that the standard design and manufacture model can be extended to encompass six major phases during the life of the product as indicated by Figure 1.

**Figure 1** The novel sustainable engineering design whole life model

![Sustainable Design Model Diagram]

*Source:* Johnson et al. (2011, 2012) and Johnson and Gibson (2014)

Figure 1 proposes six elements which govern the total life of the product into which sustainability values can be inserted.

1. sustainable sourcing
2. sustainable design techniques
3. sustainable manufacture
4. sustainable use
5. sustainable maintenance
6. sustainable disposal.

Several extra elements have been included enhancing the normal design and manufacture approach. Sustainable material sourcing begins with when the brief is received. Sustainable techniques can then be applied at each stage stretching the sustainable design influence from the reception of the brief through all the phases of product creation, to disposal.

The view is taken that if a product’s life can be extended indefinitely then there will be a reduced need to manufacture new products. Figure 1 shows that product maintenance has now been elevated to a major life phase. Maintenance along with remanufacture and refurbishing are applied to extend the life of the product reducing environmental impact by avoiding primary materials extraction. Remanufacture and refurbishing are included within the end of life disposal phase.
2.2 Design for sustainability: umbrella model

The traditional design and manufacture goal of designing to cost has now been joined by the need to design and manufacture to ensure sustainability. A quote from the anonymous industrialist, Johnson et al. (2011), can be enlarged as follows:

“Everything costs money and everything has an environmental impact.”

All new products therefore now need to be developed for low cost and high sustainability and can often be achieved at the same time. It can be argued that products designed with cost as one of the primary objectives can also be designed to sustainability principles that cover all other facets of the product life process.

2.3 Embodied energy

Energy is required whenever a process is applied to a material. A finished product has had expended on it a certain amount of energy which can be considered as ‘embodied energy’ (Ashby, 2012). This value of energy is often a combination of synthetic energy (usually derived from fossil fuels) and natural energy (e.g. solar, wind, wave, etc) (Johnson et al., 2011).

It is important that the embodied energy value is quantifiable. Since every aspect of the design and manufacture of a product demands that energy is applied, it is put forward that a value of energy per process is an appropriate measurement value. This complicated additive process has been applied (amongst others) by Granta Design Ltd of Cambridge, UK in their software package CES Edupack. Granta Design has created a sophisticated software tool which calculates the Embodied Energy at various stages of a product’s life cycle (Granta Design Limited, 2014).

2.4 The concept of embodied energy as a measurement device

The measurement of sustainability may take several forms depending on the required outcome of the quantification process. Some evaluations may use carbon footprint as a measurement device. The creation of physical products, however, requires energy at every life phase and it is therefore energy measured in Joules that is used as the metric. In order to form a product from original source material energy is applied during the processes and in transport. This total amount of ‘embodied energy’ allows the designer to apply a sustainable efficiency rating to his work.

3 Total design control management strategy

This section aims to discuss the TDCMS, as the management element for the design function which overviews and influences the entire life cycle of a product. A management strategy is explained where the design function is imbued with TDC of all the product life cycle elements. The approach is explained in detail and a sustainability measurement device is applied.
3.1 Overview

TDC is a management strategy that considers the whole life of a product so that the principles of sustainability can be implemented at the design phase of the product creation process. The life cycle of a product can be divided into six elements which range from material sourcing through to end of life disposal. TDC requires that the design team comprises appropriate specialists who can influence the design of the newly created product. Each life phase is therefore scrutinised in terms of energy usage so that the Principles of Sustainability can be applied.

During normal design activity, where reducing cost is the main focus the design function generates 80% of the manufacturing cost (Corbett et al., 1991). It is therefore reasonable to expect the design function to implement sustainability techniques as part of the design focus alongside cost reduction. The strategy is explained below and is exemplified in the case study in Section 4.

The sustainable whole life model in Figure 1 shows that the overall design of a product requires the consideration of the life cycle of the product from sourcing through to disposal. This design overview can only be achieved in its entirety by the designer or the design team. The design function is strategically placed to overview the life cycle and control of all aspects of the design from instigation of the brief through to manufacture, usage through to end of life disposal, including other necessary sections such as marketing. This then is TDC.

The application of TDC means that the designer needs to acquire wide ranging skills which cover the whole life of the product. The designer must not design in isolation or there may be a risk of missing some aspects of sustainability through inexperience or ignorance. The alternative is the assembly of a design team with expertise in material sourcing, transport, manufacturing, maintenance, marketing, recycling, etc. The product is then totally created at the design stage reducing the need for expensive iterations and modifications as each expert processes his own particular element of expertise during the life of the product. The thought given to a product at the design stage can therefore suitably include sustainability where processes can be selected for low energy input.

This approach therefore reduces the embodied energy within the product thus reducing the costs of sourcing, manufacture, lifetime use and eventual disposal. A reduction in embedded energy is a major goal of ‘design for sustainability’ and is therefore symbiotic with a desire to create products at a low cost.

The design and manufacture process should now involve:

- design for low-cost product creation
- design for sustainable product.

Life cycle products designed and created with sustainability as the primary objective also encompasses all the facets of design and manufacture for low-cost.

Consider the sustainable whole life model shown in Figure 1. This can be used as a guide to show the elements which the designer needs to consider and which are set out in the sustainable design objectives model in Figure 2.
The application of sustainability techniques at each stage of the sustainable design objectives model, Figure 2, ensures that all sustainability and cost constraints and requirements are present within the final product. These include standard design requirements such as efficient manufacturing and low manufacturing cost.

The application of the sustainable design engineering whole-life model in conjunction with the sustainable design objectives model ensures that the design function controls the whole design process and in doing so includes all the design objectives required of a new product. This strategy allows the designer to oversee the whole process, integrating procedures and techniques which will serve throughout the life of the product thus creating cost and sustainability efficiencies throughout the six phases of the life of a product.

The design objectives model in Figure 2, Johnson and Gibson (2014) also allows the use of variables for Embodied Energy at each life phase. These are explained as follows:

- **SSV**: sustainable source value: embodied energy required to extract and process the raw material
- **SDeV**: sustainable design value: embodied energy required in the product design process
- **SMV**: sustainable manufacturing value: embodied energy required to manufacture the product
- **SUV**: sustainable use value: embodied energy used by the product during its useful life

<table>
<thead>
<tr>
<th>SLV</th>
<th>SUSTAINABLE SOURCING</th>
<th>TRANSPORT, SOURCE CERTIFICATION, RECYCLED MATERIALS</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDeV</td>
<td>SUSTAINABLE DESIGN</td>
<td>SOURCING, OPTIMISATION, STRENGTH, MODULES, MANUFACTURE, PREDICTION</td>
</tr>
<tr>
<td>SMV</td>
<td>SUSTAINABLE MANUFACTURE</td>
<td>MANUFACTURE TECHNIQUES, SMART FACTORIES, MODULAR COMPONENTS, COMMON PARTS</td>
</tr>
<tr>
<td>SUV</td>
<td>SUSTAINABLE USAGE</td>
<td>POWER SOURCES, POLLUTION, MASS REDUCTION, OPTIMISATION, ENERGY USAGE</td>
</tr>
<tr>
<td>SMaV</td>
<td>SUSTAINABLE MAINTENANCE</td>
<td>REPLACEMENT PARTS, EASY ACCESS, EASY TO DISMANTLE, LONGEVITY</td>
</tr>
<tr>
<td>SDV</td>
<td>SUSTAINABLE DISPOSAL</td>
<td>RECYCLE, REUSE, REFURBISH, REDUCE</td>
</tr>
</tbody>
</table>

*Source: Johnson and Gibson (2014)*
Total design control within the sustainable engineering design process

- **SMaV**: sustainable maintenance value: embodied energy required during maintenance processes
- **SDV**: sustainable disposal value: embodied energy required to dispose of the product.

### 3.2 ISO 14040:2006 and ISO 14001:2004 environmental management systems requirements

TDCMS application provides a product creation organisation (PCO) with the management system and measurement capability for controlled sustainable development of its products. It is important that this management strategy complies with the guidance elements set out in ISO 14001 (2014) and ISO 14040 (2006) since compliance with these standards injects a robust level of quality and consistency to the TDCMS process.

The TDCMS also provides a structured management system that is integrated within the PCO, thus specifying an environmental management system that enables the PCO to develop and implement policy objectives. Such objectives should consider legal requirements and information relating to, in this case, the reduction of embodied energy in during the product creation process.

### 3.3 Design team composition

The design function possesses the wherewithal to design-in features that actively reduce embodied energy and encourage energy gleaning and in doing so combines disciplines normally considered to belong to separate phases of the life cycle. The ‘design team’ should therefore comprise expertise from: design, management, sourcing, manufacture, maintenance and material recovery to name but a few. The composition of a typical TDC development team can be seen in Figure 3.

**Figure 3** The composition of the product development team

*Source: Johnson and Gibson (2014)*
Such a core design team would therefore influence the design and coordinate the six phases by applying sustainability principles at each life phase by measuring the energy. Such measurement will enable analysis of the Embodied Energy leading to its eventual reduction.

### 3.4 Implementation of the TDCMS

The TDCMS can be seen in Figure 4 and links management control elements to the classic design process, forming a process association guide. The use of the classic design process as the general guide allows the implementation energy reduction techniques and measurement methods and permitting the formulation of an overall control strategy using market and maintenance information as a feedback parameter.

**Figure 4** TDCMS (see online version for colours)

<table>
<thead>
<tr>
<th>Total Design Control Management Strategy Phase 1 Embodied Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Management Control Coordination</strong></td>
</tr>
<tr>
<td>Process Planning and Overview</td>
</tr>
<tr>
<td>Product Design</td>
</tr>
<tr>
<td>Product Development</td>
</tr>
<tr>
<td>System Development &amp; Life Test</td>
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<tr>
<td>Manufacture Coordination</td>
</tr>
<tr>
<td>Installation &amp; Test</td>
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<tr>
<td>Market Data Collection</td>
</tr>
<tr>
<td><strong>Classic Design Process</strong></td>
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<tr>
<td>Brief</td>
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<tr>
<td>Product Design Specification</td>
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<td>Concept Design Specification</td>
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<td>Detail Design</td>
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<tr>
<td>Product Specification</td>
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<td>Market Feedback</td>
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<td><strong>Implementation Application Methods</strong></td>
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<td>Design Methodology</td>
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<td>Design Methodology</td>
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<td>Product Design Methodology</td>
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<tr>
<td>System Design Methodology</td>
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<tr>
<td>Smart Factory &amp; Quality Methods</td>
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<tr>
<td>Product Evaluation (Longevity, maintainability) (efficiency)</td>
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<tr>
<td>Maintenance &amp; Repair Data</td>
</tr>
<tr>
<td>Final Product Audit and Certification</td>
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<tr>
<td>R’s Audit (Predictive)</td>
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</tbody>
</table>

When linked to the design process there are four elements to the TDC management strategy: management control and coordination; classic design process; application of sustainable design techniques and sustainability measurement. When these four elements are integrated and linked to the guidance set out in ISO 14001 and ISO 14040, a robust management strategy is provided for sustainable product development.

### 3.5 Classic design process

#### 3.5.1 Level 1: design (product design specification)

A management strategy cannot be undertaken or implemented unless there is some form of guide. In this case the guide is the *classic design process* shown within Figure 4. As
the brief is analysed the design team creates a target list of requirements and constraints for the design. This becomes the product design specification (PDS) and is the first real indicator of the product performance profile.

3.5.2 Level 2: design (concept design specification)

The PDS is used to formulate and synthesise several possible concepts through the various processes of idea generation. This creates the Concept Design with its precise description through the concept design specification (CDS) which should match the PDS. The CDS is relatively low cost with minimal environmental impact involving comparatively few resources. The point at which the product begins to be manufactured incurs much of the initial Embodied Energy and much of the creation cost. The concept design and in particular the CDS is closely scrutinised by entrepreneurs and/or management before resources are committed.

3.5.3 Level 3: detail design (leading to product specification)

Once the CDS has been accepted the feasible theoretical design is converted into a ‘specified design’ product. This ‘detail design’ stage may involve much more work in creating drawings, performing analysis and various tests so that the design function can create a fully specified design. This precise technical output (usually drawings) allows precise manufacture. The product specification (PS) is also produced at this stage which is a factual list of metrics and performance characteristics and should closely match the PDS.

3.5.4 Level 4: manufacturing and test

The next stage is to manufacture and test the product based on the precise technical information from Level 3. Apart from material sourcing this is often the most energy intensive phase and hence the most expensive of the product creation process.

3.5.5 Market feedback

Feedback from the market is extremely important since it gives performance data to the design team which allows new iterations, modifications and confirmation that sustainability criteria have been met. Though the data analysis process is firmly positioned in the product creation element of the life cycle, feedback is returned via the data collection within the product usage and maintenance phases.

3.6 Management control and coordination

The design of the product can be considered to be the primary process leading all the other elements of the management strategy. Until elements of the design have been completed, the project cannot progress and hence design activity is crucial to leading the process.
3.6.1 Process planning and overview

The elements in the management control and coordination column of Figure 4 closely relate to the elements of the design process. At the beginning of the project the management process has several major tasks to sequentially accomplish which are listed as follows:

1. review the brief (generated by the marketing department)
2. assess the project tasks
3. plan tasks week by week (an estimate at this stage)
4. define the skill set the project requires
5. define the team
6. organise the team to discuss, dismantle and disseminate the brief.

From a sustainability point of view, elements 4 and 5 are crucial since these areas that define the team and its expertise. Figure 3 shows the composition of a typical product design team indicating the expertise required from sourcing materials to product disposal. The brief can now be investigated by the team so for complete understanding.

3.6.2 Product design

Management has a major role in controlling the design process and setting the pace, leading the team through investigating the brief to creating the PDS target specification complete with metrics and other measurement features depicting the performance of the future product.

3.6.3 Product development

Management plays a crucial role in this element since it consolidates the team as a design group creating several conceptual possibilities, investigating those possibilities and finally consolidating all the research, idea generation, experimentation into a final concept design. It is a management responsibility to guide the team to ensure that the final concept fulfils the product’s required future performance and attributes of sustainability. The product development phase culminates in a feasibility concept in the form of a CDS which should match the PDS and also look toward reducing the embodied energy during each life phase.

3.6.4 System development and life test

The management element now overviews the conversion of the concept into a real product and is linked to the process by the ‘detail design’ process group in. This phase of the creation process identifies and specifies such elements as: component shape, precise description of components, materials, bought out components, performance, manufacture methods, performance prediction, maintenance processes, end of life disposal, etc.

Management control and coordination is extremely important during this phase since much of the environmental impact and monetary cost is established. The selection of components such as lean burn diesel engines, or specific materials influences the way of
Total design control within the sustainable engineering design process

the product is used during the rest of its life. The introduction of a modern lean burn diesel engine, for instance, will reduce the environmental impact compared to a more inefficient older version diesel engine. The use of water filled solar heating panels will enable extended life through easier maintenance. Compare these to the sealed units of PV panels which cannot be maintained or recycled efficiently.

Careful management control will also specify manufacturing methods. For those products where most of the Embodied Energy is applied during manufacture the selection of appropriate manufacturing techniques falls within TDC control.

3.6.5 Manufacture coordination

Within the selected TDC team there would normally be manufacturing experts who can influence the design to take advantage of efficient manufacturing techniques. Thus far the manufacturing experts have been contributors to the design effort but at this point in the product creation process the manufacturing experts have greater influence. Some manufacturing experts have created 'eco-factories' or so-called 'smart factories' such as Marks and Spencer who have opened several eco-friendly Factories in Sri Lanka, M&S (M&S: Marks and Spencer Ltd., 2013).

3.6.6 Installation and test

Installation and test takes place after manufacture and can be translated as shipping the product to the customer and ensuring correct performance. Whilst many products are tested before they leave the factory large products such as diesel engines, compressors, ships require specialist delivery, installation and testing before handing to the customer. Other items such as toasters, computers, furniture, bicycles etc., can simply be purchased from the retail outlet.

Post manufactory logistical management is part of the process of ensuring the customer receives a quality product. This process needs to be carefully managed so that minimal embodied energy is applied.

3.6.7 Market data collection

The collection of data from products in use is important for product improvement and redesign but also embedded within this management area is that of after sales service and product maintenance. Data collection and feedback allows the product creation team to understand true behaviour of the product enabling more efficient models to be designed but also to ensure logistics are in place to offer spare parts. Market data also provides the TDC team with usage data which allows monitoring of the energy applied to a product during its usage phase. For instance, an item of plant such as a digger may use 110 litres/hr (396 MJ/hr) (Eurostat, 2013) of diesel fuel. Armed with this information the TDC team can refine the design using a more efficient diesel engine which may burn only 100 litres/hr (373 MJ/hr) (Eurostat, 2013).

This process is already achieved to great effect by vehicle manufacturers who routinely gather information on maintenance frequencies and parts use.
3.7 Implementation and application methods

The design function can design-in features into a product that can help reduce Embodied Energy throughout the product’s life cycle. This section discusses design methods and approaches that enable embodied energy reduction.

3.7.1 Design methodology

At the early stages of the design process the understanding of the brief and generation of metrics which define the product’s performance is largely the domain of the design team who would be familiar with appropriate design techniques; however it is important that the non-design specialists within the team have an input. Their influence is crucial to creating a product with reduced embodied energy. This early process leads to the (PDS).

3.7.2 Product design methodology

During the development of a design many new conceptual ideas can be put forward. This process is really the generation of possibilities where the design team may use standard solution generation techniques such as ‘brainstorming’ or perhaps ‘heuristic redefinition’. There may also be substantial research to obtain information relevant to the new product usually following standard design development techniques.

Normally, this process would be achieved by the design team however in implementing TDC, specialists representing each of the six phases of the product life span would have an input. These specialists can contribute extra information and ideas enabling the design of the product to be tuned with the aim of reducing embodied energy. An example of this influence would be that of a product that requires shipping overseas within containers. The designers created a product which, with packaging, could fill a container with only one thousand units. The packaging specialist on the design team may recommend subtle changes in product shape which would reduce the volume of the packaging thereby increasing the capacity of the container to perhaps 1,500. This clearly means that there would be less energy applied to its transport and as a further consequence would reduce the costs of transport.

The product design methodological approach leads to the concept design which is a feasibility study matching the PDS and predicting the performance of the product using metrics within the CDS.

3.7.3 System design methodology

Though designers create the technical information in terms of drawings, models, analysis, etc., the specialists within the group also have an input in terms of materials, components, shape, manufacturing methods, etc. The specialists such as manufacturing engineers, logistics, packaging and marketing will have a much greater input than in the previous solution generation phases.

The manufacturing engineers can specify leaner manufacturing techniques, and suggest particular ‘smart factories’ thus reducing embodied energy. In another example logistics engineers may suggest weight reduction techniques. Purchasing engineers will have the knowledge in locating and reusable parts and recycled materials.
3.7.4 Manufacturing techniques

Corbett et al. (1991) suggested that 80% of the manufacturing cost is developed at the design stage indicating that the design function specifies manufacturing techniques, methods, materials, etc. This is often done without consultation with manufacturing personnel. Similarly, the embodied energy within a product is also defined at the design stage. The influence of manufacturing engineers is that they can apply techniques that reduce manufacturing time leading to reduced embodied energy.

Some techniques that achieve this goal are as follows: minimise the number of parts; use modular designs; employ multifunctional parts (components which perform more than one task); design parts for multi-use (a single handle might be used on several spindles); design parts for ease of fabrication, easy assembly, easy dis-assembly (this also assists with ease of maintenance); minimise handling.

This kind of cooperation combines specialist expertise creating new approaches during the design process with the goal of reducing the embodied energy in the product.

3.7.5 Product evaluation

Before a product is released by the factory it should be thoroughly evaluated for elements of performance such as longevity, ease of maintenance, efficiency in use and ease of sustainable disposal. A customer purchasing a vehicle will need to know its performance characteristics before buying but in this case the evaluation should also include aspects of sustainability.

- **Longevity**: a long lived product avoids the need to purchase new products thereby saving embodied energy applied in initial creation.

- **Maintenance**: some products such as vehicles are maintained as standard since it is realised by users that maintenance will prolong the life of the vehicle. Maintenance may not always be easy to accomplish for the layman. Instead of maintaining the device the consumer who is faced with a broken appliance may merely consign it to the bin. If easy maintenance is therefore built into products then those products will achieve a prolonged life.

- **Efficiency**: a carefully designed product will be efficient in use and will thus have a reduced impact on the environment.

A sustainability evaluation of a finished product is therefore an important aspect in the quest for reducing the embodied energy. If a product does not meet reduced embodied energy criteria then the information should be fed back to the design team to modify the product.

3.7.6 Maintenance and repair data

The data obtained through the maintenance and repair has to be returned via the data collection within the system maintenance embodied energy element.

This data is vital for the design iteration process and feedback to the management control and coordination element who can review the data and make recommendations for the design modifications.
An example of the kind of data which can be fed back to the design team could be the number of ball bearings replaced per year. If this value is greater than the statistical failure expectation then modifications or perhaps new sources of bearing need to be integrated within the design.

3.8 Sustainability measurement and audit

The design process, management control methodology and the implementation of sustainable design methods are important aspects of TDC but cannot be efficiently applied without some form of embodied energy measurement.

3.8.1 Primary audit

The primary audit effectively acts as a first estimate and target value which needs to be reduced during remaining design process affecting the successive life phases of the product.

The primary audit takes place only when the concept design has been formulated. This is the point where a feasible, conceptual design has been created for evaluation by the client/company. The primary audit is the first estimate of the embodied energy required to create the product. Analytical tools such as CES EduPack from Granta Design Limited (2014) extend the estimate to consider much of the post manufacture embodied energy.

3.8.2 Secondary audit

The secondary audit is performed at the end of the detail design stage when components and manufacturing methods have been specified but prior to manufacturing. This audit is more accurate than the primary audit simply because components and manufacturing methods have been closely specified allowing a more accurate analysis. The audit should reveal an embodied energy value less than the primary audit estimate. The management team might accept this value or perform a design review on some high energy value or costly elements in an attempt to reduce Embodied Energy further before manufacturing commences.

3.8.3 Final product audit and certification

The final product audit is performed as the product leaves the manufactory and is an accurate total of the embodied energy applied to the finished product. Embodied energy can be reasonably accurately measured during the life phases within the product creation period. This comprises elements shown in Figure 5.

**Figure 5** Measurement values of product creation embodied energy
Total design control within the sustainable engineering design process

- SLV, sustainable life value: the total value of embodied energy (joules) during the product creation period
- SSV, sustainable source value: the value of embodied energy in sourcing material ready for manufacture
- SDeV, sustainable design value: the value of embodied energy applied during the design period
- SMV, sustainable manufacturing value: the value of embodied energy applied during the manufacturing and test period
- STV, sustainable transport value: the value of embodied energy required to transport raw materials during processing and also from the manufacture to the customer.

3.8.4 Measurement tools
Both the primary and secondary audits have relied on commercial software which is excellent for giving a general overview of embodied energy but does not have the precise detail required for an accurate value of embodied energy. Discussed below is an approach that generates a more precise evaluation of embodied energy for the product creation stage of the product life cycle.

3.8.5 Calculation of SSV
It is notable that sophisticated tools such as CES EduPack treat some elements of the life cycle in a general way. A much more detailed analysis of sustainable sourcing is required. Set out below is a general approach that can be adapted for most materials. In this case the energy source value (SSV) is that for steel.

The sourcing of a material such as steel requires several processes as follows: iron ore is mined; the iron ore is processed into ‘pig iron’; the pig iron is processed into various forms of steel then the steel is then reprocessed into raw components e.g. I-section beams, angles, hollow section, etc.

Transport is also required between processes. All these elements require the application of energy, each element contributing to the embodied energy within the SSV which represents the embodied energy required in extracting and manipulating the raw material for manufacture. It should be noted that since mass is used to measure the processed material a parameter of specific embodied energy (SEE) energy per unit mass (joules/kg) is used.

This can be defined as joules/kg and comprises energy used per kg during:

1. \( E_1 \): extraction (J/kg)
2. \( T_1 \): transport to primary processing plant (power \times time/kg) (Watt.s/kg) = (J/kg)
3. \( P_1 \): primary processing (J/kg)
4. \( T_2 \): transport to secondary processing plant (power \times time/kg) (Watt.s/kg) = (J/kg)
5. \( P_2 \): secondary processing (J/kg)
6. \( T_3 \): transport to tertiary processing plant (power \times time/kg) (Watt.s/kg) = (J/kg)
The following nominal expression can be developed which sums the energy values during the sourcing process.

\[ SEE = E_1 + T_1 + P_1 + T_2 + P_2 + T_3 + P_3 + T_4 \ (J/kg) \]  

(1)

This can be converted to the \( SSV \) by multiplying the \( SEE \) in equation (1), by the mass at each stage giving

\[ SSV = (E_{1m} + T_{1m} + P_{1m} + T_{2m} + P_{2m} + T_{3m} + P_{3m} + T_{4m}) \times \text{mass} \ (J) \]  

(2)

Further transport elements and processes can be added where necessary.

In order to analyse the sourcing process accurately it should be realised that mass needs to be extracted, processed and transported through its various phases during which energy is applied. This is the embodied energy of material sourcing. Hence, before the embodied energy of each phase can be attributed the mass flow has to be calculated.

A similar equation to (1) can be used to describe the mass flow as follows:

\[ SSV = E_{1m} + T_{1m} + P_{1m} + T_{2m} + P_{2m} + T_{3m} + P_{3m} + T_{4m} \ (kg) \]  

(3)

Equation (3) can therefore be represented in a basic mass flow block diagram as shown in Figure 6.

Figure 6  Mass flow block diagram (see online version for colours)

Notes: \( E_{1m} \) = extraction mass; \( P_{1m} \) = primary process; \( P_{2m} \) = secondary process; \( P_{3m} \) = tertiary process; \( T_{1m} \) = mass transport E1 to P1; \( T_{2m} \) = mass transport P1 to P2; \( T_{3m} \) = mass transport P2 to P3; \( W_{1m} \) = waste mass from process 1; \( W_{2m} \) = waste mass from process 2; \( W_{3m} \) = waste mass from process 3; \( N_1 \) = waste fraction from process 1; \( N_2 \) = waste fraction from process 2; \( N_3 \) = waste fraction from process 3.
3.8.6 Sustainable sourcing energy analysis

As each process progresses towards providing a usable material the embodied energy will continue to increase. Each subsequent process will be dependent on the previous process since there will be some waste which will inevitably reduce the total mass to be processed at the next process. The process of converting iron ore to pig iron, for instance, creates about 45% waste (EERE, 2014). Though this is waste, energy is still expended on the creation of usable mass and therefore needs to be added to the embodied energy.

The additive energy equation follows similar lines to the equation shown above for the mass flow process. It must not be forgotten; however, that each transport phase is dependent on the mass generated from the previous process and is reflected in the block diagram in Figure 6.

A specific value of energy of Joules/kg can now be attributed to each of the variables in the key in Figure 6 so that the total energy per unit mass can be related to the mass of material used in creating the product as shown in equation (4).

\[
SSV_{Primary\ Source} = \sum (\text{Energy / Unit Mass} \times \text{Product Mass}) = \text{Source Material Embodied Energy}
\]

\[
SSV_{Primary\ Source} = \sum (\text{joules/kg} \times \text{kg}) = \text{joules}
\]

3.8.7 Calculation of energy used in the design function (SDeV)

SDeV represents the energy used during the design process and comprises the overhead of the design function and should include:

1. heating energy
2. lighting energy
3. electrical energy to run equipment
4. embodied energy of all design function consumables (paper, discs, memo sticks, etc)

This energy would normally be measured in Watts and could be gleaned as part of the overhead energy usage for the factory. Conversion to an energy value in joules would require power × time (Watts.s) where the time element is the average time spent on the design, specification and/or purchase of all components within a product assembly.

\[
O_i = \text{overhead proportion (power \times time) (Watt.s) (joules)}
\]

\[
C_i = \text{consumable EE value (joules)}
\]

\[
SDeV = O_i + C_i \text{ (joules)}
\]

Equation (5) indicates the total energy value accrued during the design phase but this should be divided by the number of products so that a value of embodied energy per product can be attributed. This could be achieved by quantifying the number of completed products shipped from the factory within a time period, say the first year of production. The equation for the modified SDeV reflecting embodied energy per product is shown in equation (6).
3.8.8 Calculation of energy used in manufacturing (SMV)

Since manufacturing processes vary dramatically this calculation has to be tuned to a particular plant. It is suggested that the detailed efficiency of the plant is an ongoing process delivered by manufacturing engineers. The energy per product, therefore, can be linked to the factory overheads including offices where the total energy used in the creation process can be divided by the number of products shipped.

Many components are bought as complete products from specialist companies. Small components may be simple bearings, whilst other components might be engines or perhaps compressors each of which should have its embodied energy value added to the overall embodied energy for the product. Suppliers of some components already supply such a value. For those components which do not possess an embodied energy value the responsibility for providing the energy value lies with the TDC design team.

3.8.9 Sustainable transport value (STV)

This is the final element of the product creation embodied energy value and is the value of energy required to ship the product to the customer based on energy used per unit of mass transported. Equation (7) shows the formulation of the embodied energy value for STV.

\[
STV = C_e \times S \times m \text{ joules/kg}
\]

where

- \(C_e\) transport energy coefficient (Mj/m)
- \(S\) distance transported
- \(m\) mass transported.

The value of the energy coefficient will vary between the various transport modes. For example a light truck of 1.5 t capacity possesses a smaller coefficient than a 14 tonne capacity truck.

3.8.10 Sustainability certificate and the conclusion to measurement of sustainability

It can be seen that the total sustainable life value (SLV) can be evaluated throughout the product creation process as outlined in the block diagram in Figure 6.

As the product leaves the factory it is appropriate to issue a sustainability certificate defining the embodied energy within the product before it reaches the customer. This can be used as a marketing tool since competition with similar products will tend to drive the embodied energy value down with successive iterations.

Throughout the design and build process the measurement of embodied energy within the product is an important management tool by which sustainability can be measured and which the TDC management team can use to review aspects of the product to tune the sustainability requirement.
SUV to SDV embodied energy is largely predictive but an expected ‘end of life’ or SDV disposal element should also be included within the sustainability certificate.

4 Case study: flywheel rotor

Flywheel rotor is used as a case study where measurement values using embodied energy has been applied to the life cycle using an analytical measurement programme.

Figure 7 Flywheel system showing a disc type rotor of 1,600 Kg (see online version for colours)

Figure 8 Output from CES EduPack showing embodied energy throughout the life of the rotor (see online version for colours)

Upon leaving the factory a product is subject to the vagaries of use by the customer which is difficult to predict. Software such as CES EduPack goes some way into resolving these unpredictable elements of the life cycle and can be used effectively in the example of the flywheel rotor to predict usage and end of life (EoL) potential. Figure 7

Source: Granta Design Limited (2014)
A.D. Johnson

shows a conceptual disc type flywheel with the rotor which has a mass of approximately 1,600 kg. An analysis was performed using CES EduPack analytical tool with the results shown in Figure 8.

Energy used in sourcing the material ready for manufacture uses approximately 45,000 MJ and manufacture takes 18,000 MJ. Compared to these values the energy used in transport of 500 km is small at 6,300 MJ but still needs to be included. In use the rotor stores energy and though there are losses due to mechanical friction and fluid friction these are negligible compared to how much energy is saved during use.

At the end of its life the rotor is recycled which requires approximately 2,300 MJ of energy. The EoL potential is gleaned from energy saved during the usage phase and from the recycling element since recycled material avoids the excessive energy required to excavate and process raw material. Through CES EduPack this is estimated to be 36,000 MJ giving a net embodied energy expenditure of:

\[
\text{Net } EE = SSV + SMV + STV + SDV - EoL (SGBV)
\]

\[
\text{Net } EE = 45,000 + 18,000 + 6,300 + 2,300 - 36,000 = 35,600 \text{ MJ}
\]

This information indicates where the greatest value of energy is expended. Once fed back to the design team these estimates can be refined using more detailed techniques as described above in Sections 3.8.5 to 3.8.9. The TDC management team would endeavour to reiterate the design to reduce the energy used in material processing and to reduce the energy applied to the manufacturing process. In this particular case another major goal would be to increase EoL potential which could be done by careful maintenance, thus extending the flywheel life.

5 Design options for implementing sustainability within a product

Aim: since design has been imbued with the ability to influence the entire product life cycle, Section 5 explains how the design function might achieve the reduction of embodied energy throughout the product life cycle.

The reduction of embodied energy is now the main focus for the design team. If this can be reduced within each of the six phases of the product’s life then a higher level of sustainability can be achieved plus a reduction in cost since less energy will be used. Inevitably there needs to be an element of compromise as with most design decisions but a change in attitude by designers which favours sustainable techniques can make positive improvements to the product’s embodied energy value.

In order to implement sustainability techniques the challenge for the design team is wide and varied and will demand a different approach with each varied product. There are, however, universal items which can be implemented for almost any product. There follows brief suggestions of the approach designers could take on the each of the six elements of the whole life model.

5.1 Sustainable sourcing

Designers duty; it is the duty and responsibility of the designer to source materials from sustainable sources having a reduced impact on the planet’s resources. This emphasis should reduce the embodied energy value.
Total design control within the sustainable engineering design process

- source materials from a renewable source (certificated timber, vegetable oils, etc)
- source materials from a local source (thus reducing transport consequences)
- re-use components
- source recycled materials
- design smaller components where possible, thus using less material
- use wind powered/supplemented ocean transport systems as in the Skysails MV Beluga shown in Figure 9.

**Figure 9**  Skysails MV ‘Beluga’ (see online version for colours)

5.2 Sustainable design approach

The design function can apply many procedures that can improve sustainability values. Some of these are obvious and are principally used to reduce cost but equally they can be used to improve sustainability values in a product. Some of these are listed below:

- design using analytical techniques to refine the product thus using less material/prolonging product life
- design on modern 3-D CAD systems which can build the prototype in a virtual 3-D environment, reducing the need for expensive prototype build.
- reduce welding time on fabrications by stitch welding rather than continuous welding
- design for easy assembly thus reducing assembly time
- design the product with easily removable components which can be refurbished or recycled
- reduce the size of the product (reduction of vehicle engine size results in reduced body size, reduced brake systems, improved fuel consumption, etc.)
reduce the sophistication (this leads to easier maintenance)

Within this model designers are now empowered to take responsibility for the environmental impact of their equipment.

5.3 Sustainable manufacture

Energy is used to run manufacturing facilities. When a product is manufactured a portion of energy used to run the factory has to be added to the embodied energy of the product. It is important for factories, therefore, to reduce their energy output and this can be achieved by several methods some of which are suggested as follows: efficient manufacturing and assembly procedures; insulate buildings; rainwater capture systems; sewage digestion; waste recycling; evaporative air-conditioning systems; computer control for efficient component distribution. These are a mere selection of the possibilities.

5.4 Sustainable use

For certain classes of machinery and equipment, the usage element of the life cycle is that which often has the most impact on the environment. In the field of construction equipment and road transport, the energy consumed by a machine in use during its lifetime far outweighs the energy consumed during its production. There follows some suggestions which will help to reduce the energy consumption and pollution during the life of a product: reduce mass, reduce engine size; design optimisation; apply electric motors to use natural energy; use natural energy; install systems that ‘gives back’ energy such as small solar panels on the roof of vehicles.

The complete non-use of fossil fuel power may not be practically achieved in the short-term but it may be significantly reduced in the future as improved techniques become more prevalent eventually trending towards the use of natural energy.

5.5 Sustainable maintenance

If a product’s life can be extended through maintenance the sustainability value is massively improved since a new product does not have to take its place. Modern products are often designed to be ‘throw away’ which is an engrained consumer attitude that needs to change in order to accept products that are maintained for a longer life. Techniques of maintenance are generally designed into the component but could include: sacrificial elements such as bearings or seals; refurbishable components; service in the field function rather than service in the factory; modularisation of product internals (for easy and quick change); efficient lubrication.

5.6 Sustainable disposal

The designer is the creator of the product and has the influence to create a sustainably friendly disposal technique. There are several ways that a product at the end of its life may be utilised or disposed of in a sustainable way:

Sustainable end-of-life disposal techniques which are commonly termed as the 4R’s.
• recycle (common practice for many materials such as steel, glass, paper, card, rubber, etc.)
• repair/refurbish (could be included in the maintenance element but is likely to include substantial work other than pure maintenance)
• re-use (standard components can be gleaned from end of life products as in the use of second-hand vehicle components)
• reduce (reduce volume directed towards land-fill).

6 Conclusions

As world resources gradually diminish the principles of ‘build it and forget it’ can no longer be valid. The original design and manufacture model is therefore is invalid, out-of-date and increasingly irrelevant. The novel model introduced in Figure 1 incorporates the principles of sustainability expanding the original design and manufacture model. This new sustainability model considers a product from ‘source to disposal’ and embodies six sustainability elements. These include: sustainable sourcing, sustainable design, sustainable manufacturing, sustainable usage, sustainable maintenance and finally sustainable disposal.

It is a truism that 80% of the manufacturing cost is defined at the design stage (Corbett et al., 1991). Similarly, the principles of sustainability can only be applied at the design stage. It is within the gift of the designer or the design team to take an overview of the product from sourcing the materials through each phase of the product life down to designing the product so that it can be sustainably disposed.

The application of sustainability principles to a new product can be efficiently achieved by applying the principles of the new management concept of TDC where the design function is in total control of the whole product life process. The design function is the only element in the creation process that can oversee and influence the creation of a product so that the end result possesses efficiencies to achieve low cost and a high sustainability value.

The introduction of a measured value of embodied energy allows the whole life process to be precisely defined, enabling embodied energy target reduction values to be implemented at each life phase. The issue of a ‘sustainability certificate’ can only create competition within companies and between rival firms leading to a reduction in embodied energy for future product iterations.

6.1 Limitations and future study

Precise measurement of embodied energy can be determined as the product leaves the factory but as soon as the product is in the hands of the consumer it may be used in ways that detract from the original design intention. Accurate embodied energy calculation can only be achieved by feedback from the usage, maintenance, disposal elements of the life cycle. Future work will therefore concentrate on elevating maintenance and refurbishment to a level where it dominates the post factory life cycle, generating information feedback that can be accessed by the design function. Such information will
enable the design function to reiterate designs and tune them for better performance and reduced embodied energy.

Greater integration of ISO Standards is also required to platform the TDCMS creating a cohesive structure which will mesh with other ISO management standards.

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References


